Verification of the Use of Hybrid Weather Files for Concurrent Assessment of Space Heating and Indoor Overheating

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Abstract

Balanced consideration of energy use and thermal comfort performance in buildings is warranted to mitigate and adapt to climate change simultaneously in the UK, which necessitates the assessment of both space heating requirements and indoor overheating risk. In addition to heating efficiency, overheating risk assessment is in the process of becoming fully mandatory in building regulations, however, weather files of different types are needed for the evaluation of the two performance metrics via building energy modelling. This paper proposes a method of using hybrid weather data to facilitate concurrent heating and overheating assessment. Through two case studies (domestic and school buildings), it is demonstrated that adopting hybrid weather files can be accurate, time-saving and enable consistent analysis of the interplay between winter heating and summer overheating.

Highlights

- Hybrid weather files are simple yet beneficial to concurrent heating and overheating assessment.
- Computational resources can drop by 38 – 55 % with high accuracy retained at the annual scale.
- Trade-offs between airtightness and ventilation can be better captured in a consistent fashion.

Introduction

Energy performance improvement has been a primary focus in the building sector for decades, driven by policies and regulations in response to climate change (Shrubsole et al., 2019; Mitchell and Natarajan, 2020). Meanwhile, a wide range of indoor environment quality (IEQ) requirements exist for buildings of different types, regarding indoor air temperature and contamination (CIBSE, 2015; WHO, 2021). Traditionally, these requirements would be assessed at separate stages of the design process, but the growing awareness of their synergy and trade-offs in recent years, especially those concerning their impacts on occupant comfort and health, has entailed these performance metrics to be considered simultaneously in the decision-making process (Jain et al., 2020; Kovats and Brisley, 2021; Wang et al., 2021). Particularly in the UK, projections indicate that summers will become hotter and drier, with an increase in the frequency and severity of heatwaves (Murphy et al., 2018). Hence, a pivotal IEQ criterion is the summertime overheating (CCC, 2021), which has been incorporated into regulatory guidance in certain local authorities (e.g. Greater London Authority (GLA, 2022)) or for specific building types (e.g. schools (ESFA, 2018) and new dwellings (HM Government, 2021b)) over the years, and efforts are being made to extend its coverage in building regulations (DLUHC, 2021).

Building energy modelling (BEM) is often a favoured means of analysing building performance, wherein the weather data is an essential boundary condition. One particular issue with regard to concurrent heating and overheating assessment in the UK is that they require weather files of different types (Herrera et al., 2017). To test a building's resilience against heat waves in summer, a Design Summer Year (DSY) weather file is needed, which comprises weather conditions of a warm but not extreme summer. In contrast, a Test Reference Year (TRY) weather file that represents an average state of weather conditions is mostly used to calculate performance metrics in relation to energy or carbon. Building performance under both weather conditions is regulated in the UK, whilst most of other regions' current building codes cover solely the typical ones. Yet, a rich body of literature has been advocating the incorporation of (near-)extreme weather files in addition to typical ones for a more holistic evaluation of building performance around the world, it is therefore expected to be a wider issue in the near future (Crawley and Lawrie, 2015; Cecinati et al., 2019; Guo et al., 2019; Liu et al., 2021).

Two approaches to the analysis of both energy and comfort can be identified from existing literature, either to evaluate both performance criteria using the same weather file (Gupta and Gregg, 2018; Salem et al., 2019; Talami et al., 2021), or to simulate the same model twice using both TRY and DSY data (Mulville and Stravoravdis, 2016; Taylor et al., 2016; Aragon et al., 2018). The first ignores the differing requirements for varied performance metrics, which can lead to their over- or under-estimation. For instance, simulating indoor temperature with average weather conditions, rather than the warmer ones, cannot capture the full magnitude of overheating risk in heatwaves. The second is straightforward and rigorous, but can be extremely time-consuming when a fairly large number of models are involved, as each model needs to be simulated twice with two different weather files. In addition, ventilation and heating systems are affected by factors like the occupancy status that varies across the year. Their computation at different time steps of a simulation in turn influence the calculation of the heating demand and the indoor temperature. Therefore, concurrently evaluating them in one simulation would better capture such interaction and facilitate a consistent comparison of the interplay between summer overheating and winter heating under different building design scenarios.

Recognising the need for concurrent evaluation of energy and comfort performance via BEM, the approach of hybrid weather files is proposed. It was initially adopted in the work by Grassie et al. (2022), this paper aims to provide an extensive discussion on its validation and application in the scope of heating and overheating assessment of efficiency and consistency. Accompanied by two case studies of varied building types, detailed objectives of this study are:

- to present a recommended workflow of adopting the hybrid weather file approach;
- to examine the validity of the hybrid weather file approach in a case of residential buildings;
- to explore the application of the hybrid weather file approach in a case of educational buildings.

Methods

This section starts with a discussion of the recommended workflow of adopting the hybrid weather file approach, followed by a brief description of the two case studies and the common parts of their methods, with further details provided later in respective case study sections. To exemplify the approach, this work sets the context in the UK, but it is considered adaptable with ease to other regions with different weather file types and building performance metrics of interest.

Implementation workflow

The proposed workflow of incorporating the hybrid weather file approach is outlined as follows:

1. Synthesise the hybrid weather file from the two original weather files of varied types.
2. Evaluate the validity of the hybrid weather file via a sample of the study.
3. Apply the hybrid weather file to the corresponding study at full scale.

Aside from a few custom weather file formats used by commercial building simulation engines (e.g. .fwt for IESVE), the .epw format has been dominating the market driven by the popularity and the open-source nature of EnergyPlus (Crawley et al., 2001; Herrera et al., 2017). Along with the first eight lines of attributes regarding the weather location, it is a plain-text file that usually contains a whole year of numerous hourly weather variables in sequential lines (Crawley et al., 1999), which leads to an easy synthesis process by combining different lines of hourly data. The preceding attributes are less commonly used in simulation practice, extra judgement is needed during the synthesis process when they are involved.

To harness the benefits of using hybrid weather files discussed in the previous section, its validity is of vital importance. Specifically, the validity of the hybrid weather file approach refers to its ability to produce simulation outputs that are identical to or well approximate those via the original weather files. Due to the complex interaction between performance evaluation schemes and weather data they require, it is not practical to provide a theoretical/analytical validation of the hybrid weather file approach. But rather, it should be approached empirically/numerically, where a parametric analysis is recommended to confirm the result accuracy before conducting full-scale analysis.

Case studies

The first case study provides an exemplary validation of the hybrid weather file approach in assessing heating and overheating in dwellings, and the second case study intends to showcase its application potential by analysing the interaction in the fulfilment of winter energy and summer comfort requirements in schools.

In both case studies, TRY and DSY data were used for heating and overheating assessment respectively. To synthesise the hybrid weather file, hourly entries from coincident TRY and DSY files were both split into three slices around the summer period, following the definition in Technical Memorandum (TM) 52 that is shared by TM59 and Guide A (i.e. May to September inclusive) (CIBSE, 2013, 2015, 2017). The slice of 1 January to 30 April and that of 1 October to 31 December were taken from the TRY, inserted by that of 1 May to 30 September from the DSY. This synthesis process can be depicted in Figure 1.

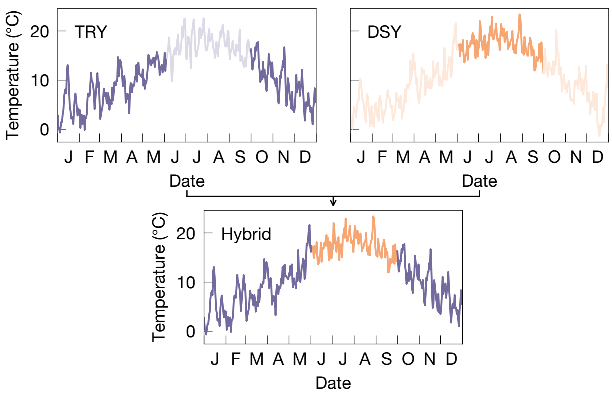

Figure 1: Synthesis of the hybrid weather file illustrated using the daily outdoor dry bulb temperature.

The modelling was conducted via EnergyPlus (Crawley et al., 2001), a key principle in both case studies was the non-overlapped heating and overheating assessment. That is, the overheating risk was evaluated only during the summer period, and the space heating outside the summer period (i.e. October to April inclusive). Whilst heating is a direct EnergyPlus output, overheating risk was assessed based on the TM59 methodology, which provides a standardised approach to overheating prediction and includes two separate criteria for sleeping and non-sleeping occupied hours. The second case study used only the diurnal criterion, as a nocturnal assessment is not needed for educational buildings. In contrast, the first case study on residential buildings applied both criteria, but adjustments were made to the nocturnal criterion to meet the 'non-overlapping' principle, which was discussed in detail in the work by Cui et al. (2022). The criterion thresholds were not followed as a pass/fail outcome is unnecessary in this study.

Case Study 1 – Validation

Methods

This case study was conducted in the context of dwellings. Three streamlines of modelling were separately conducted using TRY, DSY and hybrid weather data, with identical model configurations and performance evaluation schemes for coincident weather files. A two-storey mid-terraced house (three bedrooms, one living room, one kitchen, one dining room and one bathroom) and a top-floor high-rise flat (two bedrooms, one living/dining room, one kitchen, one bathroom) were modelled. They were adapted from the models developed by Cui et al. (2022), where a detailed description of model geometry, summertime internal gain profiles and base building fabric properties can be found. The main modification was adding a wet heating system for space heating assessment, where the heating set points and operating schedules, along with winter internal gain profiles, followed the National Calculation Methodology databases (BRE, 2022).

In evaluating the validity of hybrid weather files across diverse building design strategies, a parametric study was incorporated. Specifically, the PROMETHEUS future weather dataset (Eames et al., 2011) was used along with five building fabric parameters, their variations are tabulated in Table 1. The PROMETHEUS weather files are accessible in the format of three time periods (2030s, 2050s, 2080s), two emissions scenarios (A1B, A1FI) and five percentiles (10th, 33rd, 50th, 66th, 90th). This resulted in a search space containing 4.5×10^4 possible combinations of the six parameters, from which 400 simulations were sampled as per the Monte Carlo method. Natural gas consumption of the hot water boiler in the model was adopted as the indicator for the heating energy use. The coefficient of determination (R^2) was used to facilitate statistical measurement of discrepancy between evaluation results generated by the hybrid weather file and those by the original weather files.

Table 1: Parameters and variations in dwelling models.

Parameter		Variations		
Weather		2030s, 2050s, 2080s	A1B, A1FI	10th, 33rd, 50th, 66th, 90th
Insulation thickness	Wall Roof Ground floor	0, 50, 100, 150, 200 mm		
Glazing conductivity		0.8, 1.2, 1.6, 2.0 $\mathrm{W\,m^{-1}\,K^{-1}}$		
Window gas		Air, Argon, Krypton		

Results

Reducing simulation time is the most straightforward benefit of the hybrid weather file approach. Figure 2 depicts the distribution of ratios of the simulation time via both the TRY and the DSY weather files to that via the hybrid one for each dwelling on the same computer. The ratios have a median of 2.02 with a 90 % interval between 1.96 and 2.07 for both the mid-terraced house and the top-floor flat (after rounding). This suggests that the hybrid weather file approach will save the simulation time by at least 48.97 % in the majority of cases, and most likely only half of the computational resources will be needed. The slight deviation from the baseline (50 %) in some cases may be a consequence of computing overheads.

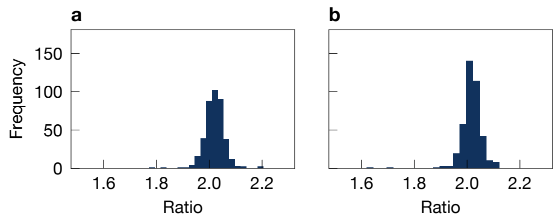

*Figure 2: Distribution of ratios of the simulation time via both the TRY and the DSY weather files to that via the hybrid weather file for the mid-terraced house (**a**) and the top-floor high-rise flat (**b**).*

The annual heating energy use for both dwellings was normalised by respective total floor areas, their coincident TRY and hybrid results are separately plotted against one another in Figure 3. As clearly indicated, the natural gas consumption simulated by both weather data is in great alignment, with a very limited number of data points visibly deviated from the identity line[1]. This high proximity can be quantitatively measured using R^2, which is above 0.9999 for both dwellings. Similarly, Figure 4 depicts the coincident DSY and hybrid results of summertime overheating rates, with high proximity to the identity line and high R^2 values for both dwellings. They collectively suggest that the error stemmed from the hybrid weather data is considerably marginal at the annual scale.

[1]The identity line in this context is a reference to an identical evaluation result via the hybrid and the original weather data.

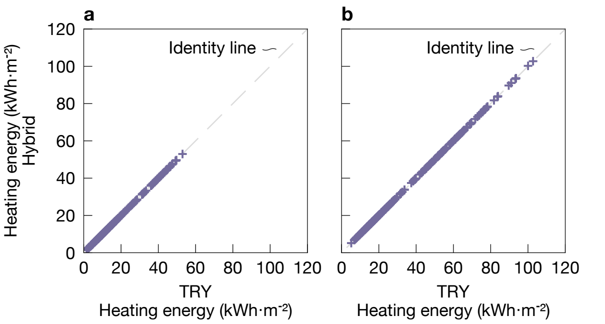

*Figure 3: Comparison of annual heating energy consumptions between the TRY and the hybrid weather file outside the summer period for the mid-terraced house (**a**) and the top-floor high-rise flat (**b**).*

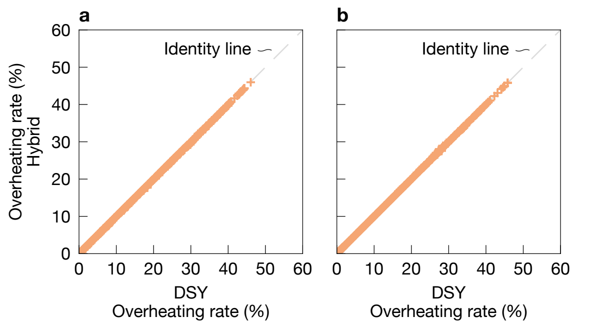

*Figure 4: Comparison of annual overheating rates between the DSY and the hybrid weather file during the summer period for the mid-terraced house (**a**) and the top-floor high-rise flat (**b**).*

Acknowledging that the use of hybrid weather data can lead to very limited error, it is still worth taking a closer look at the source of this marginal discrepancy. Figure 5 and Figure 6 illustrate the changing in R^2 of heating and overheating data respectively on a daily basis. There is a clear pattern of considerably low R^2 values occurring at the beginning of a new assessment period (i.e. early May or October) for both building performance metrics, which seems more drastic concerning the overheating rate. Nonetheless, these values will swiftly bounce back to higher than 0.9 within 15 days. This indicates that the simulation results between the original and the hybrid weather files can have a fairly weak agreement entering a new assessment period, but such difference tends to diminish over a very short time. This temporary deviation is likely a phenomenon of thermal inertia in buildings, where a time series of different preceding weather conditions exists in the hybrid weather file from those in the original weather file.

Distinct from heating energy use as a direct BEM output, the overheating rate is a secondary performance metric, calculated by indoor operative temperature, outdoor running mean temperature and occupant presence. In this study, the occupant presence was fixed as per the TM59 methodology, and the same DSY-generated running mean temperature series was used. Therefore, the difference in the assessed overheating risk solely originated from that in the indoor operative

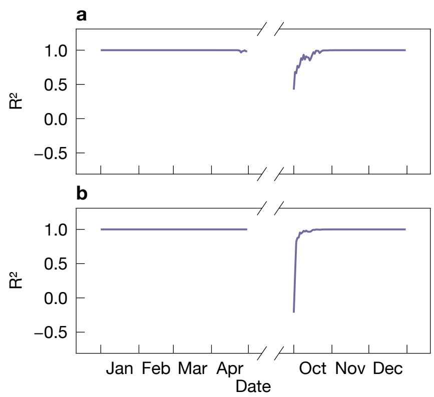

*Figure 5: R^2 of daily heating energy consumptions between the TRY and the hybrid weather file outside the summer period for the mid-terraced house (**a**) and the top-floor high-rise flat (**b**).*

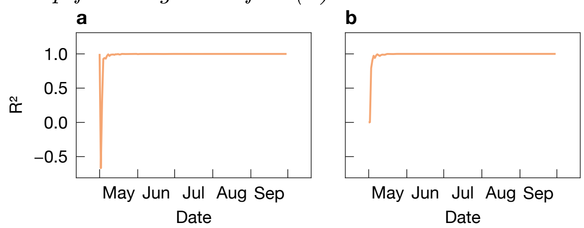

*Figure 6: R^2 of daily overheating rates between the DSY and the hybrid weather file during the summer period for the mid-terraced house (**a**) and the top-floor high-rise flat (**b**).*

temperature, visualised in Figure 7. The consistency in the temporal trend between Figure 6 and Figure 7 is evident, the absolute difference in daily mean operative temperature drops to below 0.3 °C within ten days for both case study dwellings. With a temperature deviation of such magnitude, which is even more insignificant in later days, it is difficult to determine whether this should be attributed to different thermal inertia characteristics, or algorithmic noise.

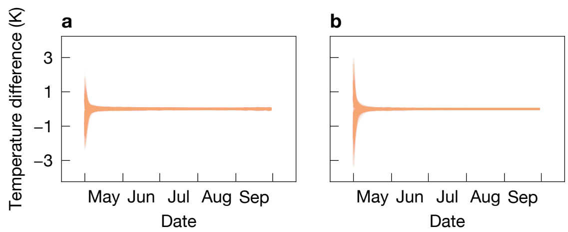

*Figure 7: Difference in daily mean temperature between the DSY and the hybrid weather file during the summer period for the mid-terraced house (**a**) and the top-floor high-rise flat (**b**).*

Case Study 2 – Application

Methods

Within the UK school building stock, the consequences of retrofit on health and attainment of children have provided an ideal setting for analysing the application of the hybrid weather files, over a large number of classroom settings (Grassie et al., 2023). These simplified single-sided ventilation models applied the following constraints:

- Classrooms were occupied from 9 am to 4 pm on every weekday of the year (ignoring holidays) at a density of 0.55 students per square metre, with each student emitting 70 W of heat.
- An ideal heating system was applied when indoor temperature dropped below 20 °C from 7 am to 6 pm during occupancy. Otherwise, a minimum temperature constraint of 12 °C was applied.
- Natural ventilation was provided through a single window, covering 25 – 30 % of the external wall, depending on the construction era and the glazing ratio of corresponding buildings as per EFA (2015). For the base operation scenario, ventilation was available when temperature in occupied classrooms exceeded 23 °C. For the overheating mitigation scenario, ventilation was available even without occupancy on weekday nights. Forced ventilation was applied for ten minutes at the start of each hour, to simulate the purging of excess carbon dioxide at the start of each class.

The case studies were provided by Grassie et al. (2023), who created school archetypes of different construction eras and geographical regions across the UK. These were then simulated for a range of energy and comfort performance criteria across various climate, retrofit and overheating mitigation scenarios. A subset of settings used within the school building stock models has been selected to specifically demonstrate the interactions between winter heating and summer overheating, as set out in Table 2. In contrast to the first case study, heating demand was applied as the energy indicator, and the CIBSE weather dataset was used.

Table 2: Settings and scenarios in school models.

Category	Stock model	Chosen
Climate conditions	13 climate regions 3 time periods	London 2020s, 2050s
Base archetypes	5 construction eras 4 orientations	Pre-1918 North, East, South, West
Design scenarios	4 retrofit scenarios 6 IEQ scenarios	Base, IntR BaseOp, Cumtve

Base: no retrofit; IntR: intermediate retrofit;
BaseOp: no overheating mitigation operation;
Cumtve: full overheating mitigation operation.

Results

When applied to design of school buildings, overheating is usually determined as a pass or fail rather than an extent to which a building may be susceptible. The TM59 criterion for the non-sleeping hours concerns the total overheating hours, and specific school heating and ventilation guidance prescribes that new building design should result in no more than 40 hours of annual overheating hours (ESFA, 2018). However, a key issue is that, close to the 40-hour limit, very small changes in design can lead to large changes in evaluation. The distinction between cooling and heating seasons was also verified, since no overheating hours were recorded outside summer and no heating loads during summer for any of the models.

In contrast, a 'low as reasonably possible' approach was applied to annual energy consumption, based on required maximum U-values of various building fabrics such as windows, walls and roofs based on the UK Building Regulations (HM Government, 2021a). Within any cost constraints, optimising design will involve minimising energy consumption after separately verifying that the threshold for overheating hours is met. Figure 8 overlays heating demand and overheating hours across the year for the non-retrofit case with full overheating mitigation measures (Base+Cumtve[2]) in a west-facing classroom in the 2050s.

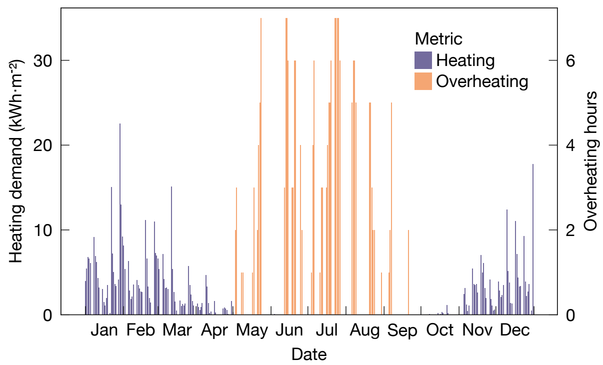

Figure 8: Daily heating demand and overheating hours for the west-facing Base+Cumtve case in the 2050s.

Figure 9 is a scatter plot of overheating hours versus heating demand for the four combinations of retrofit and overheating mitigation scenarios with different time periods and orientations. This plot shows the trade-off between minimising overheating hours and heating loads as retrofit is applied. In this case, it is clear that applying the range of overheating mitigation measures is beneficial in reducing the overheating hours for both Base and IntR retrofit scenarios. However, the optimum degree of retrofit for reducing both overheating hours and heating demand is unclear, since the additional retrofit, whilst reducing heating loads in winter months, leads to a greater number of overheating hours.

Discussion

Critique of the approach

This paper proposes the use of hybrid weather files, when weather files of different types are required to assess building performance via BEM in the decision-making process. Two cases studies were presented to demonstrate the validation for and the application of the proposed approach. It is important to highlight

[2]The combination of the two retrofit scenarios (Base, IntR) and the two overheating mitigation scenarios (BaseOp, Cumtve) from Table 2, namely the design candidate, is denoted by their concatenation via '+' hereafter in this paper.

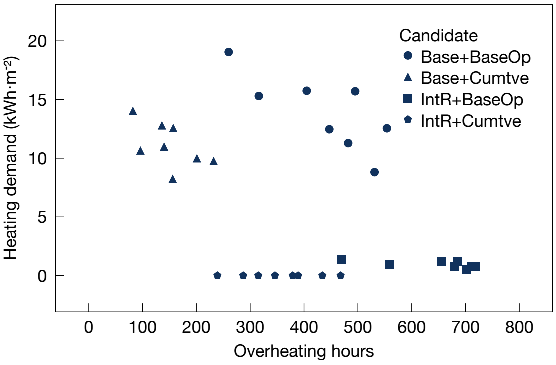

Figure 9: Comparison between annual overheating hours and heating demand for the four design candidates with different time periods and orientations.

that this work has no intention to claim universal applicability of the approach, but rather to verify its validity given certain conditions, where its implementation is simple conceptually and operationally, yet beneficial to efficient and consistent evaluation. It is recommended to undergo a validation test pertinent to the specific weather data and building performance metrics in action, before applied at scale.

One straightforward benefit is the significant reduction of simulation time with high accuracy retained. Varied by different model specifications, using the hybrid weather data should take roughly half of the time that is needed by using the TRY and the DSY separately to evaluate both heating and overheating performance. This may seem trivial when only a small number of simulations are involved, but can be significant in large-scale applications. One example is when simulations need to be carried out for a large number of climate change projections, which may become a routine for modellers in assessing building performance in the near future. It helps not only improve the viability of such studies that require considerable computational resources, but reduce their environmental impacts, as relevant concerns have recently risen around high-performance computing (Portegies Zwart, 2020; Lannelongue et al., 2021). Meanwhile, the additional error introduced by the hybrid weather file is negligible as shown in the first case study, especially at the scale of annual variables. It can be observed that such accuracy varies as per the temporal resolution of assessment, where a higher resolution may reveal larger deviation from the TRY and the DSY outputs. During the analysis, hourly data (not presented in this paper) were characterised by more fluctuations in the evaluation error than the aggregated (i.e. daily or annual) data analysed in the first case study. This provides a threshold for the validity range of the hybrid weather data, suggesting that high discrepancy should be expected when the analysis of variables of high temporal resolution is in demand. On the other hand, annual data, or aggregated data across the run period, is more commonly used in a wide range of BEM-based techniques, such as sensitivity analysis and optimisation, where intrinsically a scalar variable is needed as a proxy of each building performance metric that is coincident with a certain combination of building characteristics.

Implications of the discrepancy

Meanwhile, the increased error in high-resolution data follows a certain pattern, which is to a certain degree predictable. As depicted in the daily R^2 and indoor temperature values, large deviation is observed at the beginning of the assessment period, and tends to decline considerably over time. As previously analysed, these errors are considered to mostly stem from building thermal inertia, as the only variation in simulation settings between a comparison pair is the weather file in use. The varied durations of fluctuations, therefore, result from the difference in thermal mass across models with different fabric configurations. Consequently, models with a light-weight structure should mitigate this deviation more swiftly, as they are more responsive to the varying ambient climatic conditions. In the case studies of this work, it is assumed that the assessment periods of heating and overheating are adjacent, which may not always be the case. In reality, a heating-dominant region such as the UK may have a transition period between winter and summer seasons, which can further reduce the deviation caused by the hybrid weather data. In contrast, the assessment periods may overlap with one another in the case of stricter requirements such as in care homes, or in the case of non-seasonal building performance metrics such as equipment electricity consumption. On such occasions, caution should be engaged in pre-assessing the validity of the hybrid weather file approach, which may even be entirely invalidated.

Particularly in the first case study, it is worth mentioning that another factor is influencing such deviation in the mid-terraced house case. Rather than a fixed ground temperature that is usually adopted in practice, the Kiva algorithm (Kruis and Krarti, 2015) was used to manage the ground floor heat transfer, which takes the annual weather conditions into account to initialise the periodic soil thermal conditions. This induced slightly larger deviation, especially visible from the heating energy consumption in the first period of assessment, where there is no otherwise impact of thermal inertia from the preceding simulation period.

Future considerations

The second case study illustrated a method of calculating combined heating load and overheating hour changes to the building stock within the same model. While these changes are easy to quantify individually, this work demonstrated the need for more informative metrics which provide additional details on the trade-off between overheating and heating load of new or retrofitted buildings. Meeting a maximum total of annual overheating hours and assessing it at a different phase from energy-in-use could lead to thermal comfort performance being devalued later on in the design process, when analysing how to minimise heating demand, since both are heavily interlinked. While a ratio of overheating hours to annual heating load could trivialise differing features of heating and overheating profiles for different conditions, a suite of metrics describing the annual profile of heating load and overheating hours could lead to more informed decisions being made on design and operation. Also, it is recognised that the warming climate can potentially exacerbate chronic overheating (McLeod and Swainson, 2017), which would essentially provoke uncertainty in winter-summer transition.

Conclusion

This paper demonstrated a hybrid weather file approach to concurrent assessment of building performance that requires different types of weather data, via two case studies of space heating and indoor overheating. The validation suggested that using hybrid weather data can produce performance evaluation results of fairly small discrepancy, whilst reducing computing cost significantly. It has also been shown that the approach poses great potential of facilitating consistent and transparent analysis of the interplay between summer comfort and winter energy in the UK context. Despite these key benefits, one major limitation of the hybrid weather file approach is its uncertain applicability under varying performance assessment requirements across different regions. A validation test, as showcased in this paper, is recommended to be conducted before its implementation at scale.

Acknowledgement

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