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Towards an overheating risk tool for building design

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Structured Abstract

Purpose

The work set out to design and develop an overheating risk tool using the UKCP09 climate projections that is compatible with building performance simulation software. The aim of the tool is to exploit the Weather Generator and give a reasonably accurate assessment of a building's performance in future climates, without adding significant time, cost or complexity to the design team's work.

Methodology/approach

Because simulating every possible future climate is impracticable, the approach adopted was to use principal component analysis to give a statistically rigorous simplification of the climate projections. The perceptions and requirements of potential users were assessed through surveys, interviews and focus groups.

Findings

It is possible to convert a single dynamic simulation output into many hundreds of simulation results at hourly resolution for equally-probable climates, giving a population of outcomes for the performance of a specific building in a future climate, thus helping the user choose adaptations that might reduce the risk of overheating. The tool outputs can be delivered as a probabilistic overheating curve and feed into a risk management matrix. Professionals recognised the need to quantify overheating risk, particularly for non-domestic buildings, and were concerned about the ease of incorporating the UKCP09 projections into this process. The new tool has the potential to meet these concerns.

Originality/value

The paper is the first attempt to link UKCP09 climate projections and building performance simulation software in this way and the work offers the potential for design practitioners to use the tool to quickly assess the risk of overheating in their designs and adapt them accordingly.

Keywords:
Buildings, climate change, overheating, thermal comfort.

Introduction

The global climate is getting warmer, a reality that is most probably due to increased levels of greenhouse gases in the atmosphere as a result of human activity (Stott et al, 2000). Consequently, governments worldwide have pledged to reduce emissions in order to slow down the rate of warming (UN, 2012). In the built environment this mitigation typically takes the form of a move, backed up by regulations, towards low carbon buildings that are more highly insulated and more airtight, and use less energy, with an increased proportion of that energy obtained from low carbon sources (EC, 2010). However, even if this strategy succeeds in slowing the rate of warming, the climate-changing legacy of the existing high levels of greenhouse gases will remain. Furthermore there is, unfortunately, no sign of building occupants giving up their (unregulated) energy-consuming appliances, even if these are driven by low carbon electricity. When the incidental gains from appliances and the metabolic gains from occupants combine with a warmer climate there is potential for overheating because the heat produced is retained in the internal environment of highly insulated, airtight low-carbon buildings. Serious overheating has been observed in schools, offices and dwellings, and required remedial measures (Waite, 2009, Colley, undated). Apart from the issue of thermal comfort, overheating encourages the use of artificial cooling, where none was needed previously, and this introduces a fresh source of emissions, making it more difficult to meet the reduction targets. Therefore, overheating that leads to increased cooling demands runs counter to the carbon reduction agenda and must be avoided wherever possible.

At the same time, both existing buildings and those currently at the design stage must continue to perform satisfactorily in the environment over their lifetime (at least several decades): a designed Normal Life of 60 years (BSI, 2003) means that buildings being designed now will be just reaching the end of their life in 2080, when the climate will be much warmer than that used in their design. Since adaptation of buildings costs money and resources, to say nothing of the disruption and inconvenience caused by a retrofit programme, design practitioners need the tools now that will enable them to design buildings to function in future climates. Important questions are the extent and adequacy of our understanding of what the future climate will be and how this understanding can guide the design and retrofit of the built environment.

In the UK, several research projects under the umbrella of the Adaptation and Resilience to a Changing Climate Coordination Network (ACN, 2013) have addressed the impact of climate change on the built environment and provided evidence to enable the design of urban and suburban systems that are more resilient to climate change. Mavrogianni et al (2011) investigated the implications of the urban heat island effect, with special reference to London, using an energy demand prediction technique developed by Kolokotroni et al (2010). Gupta and Gregg (2011, 2012) assessed adaptations to suburban dwellings and neighbourhoods to deal with a warming climate. Porritt et al (2012a,b) simulated existing dwellings and confirmed that retrofitting for energy efficiency has the potential to increase overheating dramatically. In addition, Eames et al (2011) and Kershaw et al (2010, 2011) developed future climate 'reference years' that can be used in performance simulation of new buildings at the design stage. However, none of this work meets the requirements of building design practitioners needing to assess overheating in their designs. The objective of the work described in this paper was to produce a method of assessing overheating that would be able to use the latest climate projections in building performance simulation software in a way that design teams can understand.

Climate projections

Computer models of the climate have been developed over many years and are based on the known laws of physics, describing mass and energy transport. These equations are solved at intervals of time at a number of points forming a grid over the globe and attempt to replicate the interaction between physical processes occurring in the atmosphere (solar radiation, convection etc) and in the oceans (currents, circulation etc) to estimate climate conditions. They are intensive in computing power and ultimately predict how the weather variables such as temperature, solar radiation, wind speed and direction, relative humidity, cloud cover and snowfall will vary with time. The UKCIP02 climate change scenarios (Hulme et al, 2002) were based on four 'storylines' developed using economic and political judgment by the Intergovernmental Panel on Climate Change (IPCC, 2000). From these storylines four CO_2 emissions scenarios – low, medium-low, medium-high and high – were developed and give global CO_2 concentrations over successive 30-year time-slices (i.e. 30-year periods centred on a particular decade, e.g. '2080s' implies the period 2070-2099). The UKCIP02 report is explicit about its inability to attach probabilities to the four future climates so produced (Hulme et al, 2002) and these are therefore deterministic climate projections, giving at a 50km spatial resolution a single value of each weather parameter with no associated indication of uncertainty. These projections are widely used and a morphing algorithm can be used to produce weather data for building design in future climates (Belcher et al, 2005).

The latest generation of climate projections – UKCP09 (Murphy et al, 2009) – are a development of the previous set at 25km spatial resolution, include more sophisticated feedback modeling, and for the first time are probabilistic. Three of the IPCC storylines, giving three emissions scenarios (high, medium and low), are used to produce weather parameters in the form of probability density functions and cumulative density functions. The probabilities represent the relative degree to which each climate outcome is supported by the available evidence, and are presented as percentiles. The median or 50th percentile climate means that the evidence suggests that this climate is as likely as not to be exceeded, whereas the 10th percentile is very likely to be exceeded and the 90th percentile is very likely not to be exceeded. An example of the changes by the 2080s under the medium emissions scenario is that summer mean temperatures increase by 4.2°C (50th percentile) in southern England and 2.5°C in the Scottish islands, with 10th and 90th percentile ranges of 2.2-6.8°C and 1.2-4.1°C respectively. The UKCP09 projections used in this paper are derived from the Weather Generator (Jones et al, 2009) which provides synthetic daily time series of weather parameters at 5km scale. It requires the user to choose an emission scenario (low, medium, high), the time period of study (decades 2010-2099) and the location (5km grid squares in UK), from which 3000 climate files are produced to build up the probability density function.

Risk and its management

Risk is an everyday word with shades of meaning and consequently many definitions have been proposed, including 'the existence of threats to life or health' (Fischhoff et al, 1984), 'the chance of some adverse outcome [such as] death or contraction of a disease' (Kleinbaum et al, 1982), 'opportunities whose [economic] returns are not guaranteed' (Camerer and Kunreuther, 1989), 'the possibility of either financial or physical damage (Starr and Whipple, 1980), 'the possibility of some adverse effect resulting from a hazard' (Lowrance, 1976), 'the potential of unwanted negative consequences' (Rowe, 1977), and 'a measure of the probability and severity of adverse effects' (Yates, 1992). These definitions suggest that risk has two characteristics: uncertainty, i.e. the probability of an event happening, and impact,

i.e. the unwanted consequences of the event. Therefore risk management, which is a well developed approach in the construction sector (Godfrey, 1996), involves identifying the individual hazards facing a project, organization or activity and placing them on a risk matrix of the type shown in Fig. 1. The two axes can be represented as either ordinal scales, for example zero to 100% probability (0 = will not happen, 100% = certain to happen) and zero to a finite financial impact, or subjective categories, for example low-medium-high. Since it is normally impossible to eliminate all risk in an activity, risk management aims to consider all hazards, to identify those with both high probability and high impact and then to manage them in such a way that they congregate towards the bottom left of the matrix. Acceptable levels of risk are usually defined in a workshop process, which captures the perspectives of different stakeholders, and one way of visualising this is by the curve marked on Fig. 1: hazards above and to the right of the curve would be considered unacceptable and need management action to move them into the acceptable region.
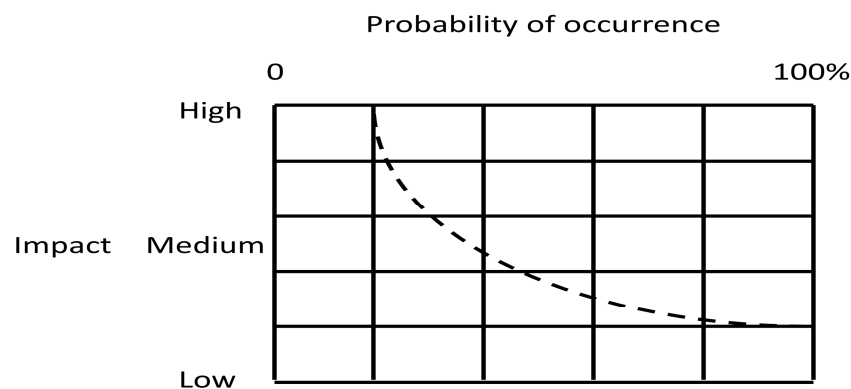
Probability of occurrence

Fig. 1 An example of a risk matrix with a hypothetical acceptability curve.

In the context of this paper, managing the risk of future overheating in buildings needs practitioners to consider both the probability of overheating in the future climate and the impact of that overheating. Probability is a familiar concept to most people, who recognize that it underpins, for example, the chance of success in lotteries and betting, the price of insurance against a range of hazards, and probability of death from cancer, even if they struggle to recognize a numerical formulation such as a 1 in 400 chance equating to 0.25% probability and odds of 400 to 1. Construction professionals should be better informed because many design concepts involve probability. For instance, in the code of practice for design of structures loads are expressed as characteristic values, which have a 5% probability of being exceeded in operation, and are then multiplied by safety factors of 1.4-1.6 to give the design loads for the structure to meet (BSI, 2004). Similarly, wind loads are cited as characteristic values with a 2% annual probability of exceedence, corresponding to a 50 year return period (BSI, 2008). Lightning damage risk is managed by the process described above (BSI, 2006) with the UK tolerable risk of loss of death or permanent injury set at 10^{-5} and contour maps showing lightning flash density given in the code of practice.

Therefore, in principle, the risk of a building overheating needs to be defined in terms of both probability and impact. The best predictions of building performance involve understanding the way buildings perform in their environment and use simulations as described in the next section. Using the probabilistic climate change projections in these simulations should enable designers to estimate the probability of a building exceeding a defined overheating criterion. While in extreme situations overheating leads to loss of life (Salagnac, 2007), at the design stage the impact of an overheating prediction could be considered in terms of actions required

– for example, design modifications, some of which might lead to higher cost or reduced convenience, serviceability or appearance. This paper focuses on the probability aspects of an overheating risk tool which would need to be refined by engagement with practitioners to establish the impact aspects.

Building performance simulation

Building performance simulation is the application of physical models for the heat and moisture transfer through the building fabric, air flows around and within a building, solar gain and the effects of occupancy, taking account of interactions and feedback effects, to show how the internal conditions in a building vary over time. It is widely used to optimize potential design elements and guide the design towards best performance. With buildings having become interacting systems that must be looked at holistically, it is no longer possible for the ordinary designer to recognize all the potential synergies and conflicts that result from optimizing building elements individually: the sophisticated modeling software now available, while computationally intensive, enables options to be appraised in a reasonable time. Virtually every building design of any significance is now routinely subjected to simulation and the great advantage is that from information about the external climate, the details of the building construction and services systems used, together with the occupancy profile, typical software provides output on environmental performance parameters, such as annual energy consumption, running costs, heating / cooling loads, thermal comfort and CO_2 emissions, some of which can be used to assure regulatory compliance. ESP-r, an open source software, was used in this work, but several commercial software packages are available including IES-VE (2012) which was developed from it, and consequently the tool described in this paper would be readily compatible with IES-VE.

The challenges facing the designer who would potentially use the probabilistically-based UKCP09 climate projections in building performance simulation are (i) which climate to use out of the hundreds generated by the weather generator and (ii) how to deal with the uncertainty produced by the probability density function. It is clearly unrealistic to expect the design team to devote significantly more time and effort than at present to test their design and appraise options in a range of future climates. Therefore, what is required is a shortcut that meets the following desiderata.

1. It must be compatible with existing simulation software.
2. It must be able to use a variety of overheating criteria.
3. It must exploit the richness of the weather generator output.
4. It must give a reasonably accurate assessment of building performance in future climates.
5. It must do all this without significantly adding time, cost and complexity to the job of the design team.

This was the starting point for the work described in this paper.

Development and validation of the overheating risk tool

Regression process for weather data

Dynamic simulation of the performance of a building over one year at hourly temporal resolution gives 8760 data points for a single variable (e.g. internal temperature) in one climate. Since a large number of climates are needed to establish probabilities, the amount of information rapidly becomes unmanageable and it is clearly impracticable to simulate a building in every possible climate.

The solution chosen here is to emulate the simulation process by multiple regression. In summary, 100 climates are chosen at random from the 3000 produced by the UKCP09 weather generator (Jones et al, 2009) for a particular scenario (e.g. medium emissions, 2070-2099 time period at a chosen location). The weather generator then produces an hourly time series for each of seven weather variables (temperature, precipitation, relative humidity, vapour pressure, sunlight fraction, direct radiation and diffuse radiation). The concept of the regression model is that the internal conditions in a building depend on a contribution of each of these variables both at the current time and, through the inertia of the building fabric, at each of the preceding 72 hours. (It was expected that the contributions of each time point would decrease towards the 72nd hour before the present and that those of points more than 72 hours earlier would be negligible and merely contribute to an error term.) As a result there are 504 (=7x72) input weather data points at each hourly value. It is to be expected that there will be correlations between these variables but, without making any assumptions about their precise nature, Principal Component Analysis (PCA) was used to simplify the correlations between pairs of variables (Patidar et al, 2011).

PCA is a statistical method for the analysis of data with a high number of dimensions, and can transform a large number of variables which are possibly correlated together into a small number of uncorrelated variables (Joliffe, 1982). PCA was done in two steps: first, exploiting the correlations within the 72 hours of each individual weather variable, and then exploiting the correlations between different weather variables. This reduced the 504 components to 33 sub-components, made up of 11 for temperature, 6 for the combination of precipitation, relative humidity and vapour pressure, and 16 for the combination of sunlight fraction, direct radiation and diffuse radiation. The transformed data in this 33-dimension set retained 95% of the total variation in the original dataset (Patidar et al, 2011). Multiple regression was then used to establish a simple linear relationship between the transformed dataset obtained from the randomly selected climate file and the corresponding building simulation outputs. Because not every climate has to be simulated, this regression based approach drastically reduces the number of building simulations that must be carried out for a given climate scenario, and hence the time taken, and this makes emulation feasible.

The multiple regression approach has also proved to be effective for performing a systematic analysis of various aspects of heatwaves, including the frequency of extreme heat events in future climates, their impact on overheating issues and effects of specific measures to offset overheating (Patidar et al, 2013). Indoor temperatures could be correlated with extreme air temperatures in a heatwave, with effects that differ subtly from those obtained by analyzing the effect of an average rise in temperature over a year.

Application in building simulation

The starting point for the use of the LCF tool is a single dynamic simulation at hourly resolution using ESP-r, IES-VE or similar for a single weather file. This simulation needs to be done afresh for each building version that is to be investigated and yields a results file, giving internal temperatures, heating or cooling loads, etc also at hourly resolution. This single results file is sufficient to calibrate the coefficients in the multiple regression equation. Having specified some information about the building, such as times of occupancy, the assessment criterion (e.g. 1% of occupied hours above 28°C), the form of assessment required (overheating or load analysis) and the chosen future climate scenarios, the user can then run the tool from the weather file and the results file. The tool incorporates up to 1000 weather files from the UKCP09 weather generator for each climate scenario (emissions level and timeline) to deliver hourly results, such as temperature in each zone of the building (Jenkins et al, 2011). These outputs are automated so the user can choose between several graphical or textual formats. The whole process is complete in about half an hour.

Validation of the tool has been carried out on different versions of four buildings: (i) the filled-cavity brickwork detached dwelling described by Jenkins et al (2011), (ii) the primary school described by Jenkins et al (2009), (iii) the mechanically cooled four-storey office described by Jenkins et al (2008), and (iv) two versions (pre and post retrofit) of the 1930s solid walled semi-detached dwelling (Banfill et al, 2012). The validation was performed by running 100 hourly dynamic simulations and comparing them to 100 hourly regression model profiles that effectively emulate the simulations. In real use, all 100 hourly dynamic simulations are not needed; only the single calibration simulation is necessary and this saves considerable computing time, making the tool a practicable add-on as part of the building design process. Fig. 2 shows the good agreement (i.e. small residual differences) between the emulated results and the dynamic simulation results for the house (i) above: more than 93% of the hourly temperatures are within ±1.5°C of the simulation (Jenkins et al, 2011).
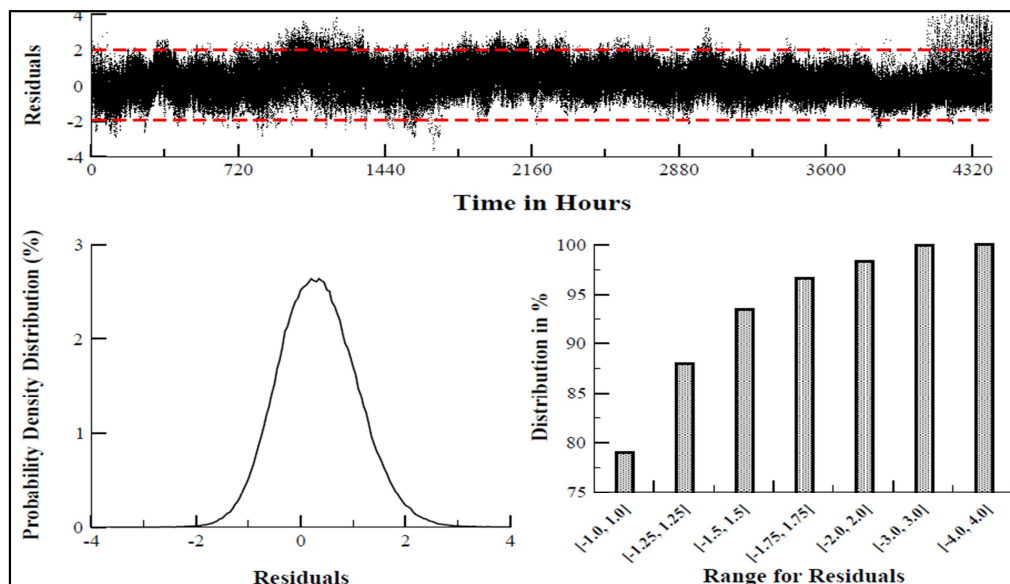

Fig.2: Validation of the regression model for a house in London under the medium emission scenario for the 2020-2049 period, based upon 100 representative weather files. The residuals are the differences between the hourly temperatures estimated by 100 dynamic simulations and by the regression model.

The LCF tool outputs

As already noted, the tool can provide output in several forms. Fig.3 shows a comparison between a future climate scenario and the baseline performance of the same building in the current climate. It shows the cumulative frequency of the percentage increase of the overheating metric (number of hours over 28°C) compared to the average for the baseline scenario. It indicates that the house has a 96% probability of being warmer if no action is taken, whereas using a simple window opening adaptation reduces this to 72%, and, combined with external shading and reduced internal heat gains from equipment, the probability is further reduced to 14%. An alternative way of understanding this information is to choose a level of risk that might be acceptable for a designer. For example a 90% probability level would cover all but the most extreme results from the tool. If designing to this level for the same future climate Fig.3 shows, with 90% certainty, that the number of hours above 28°C for this building will show an increase of at least 8% when no adaptation is used but a decrease of at most 10% when the windows are opened and a decrease of at most 42% when windows, shading and reduced gains are all employed. Fig.4 shows that the progressively warming climate increases the probability of overheating in the unadapted house, expressed as the percentage of occupied hours above 28°C. Again 96% of climates in the 2080s medium emissions scenario will give more than 1% of occupied hours above 28°C. It should be noted that any other overheating criterion can be used in the tool outputs.

A further, simpler display of the overheating risk, developed in response to feedback from professionals (as described in the next section), is shown in Fig.5. Here the graphical colour-coding corresponds to the value on the vertical overheating threshold line in Fig.4; the value corresponding to 96% of climates in the unadapted house is indicated by the intense colouration in the chart. This also shows other climate scenarios, processed in the same way as the London, 2040-2069, medium emission scenario of Fig.3. Similar results have been obtained for the other buildings and in the interests of brevity are not described here. They will be presented elsewhere.
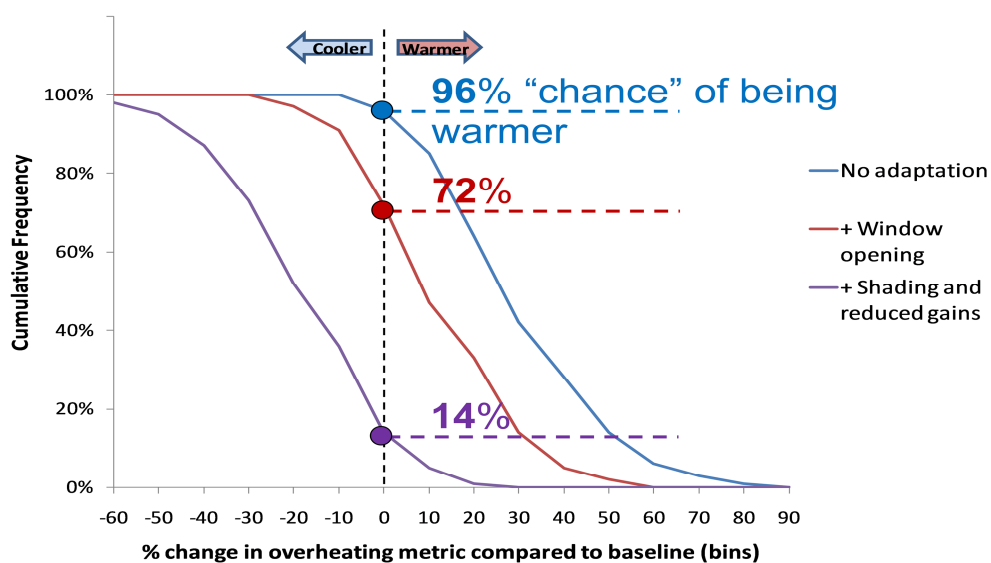
Fig.3: A probabilistic failure curve, showing % change in the number of occupied hours above 28°C for a 3 bedroom detached house in London, 2040-2069 climate, medium emissions.
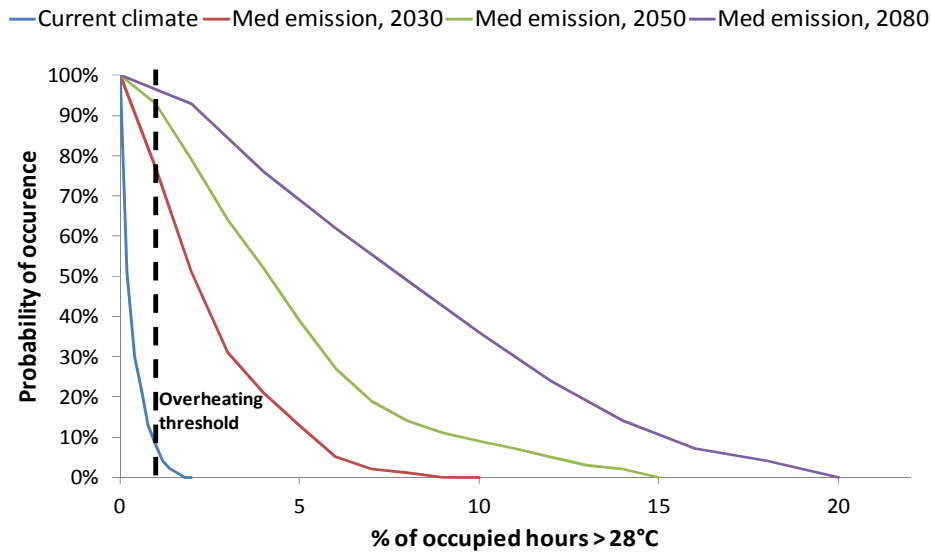

Fig.4: Effect of climates on the same house as Fig.3 with no adaptation measures used.
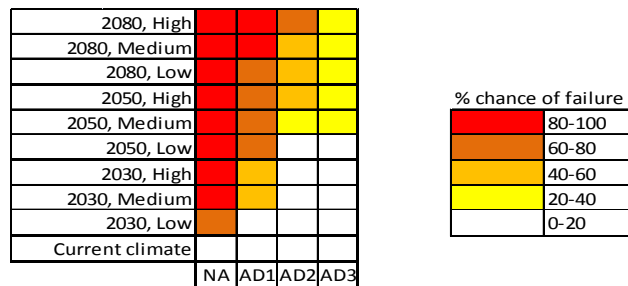

Fig.5: A simplified representation of the data from Figs.3 and 4. NA = no adaptation (baseline), AD1 = window opening, AD2 = AD1 plus window shading, AD3 = AD2 plus reduced gains.

Relevance to design professionals

A series of focus groups, interviews and questionnaires were administered with professionals working in building design in order to elicit their preferences for the form of a possible design adaptation tool and to translate the outcomes to a practical level. 46 responses to a questionnaire on present-day building design practice confirmed that buildings are typically designed to minimize capital cost and to comply with (rather than exceed) current legislation / regulations. Assessment of overheating is not a priority and optimization of performance in a future climate would not normally be considered unless driven by the future occupant (Gul and Menzies, 2012). These themes informed the questions used in focus groups and interviews, in which 41 professionals participated. The research questions addressed whether overheating is seen as a problem, the kinds of climate data, tools and software in current use in building design, use of probabilistic climate projections and the preferred form of an overheating tool (Gul et al, 2012).

It was concluded that overheating is not currently considered as a risk in the domestic sector but it is seen as increasingly important in non-domestic buildings, with inappropriate fabric, south-facing glazed facades and inadequate ventilation all giving concern. However, the typical professional's response is to put in some cooling provision to deal with the overheating. Future overheating is seen as a problem for complex buildings and schools, rather than housing, although it is recognized as becoming an issue in new dwellings in the south of the UK. In the non-domestic sector, something happening in 50-60 years is not high on the industry's agenda and there is minimal concern for future overheating risks, partly because cooling plant is over-sized and, with a limited lifetime, is likely to be replaced before the problem gets serious. Climate data is scarcely used in domestic building design, which is based on the feeling that "it worked last time", whereas non-domestic designers use detailed data if required, in which case CIBSE Test Reference Years are the benchmark, although designers lacked guidance on which climate files to choose. Probabilistic climate projections are perceived as a valuable way to look ahead and allow adaptation to future climates but in practice will be used only if required by law, and even then they must be user friendly otherwise there will be limited uptake. Overheating analysis is considered to be a resource intensive exercise that would not always be justifiable to a client, and as a result the domestic sector relies on basic steady state calculations like SAP or PHPP, whereas in non-domestic buildings SBEM (steady state) would be supported by dynamic simulations using IES-VE, TAS, ESP-r, Hevacomp and ClassCool.

Accepting that an LCF tool will be needed eventually, professional preference is for something that can be added simply to existing modeling procedures, which would need to be cost effective, and preferably sit within a single level of expertise within an organization. As a software solution, it might end up being part of the Building Regulations and therefore use the same building specifications as those required for SAP calculations. One professional suggested that "two levels of a tool, one with a high level of information for someone trying to understand the issues, and another simple one that can be used for a report" would be suitable, but another was cynical about the cumulative probability graph (Fig.3) because it would be "off-putting to people who struggled with graphs at school". This suggested that a colour-coded display (such as Fig.5) might be more appropriate, although this could be given in addition (rather than as an alternative) to the output shown in Fig.3.

Discussion

The LCF tool has proved to be useful and efficient in carrying out the overheating analysis of the naturally ventilated buildings for which it was originally designed. In this situation it delivers the temperature in the different zones of a building at hourly resolution and can assess the probability of failure, expressed in terms of the percentage of occupied hours above a threshold temperature. However, it works equally successfully for the analysis of cooling and heating loads in mechanically ventilated buildings, where the failure criterion is more difficult to define. For example, neither cooling nor heating plants are normally sized to close tolerances, so an increase in cooling load is likely to result in a higher number of hours of operation and a decrease in heating load is likely to result in lower heating plant efficiency. Neither of these are clear cut 'failures' but the LCF tool could assess cooling energy consumption and associated CO_2 emissions: its merit is its potential to assess performance against any desired criterion.

The output of the tool can also be considered in terms of the risk matrix presented in Fig. 1. If the probability of overheating, as given in Fig. 5, is evaluated in terms of the building

adaptations, where AD1 = window opening, AD2 = AD1 plus window shading and AD3 = AD2 plus reduced gains, then these adaptations can be placed on the impact axis of Fig.1. Clearly the axis could be extended further to other (unspecified) design adaptations (denoted ADn) in order to deal with the remaining probabilities of overheating. Fig. 6 places the hazards in the form of future time-slices and emissions scenarios on a risk matrix of this form. Each adaptation is a response that reduces the probability of overheating, so the impact of the overheating is dealt with by the adaptation. This can be clearly seen in the example of the 2080 low emissions climate: the no adaptation (NA) baseline case is certain to overheat, but AD1, AD2 and AD3 reduce the probability successively to the 60-80%, 40-60% and 20-40% levels respectively, and the 2080L scenario moves progressively towards the lower left of the matrix.

Further validation on more buildings and using different adaptation technologies will be needed in order to test the limits to application of the tool, and based on feedback from potential users different forms of output can be tailored to be more specific to the needs of particular clients. The format chosen for the improved interface will depend on whether the tool is to be used as an open-source, stand-alone model or within existing building simulation software or used as a consultancy tool by the developers. It is recognized that it would not immediately be a routine tool for every design, but rather an additional analysis that some clients might value. However, its potential will be realized in the future, when deterministic climate projections are recognised to be no longer adequate. It is difficult to imagine that subsequent generations of climate projections after UKCP09 will revert to deterministic forms, and probabilistic projections will eventually be accepted as normal, whereupon the LCF tool could be adopted as the industry standard.

Response to impact	0–20	20–40	40–60	60–80	80–100
NA	Current			2030L	2080H 2080M 2080L 2050H 2050M 2050L 2030H 2030M
AD1	2030L Current		2030H 2030M	2080L 2050H 2050M 2050L	
AD2	2050L 2030H 2030M 2030L Current	2050M	2080M 2080L 2050H	2080H	
AD3	2050L 2030H 2030M 2030L Current	2080H 2080M 2080L 2050H 2050M			
…ADn					

Fig. 6 Part of a notional risk matrix for overheating in the building referred to in Figs. 3-5. Entries in each cell signify future climates under emissions scenarios, e.g. 2080H denotes the 2070-2099 period under the high emissions scenario. ADn denotes further (unspecified) adaptations.

Since the tool can run multiple weather files for the same building, it is compatible with other climate projections and it could be useful for the study of other climate variations like locations, micro-climates and altitude or coastal factors. The advantage of the tool is that a single building simulation is all that is required in order to carry out sensitivity analysis on these factors.

Finally, as hinted at above, the failure analysis can be converted into an energy analysis in order to answer questions on the most probable energy consumption of a building for a given future climate scenario. This could be done at a single building scale or, suitably scaled up with appropriate diversity, to the district, city or region scale and would therefore be useful for power network operators needing to assess the capacity of infrastructure to meet the demands of buildings.

Conclusion

Calculating overheating risks due to probabilistic projections of future climates through empirical regression formulae based on a single simulated climate can achieve very similar results to those of detailed simulations of many different climates. A validated tool that

converts the building performance results from a single weather file into multiple climate results has been developed. It gives satisfactory results for different building types, with about 93% of hourly temperatures being within ±1.5°C of the simulated values, based upon over 20000 annual simulation results. A prototype user interface gives efficient use and delivers outputs that describe the results in terms of probability of failure, which could be incorporated in a risk matrix.

Acknowledgements

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