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Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: A UK case study

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ABSTRACT

This study explores the uncertainties and sensitivities in the prediction of the thermal performance of buildings under climate change. This type of analysis is key to the assessment of the adaptability and resilience of buildings to changing climate conditions. The paper presents a comprehensive overview of the key methodological steps needed for a probabilistic prediction of building performance in the long term future (50 to 80 years). The approach propagates uncertainties in climate change predictions as well as the uncertainties related to interventions in building fabric and systems.

A case study focussing on an air-conditioned university building at the campus of the authors is presented in order to demonstrate the methodology. This employs the most recent probabilistic climate change projections for the United Kingdom (UKCP09 dataset) and takes into account facility management uncertainties when exploring uncertainties in the prediction of heating energy, cooling energy, and carbon emissions.

1. Introduction

In the UK, buildings account directly or indirectly for approximately 40% of national carbon emissions [1]. This is a major constituent of the human-driven greenhouse gas emissions, which are increasingly tied to global warming [2]. Reciprocally, building thermal performance is directly affected by changing weather conditions. Hence it is important to make sure buildings remain thermally comfortable, while being energy efficient and employing low carbon technologies.

The impact of climate change on building thermal performance and the adaptation of buildings to changing environmental conditions have become active research areas [3–20]. CIBSE TM 36 provides a comprehensive analysis of energy use and overheating in different types of buildings by using climate projections for the UK released in the 2002 (UKCIP02) [4]. Research by Guan [5], studying the impact of climate change on air-conditioned buildings in Australia, indicates that under the 2070 high emissions scenario a 28–59% increase of cooling capacity will be needed to maintain thermal comfort conditions. De Wilde and Tian [6] have implemented a probabilistic method and sensitivity analysis to identify the key variables affecting the thermal performance of a mixed-mode office building in Birmingham, UK. Coley and Kershaw [7] propose "climate change amplification coefficients" to correlate indoor air temperature to predicted weather conditions. More research has been carried out based on different climate change scenarios in different countries, such as Canada [8], the Netherlands [9], New Zealand [10], Portugal [11], Slovenia [12], Switzerland [13,14], the United Arab Emirates [15], and the UK [16,17]. Some research takes a wider view and compares the trends in building behaviour in a range of different climate zones [18–20]. However, most of this existing work on the impact of climate change on building thermal performance is deterministic in nature. Furthermore, any application of sensitivity analysis in building performance simulation (the main methodology for predicting future building behaviour) is mostly focussed on local sensitivity analysis (one-factor-at-a-time). At the same time meteorological research progresses quickly. In the UK, a new set of climate change projections (UKCP09) was released in June 2009 [2]. This new dataset is the first to attach probabilities to different levels of future climate change. However, this new data is also a challenge to the building science disciple due to its complexity. At the same time it also provides an opportunity to further analyse building behaviour under climate change by using (sampling-based) Monte Carlo approaches. This is a commonly used method for estimating the impact of uncertainty in inputs on a corresponding uncertainty in outputs [21,22]. There are many sources of uncertainty in building energy simulation, such as weather conditions, physical properties of building materials, internal heat gains [23–26], and accordingly the sampling-based methods are very suitable for research on impact and adaptation to climate change in the built environment [6].

This study explores the uncertainties and sensitivities in the prediction of the thermal performance of buildings under climate change. It presents a comprehensive overview of the key methodological steps needed for a probabilistic prediction of building performance

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in the long term future (50 to 80 years). The approach propagates uncertainties in climate change predictions as well as the uncertainties related to interventions in building fabric and systems. The methodology is demonstrated by means of a case study that quantifies the likely impacts of climate change on energy performance and carbon emissions of a real, complex case study building using sampling-based uncertainty and sensitivity analysis. The case selected for this work is the Roland Levinsky Building at the University of Plymouth. The study considers the uncertainties in building simulation due to weather conditions (UKCP09) and other inputs in building performance simulation and identifies the dominant factors affecting thermal performance using global sensitivity analysis. The research employs the UKCP09 climate change predictions and incorporates the uncertainties in other inputs into the building energy simulation. Sensitivity analysis is used to identify the most influential factors that affect three performance indicators: annual heating energy, annual cooling energy, and carbon emissions. Uncertainty analysis provides more information for lifecycle building performance assessment [27], taking into account that the weather conditions will change within the life expectancy of buildings.

The structure of this article is as follows. First, the probabilistic climate projections from UKCP09 are briefly presented, and the method of creating weather files for building simulation according to Finkelstein–Schafer statistics is described. Then the article reports on the thermal model which is used for transient thermal simulation, using the EnergyPlus programme. Finally, the predicted energy performance and carbon emissions of the case study building are explored, employing uncertainty and sensitivity analysis.

2. Climate change projections from UKCP09

In June 2009 a fifth generation of climate information for the United Kingdom named UKCP09 (UK climate change projections 2009) was published by the Department of Environment, Food and Rural Affairs 2009 [2]. For the first time, this provides probabilistic projections of climate change with monthly, seasonal and annual projections at a spatial resolution of 25 km for a number of weather variables. UKCP09 considers three types of uncertainty: natural internal climatic variability; modelling uncertainty in the climate models due to an incomplete understanding of the physical processes of the climate system; and uncertainty in future emissions. The projections are reported for seven overlapping 30-year time periods, starting with the 2020 s (2010–2039), stepping forward by a decade, and ending with the 2080 s (2070–2099). The climate change predictions are designed to express 30-year averages relative to a historic baseline period (1961–1990). These 30-year time periods are used to minimise the natural climate variability. For each future time period, the projections are given under three future emission scenarios (low, medium, high) to represent possible future pathways for emissions. The confidence in the climate change projections depends strongly on the weather variable being considered. For example, there is relatively high confidence in projections of temperature and low confidence in cloudiness. A Weather Generator (WG) in the UKCP09 [28] is used to create synthetic daily or hourly time series of weather variables for the baseline period and the future at a spatial resolution of 5 km. The weather variables in the WG include precipitation, dry-bulb temperature, vapour pressure, relative humidity and sunshine, which are internally consistent and match the inter-variable relationships observed in the baseline period. It should be recognised that WG outputs have some limitations. For example, the results from the WG are not based on physics or meteorology, but on statistical relationships from observed weather data. Therefore the WG may be less suitable to predict some aspects, for instance future weather extremes.

Transient building energy simulation programmes normally require four key weather variables: dry bulb temperature, solar radiation, humidity, and wind (speed and direction) [29,30]. For the research described in this article, the first three weather variables have been obtained by using the UKCP09 User Interface, which is a web-based portal to access to the UKCP09 datasets, images and numerical products. The climate information used pertains to the baseline and 2050s (2040–2069) time periods. The input parameters used for the WG are listed in Table 1. When the UKCP09 WG creates hourly time series, the number of model variants will be limited to 100 and the duration of runs will be 30 years to avoid producing overly large files. Regarding the fourth weather variable, wind, UKCP09 does not provide predictions. This is because the projections of change in wind have a large uncertainty. Instead hourly wind speed and wind direction have been obtained from measured weather data (year of 2006) at the University of Plymouth campus weather station. This is deemed satisfactory because the wind data can be assumed to only have relative minor influences on annual energy use [30–33].

The UKCP09 WG will generate 3000 weather files (100 annual data sets per year to account for variability, over a 30-year period) for a given time horizon and emission scenario. The detailed descriptions of the method of creating the weather files for this research are available in Ref. [34]. Fig. 1 shows annual mean temperature from 2020 s to 2050s in Plymouth from UKCP09. For every time series, Finkelstein–Schafer (F–S) statistic is applied to the distribution of dry bulb temperature and global solar radiation based on the method given in Refs. [35,36]. The use of F–S statistic cannot only reduce the computational burden for building performance simulation, but also maintain the probabilistic nature from UKCP09 weather generator. For a given month, the F–S statistic is calculated by summing the differences in cumulative distribution functions of a weather variable between a specific year and all years (30 years in this case). Then the smallest F–S among all years means the corresponding year can represent typical weather conditions in all years considered. The procedure can be divided into four steps:

(a) For dry bulb temperature and global solar radiation, the cumulative distribution functions (CDFs) for each month are constructed for a given year and over the 30 years based on the daily data generated by the WG.
(b) The sum of two F–S values (air temperature and solar radiation) based on the CDFs from the last step is calculated by equally weighting dry bulb temperature and solar radiation.
(c) A typical weather file (TWF) is obtained by choosing the lowest F–S value for different months.
(d) The hourly data between 21:00 PM on the last day of a preceding month and 02:00 AM on the first day of a following month is removed from the typical weather files. This is replaced with a linear interpolation between preceding and following values in order to provide a smooth transition between consecutive months.

Using this approach for each time horizon and emission scenario a set of 100 new typical weather files are created from the 3000 original UKCP09 WG files. Excel VBA (Visual Basic for Application) has been used to automate the steps. This process creates 100 alternative

Table 1
Input parameters for UKCP09 Weather Generator.

Parameter	Value
Emission scenarios	Low, medium, high
Time periods	2050s (2040–2069)
Spatial average	grid_box_5km
Location	2,500,055 (latitude: 50.35 N; longitude 4.15 W)
Sampling method	Random
Temporal frequency	Hourly
Number of random samples	100
Run duration	30 years
Random seed value	20,000