PRELIMINARY APPLICATION OF A METHODOLOGY FOR RISK ASSESSMENT OF THERMAL FAILURES IN BUILDINGS SUBJECT TO CLIMATE CHANGE

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ABSTRACT

Climate change is now recognized as a prime challenge of the 21st century. It is increasingly clear that there is a need to take action in order to adapt specific buildings to changing circumstances, in a cost-effective way. This paper presents the results of the first step of an EPSRC-funded research project that aims to manage the thermal risks in buildings subject to climate change, employing building simulation (coupled with uncertainty analysis) to quantify these risks, their consequences, and risk abatement options.

KEYWORDS

Thermal performance prediction, climate change

INTRODUCTION

Buildings all over the world need to remain thermally comfortable and energy efficient in the long-term future, while being subject to many different developments. These include changing environmental conditions (e.g. climate change and urbanisation), social-economic developments (e.g. number and type of occupants, trends in office work), changes in legislation, and technological advances (e.g. advances in consumer and office electronics). Amongst these developments, climate change is an important concern; see for instance Hulme et al. (2002). As a consequence, the adaptation of buildings to climate change has been identified as a key area for research and development by for instance the Stern Review (2006) and EPSRC (2007). Yet the building industry is known to be a fragmented, slow-changing sector. It is not very aware of the challenges of climate change adaptation. Still, climate change is a concern for building owners and occupiers who will want to limit the risks to their health (e.g. allergies, heat strokes and similar) and their property (mould growth, cooling systems failing to cope, etc). One building sector that already does see climate change impacts on building as an important concern is property insurance, which faces a rapid increase in claims related to issues like mould growth, indoor air quality and electricity reliability (Mills 2003, Ross et al. 2007).

So far building and construction science, when dealing with climate change, has mostly been focussing on the mitigation (prevention) of climate change rather than adaptation to changing conditions (Lowe 2003; Hardy 2003, p 206; Sanders and Phillipson 2003). In academia there is an abundance of literature on energy efficient buildings and energy saving technology, while first results of research into the adaptation of the built environment to climate change have only started to appear recently. See for instance Hacker et al (2005a), Hacker et al. (2005b), Gaterell and McEvoy (2005), Frank (2005), Roaf et al. (2005) Holmes and Hacker (2007) or Crawley (2007) for recent publications. However, none of these are based on probabilistic analysis, and none of them quantify risks or their acceptability. As such, they are insufficient to support decisions to plan the adaptation (or not) of buildings to changing conditions.

The risks and consequences for buildings that come with climate change are not yet understood, making it hard to answer the ultimate question on whether there is a need to take action in order to adapt specific buildings to changing circumstances, and if so, how and when. A number of new, high profile UK buildings can serve as (fully arbitrary) examples. The Civil Justice Centre in Manchester (Denton Corker Marshall - DCM) comes with a double skin façade, the Royal London Hospital in Whitechapel (HOK Architects) includes a large atrium, and the John Madesjki Academy in Reading (Wilkinson Eyre Architects) depends on cones/chimneys for natural ventilation. In all three cases, one can ask whether or not these buildings will continue to function if the climate conditions change. Or is there indeed a significant risk of disruption of the administrative/health care/academic processes carried out inside? Can the buildings adapt to changes by changing the behaviour of existing systems (e.g. changing set point values) or is there a need to upgrade or add systems, like larger cooling units and external shading devices? Similar questions can be asked for almost all offices, hospitals, laboratories, libraries and other buildings across the UK.

Within that context a research project has been started to develop an approach to manage the real risks that climate change and other long term (40 to 100 years) change scenarios pose for the thermal behaviour of buildings. It will deliver actionable information on the consequences of shifts in the energy use and thermal comfort of buildings, especially in terms of the risks posed to the health and productivity of building occupants, and in terms of the risks of an increase of the energy use / CO_2 emissions by the building sector in general. It studies the acceptability of these risks, and any corrective action deemed necessary.

The overall aim of the project is to provide a novel approach to manage thermal performance risks in buildings (both domestic and non-domestic) subject to climate change and other long-term change scenarios. In general, risk management encompasses three main components: risk assessment (identification of potential areas of risk); risk analysis (determination of the probability of risks, and the consequences associated with their occurrence) and risk abatement (intervention to reduce, control or eliminate risks).

This paper reports on initial building simulation research undertaken to set the stage for deeper studies of operational scenarios, uncertainties, timescales, building functions at risk, and the quantification of building performance and associated risks.

RESEARCH PROJECT FRAMEWORK

The main methodology applied in studying the impact of climate change on the thermal behaviour of buildings is building performance simulation. In general, the international building research community has been addressing the thermal aspects of buildings since the energy crisis of the 1970s. Since then, it has developed a large number of methods and software tools to analyse and optimize thermal building performance. These tools are now used in building engineering on a regular basis. For good overviews of the related field of building performance simulation see Malkawi and Augenbroe (2005), Jiang et al. (2007) or Clarke (2001).

In general risk can be calculated according to the following, universal formula:

$$RF = P \times C \qquad (1)$$

Where RF = Risk Factor, P = Probability of failure, and C = Consequence of failure.

Calculation of RF allows to set thresholds to identify low (> x), medium (> y) and high (> z) risks, and highlight those risks requiring further attention.

This formula raises four research stages: one dealing with risk assessment (P), one dealing with risk analysis (C), one quantifying risks (RF), and one applying the work to real cases, studying risk acceptance and abatement. Accordingly, the four stages that make up the programme of work of the project are:

Stage 1: Risk Assessment Study

The first step of the project analyses current operational scenarios of buildings (Sc, for Scenario, current) and makes a scientifically underpinned projection of how these scenarios might be under future conditions (Sf, for Scenario, future). A scenario will be a function of operational conditions (O) and uncertainties (U); for future scenario's there will also be a dependency on the timescale of the prediction (T). In mathematical terms:

$$Sc = function(Oc, Uc); Sf = function(Of, Uf, Tf) \quad (2)$$

Expert panel sessions will be conducted to lay down current operational scenarios, quantify the uncertainties in these current scenarios, and to make a scientific projection of long-term changes to operational scenarios (climate, user behaviour, electronics) and the uncertainties involved.

A set of probable change scenarios will be formally and explicitly modelled, including the uncertainties involved, that can be used as input to simulation efforts ('change scenario file').

Building functions will be investigated that are related to energy use and thermal comfort and that might fail under Sf. Focus areas are occupant health, productivity, and energy use/CO2 emissions curbing, but others might be added depending on the research findings.

Current building requirements related to energy use and thermal comfort, and the way these requirements are operationalised, will be studies by means of both a deep literature survey and a study of current building briefs.

Stage 2: Risk Analysis Study

The risk analysis looks closer at the critical functions at risk, especially occupant health, productivity, energy use / CO_2 emissions curbing. It will analyse the failure criteria for each building function as laid down in building specifications, but will also widen the search beyond current practice. It will define the probability of the failure of each of these building functions P as a function of the future operations scenario (Sf), the specific building system configuration (config) and the actual building operation settings and usage (set):

$$P = function\ (Sf, config, set) \qquad (3)$$

A formal relationship will be developed that describes how the meeting (or failing) of the requirements is dependent of the actual configuration of the building, how the building and its' subsystems are controlled, and the operational scenario.

This is followed by the development of metrics to quantify the impact / consequences of not meeting the criteria as laid down in the buildings specifications (C) for each of the building functions.

Appropriate methods to quantify consequences of buildings not meeting energy and thermal comfort criteria on aspects like occupant productivity, health etc will be investigated. A relation will be established between energy use and thermal comfort indicators and these quantification methods for productivity, health etc.

Stage 3: Development of a Risk Quantification Methodology

This stage sets out with the development of a risk-based performance indicator PI for each of the building functions. These performance indicators will relate to the energy use and thermal comfort of the building, and be a function of the risk and consequences of failure. In formula:

PI = function (energy use, thermal comfort, P, C)   (4)

The findings of the previous research activities will be integrated into a set of performance indicators that formally capture the relationship between essential building functions, the risk of the building failing to provide that function, and the consequences of that failure. The performance indicators must be applicable under both current and future operational scenarios, while being explicit in all underlying assumptions.

The stage then develops a software environment that allows to propagate Sc, Sf into PI. The environment will be centred on an existing thermal simulation engine like ESP-r or EnergyPlus, adding functions needed to streamline the input of operational scenarios (current and future) and automating the quantification of performance (by means of providing appropriate input as well as by aggregation of simulation output where needed).

Appropriate front-end and back-end routines will be constructed that allow the quantification of building performance for each of the essential building functions under different change scenarios. Note that this capacity is not provided by current simulation kernels.

Stage 4: Study of Risk Acceptance and Abatement

Stage four undertakes the actual analysis of risk-based performance, quantifying the risk (RF) under both present and future conditions. It takes forward the findings of stages 1 and 2, and employs the software environment from stage 3 to do so.

This stage investigates how buildings currently perform in terms of risk factors, under current and future conditions (scenarios): analyse the RF under Sc and Sf when computing PI.

The next phase is to evaluate the risk-based performance found. Through input from academic and industrial experts it grades risks by setting risk thresholds, with risks considered low (RF > x), medium (RF > y), or high (RF > z). Furthermore, it states which risks are deemed acceptable, and which are not. Findings are presented as actionable information, in the form:

> "There is a chance of A that B% of our buildings do not meet criterion C, where C requires RF > x, y".

Expert panel will be held with facility managers and academics to discuss the risks found, under both present and future conditions, and the acceptability of these risks. These will be formulated in terms of criteria, risk factors and acceptability thresholds.

The final step explores the options to abate the risks in those cases where an increased risk is deemed unacceptable. It re-uses the set-up developed in stage 3 to study the prospects of interventions at different system levels (building structure, infill, and systems), different categories of interventions (maintenance, upgrade and replacement) and of interventions on different time scales (prevention, just-in-time, corrective).

Expert panels will be conducted with facility managers and academics to discuss potential interventions to reduce risks. Case studies will be carried out to quantify the impact of risk abatement interventions. This includes an estimate of investments needed to realise the abatement interventions. Furthermore, a crude extrapolation will be made of investments needed in the building industry, or main sectors thereof, if abatement interventions are needed on a larger scale.

INITIAL BUILDING SIMULATION EXPERIMENT

As initial step, a building simulation experiment was set up to get hands-on experience with the modelling of operational scenarios (current and future, capturing the underlying timescales and uncertainties) and their handling in predicting straightforward building performance aspects. This initial set-up will then be refined as the research project fully progresses through stages 1, 2 and 3.

Methodology

As simulation engine EnergyPlus Version 3.0.0 Build 028 has been selected (LBNL, 2009), due to it's extensive validation, free availability, and capacity to simulate advanced building features. Openstudio

V1.0 is used to create the building geometry of the EnergyPlus model.

In order to manage a multitude of possible EnergyPlus input variants and corresponding simulation results use has been made of Minitab (2009) statistical software. Minitab allows to make use of the response surface methodology in order to carry out sensitivity analysis. It selects model input parameters according to optimal sampling techniques and then develops a response surface model for the original model. Uncertainty and sensitivity analysis are straightforward once response surface model has been generated based on stepwise or other model-building techniques (Modarres, 2006).

Building description

For the initial simulation work an office building has been modelled. For reasons of comparison, this is based on the O2 modern office with mixed-mode ventilation control as studied by CIBSE TM36 (Hacker et al, 2005), which is a three-storey office with floor area of 3864 m^2, as depicted in figure 1.

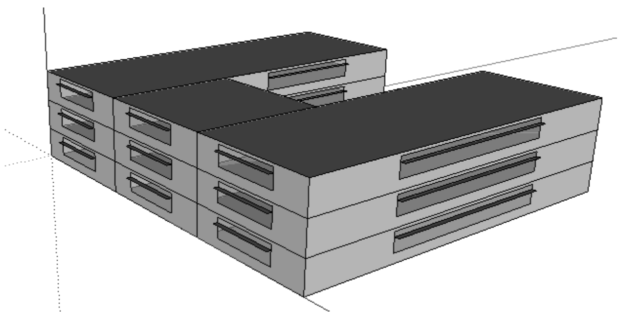


Figure 1: 3-D view of the office building model

The main parameters of this model, and their base values, are summarized in Table 1. It is well insulated with overhang to shade windows in summer and provides ample thermal mass for heat storage.

Note that on the timescales that will see an impact of climate change on thermal building performance, it is highly likely that the building will be subject to renovation and upgrading/replacement of (sub)systems. It is assumed that the building will undergo at least an upgrade of the façade (glazing and cladding) after about 20-25 years, and that the HVAC system at that time will at least require installation of a new boiler/chiller.

The minimum seasonal efficiency of natural-gas boilers is set at 80% gross based on the Part L guidance and the highest seasonal efficiency of condensing boilers may currently attain 95.6% gross (MTP, 2008).

Glazing has obvious effects on the heating load and cooling load. Low-e windows have already contributed to significant energy saving for heating and cooling energy use. Dynamic windows, which adjust solar heat gain on a seasonal basis, are most promising in northern climates of USA (Arasteh et al., 2006). The future high-performance windows are expected to have very low U-factors (0.57W/m^2 K), which can be obtained by application of aerogel, vacuum glazing, or gas-filled low-e three or more glazing layers (Arasteh et al., 2006). Window U-values for new building would be within the range of 0.6 to1.7 W/ m^2 K by 2050. These changes are reflected in the values in table 4.

Table 1 Building description

PARAMETER	VALUE
total building area	3864 m^2
Window wall ratio	30%
Number of zone	9
U value for wall	0.22 W/m^2 K
U-value for roof	0.18 W/m^2 K
U-value for floor	0.20 W/m^2 K
U-value for window	1.5 W/m^2 K
SC	0.66
Cooling system	Indirect evaporative cooler
Heating system	Controlled radiators supplied from a gas-fired water boiler

Operational scenarios

Schedules and control settings for lighting, equipment and occupancy are according to the British data for the open plan office as described in the National Calculation Method (NCM, 2009). The main parameters are summarized in Table 2.

Table 2 Control settings

PARAMETER	VALUE
Infiltration	0.25 ACH
Lighting	12 W/m^2
Equipment	12 W/m^2
Occupancy	10 m^2/person
Heating setpoint	22 C operative temperature, setback 12 C
Cooling setpoint	25.5 C operative temperature
Ventilation	Mixed mode
Natural ventilation	6 ACH
Mechanical ventilation	100% outdoor air with heat recovery unit, fixed flow 4 ACH, Supply air temperature 19 C

Again, some of this information will be subject to change on longer timescales. Internal heat gains in office buildings, which include equipment, lighting, and occupant gains, are proportional to occupant density. Under current conditions, when the density of occupation is 16 m^2/person, both the lighting and equipment heat gain are 12 W/m^2 and the total heat gain is 33W/m^2 (CIBSE, 2006). Based on estimations by Jenkins et al. (2008) estimation the annual energy use for equipment in an office will change from 236 MWh in 2005 to only 93 MWh in 2030 due to more efficient PCs, low energy LCD display technology, and improved power management. The change for lighting is expected to show a trend from 214 MWh in 2005 to 48 MWh in 2030 through the introduction of the LED lighting. The resulting changes are once more represented in the values in table 4.

Climate scenarios

For the UK, detailed regional climate scenarios for the years 2020, 2050, and 2080 have been developed by the UK Climate Impacts Programme (Hulme et al., 2002), which consider four emissions scenarios: low, medium-low, medium-high, and high. These scenarios range from a sustainable future with decreasing greenhouse gas emissions from mid-century onwards (low), to an intensive fossil fuel use future with greenhouse gas emissions at over three times present levels by mid-century onwards (high). These scenarios expect the mean temperature to increase by 2 to 3.5^oC by 2080, with more frequent high summer temperatures, wetter winters and drier summers, and more frequent heavy winter precipitation. However, these climate scenarios are not suitable for building energy simulation, since they have a temporal resolution of 24 hours, while most building simulation software requires hourly weather data. Therefore these climate change predictions need to be downscaled in time. Some methods of hourly future weather data generation are discussed by Guan (2009) and Belcher et al. (2005). A weather generation tool has been developed based on the morphing methodology, which can use UKCIP02 climate change scenarios to transform CIBSE/Met office TRY/DSY weather files in to climate change TMY2 or EPW weather files (Jentsch et al., 2008).

To represent different climate conditions in EnergyPlus, current weather file for Birmingham, UK was downloaded from the EnergyPlus website. The Climate Change Weather File Generator (Jentsch et al., 2008) was used to generate EnergyPlus Weather (EPW) files the future, for different emission scenarios. For comparison, the resulting annual heating-degree days are shown in Table 3.

Table 3 Annual heating-degree days (base temperature 15.5 °C) for Birmingham, UK

YEAR	EMISSION SCENARIOS			
	LOW	MEDLOW	MEDHI	HIGH
2020s	2000	1973	1973	1958
2050s	1833	1767	1717	1630
2080s	1686	1606	1400	1283
Note: 2227 for baseline weather file; emission scenarios are derived from UKCIP02				

Building failure criteria and their operationalisation

For free-running (non-air conditioned) office buildings in UK, an acceptable indoor temperature during the warm summer weather is 25 C. Any temperature rise over this value would likely result in a decline in the productivity of office work (CIBSE, 2006). Indoor air temperatures in the 21 to 22 C range are associated with maximum overall work and school performance (Seppanen et al, 2006; Fisk et al, 2007). In the office environment, the reduction in work performance at the temperature of 30 C is 8.9% in comparison with that at 22 C.

Sampling for simulation runs

Based on the earlier discussion three important parameters that will see change over the lifetime of the building have been taken forward: window U-value, heat gains from equipment and lighting, and boiler seasonal efficiency. Table 4 shows actual and coded levels of these three factors. It is common practise to code the actual levels in the design of experiments for normalizing the data and eliminating unit confusion.

Coded value = (Original value - mean)/(range/2) (5)

For the year of 2020, a simulation run is performed for each combination of the factor levels because of low number of combination. Box-Behnken designs (Montgomery, 2001) have been employed in this study for the years of 2050 and 2080; these are very efficient in terms of the number of required runs. Design of experiments and regression analysis is performed using MiniTab V.15. Application of Box-Behnken has reduced the number of runs by 50% compared to full factorial experiments.

Table 4 Coded and actual levels of factors

TIME	METHOD	WINDOW U VALUE (X1)		INTERNAL HEAT GAIN (X2)		BOILER SEASONAL EFFICIENCY (X3)	
		W/m2 K		W/m2 (equipment + lighting)			
		coded	actual	coded	actual	coded	Actual
Now			1.5		12+12=24		0.8
2020	Full factorial	0	1.5	1	12+10=22	1	0.8
				1	10+8=18	0	0.85
				-1	8+6=14	-1	0.9
2050	Box-Behnken	1	1.4	1	8+6=14	1	0.86
		0	1	0	6+5=11	0	0.9
		-1	0.6	-1	4+4=8	-1	0.94
2080	Box-Behnken	1	0.8	1	5+5=10	1	0.92
		0	0.6*	0	4+4=8	0	0.94
		-1	0.4	-1	3+3=6	-1	0.96

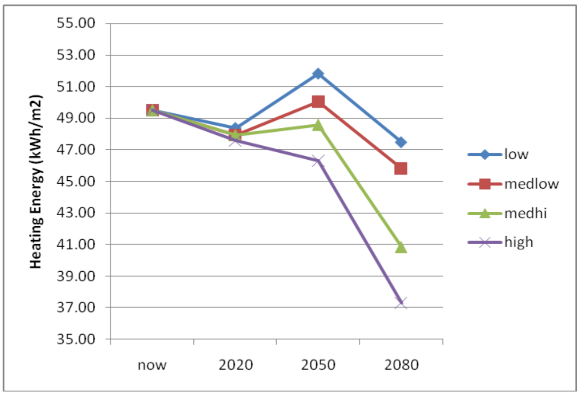
Simulation results and findings

Figure 2 shows change of heating energy, cooling energy, and overheating hours due to climate change and the other change factors considered (see Table 3). As expected, the general trend shows heating energy gradually decreasing with time, and cooling energy and overheating hours increasing with the decrease in heating-degree days (compare Table 3). Note that cooling energy prediction is very low because this value only includes energy consumed by the secondary air fan and pump in the adiabatic cooling systems. The reduction of heating energy due to climate change is beneficial, so no adaptation strategies are needed. Overheating risk in the office building becomes increasingly serious, and further research using uncertainty and sensitivity analysis is necessary to reduce this risk.

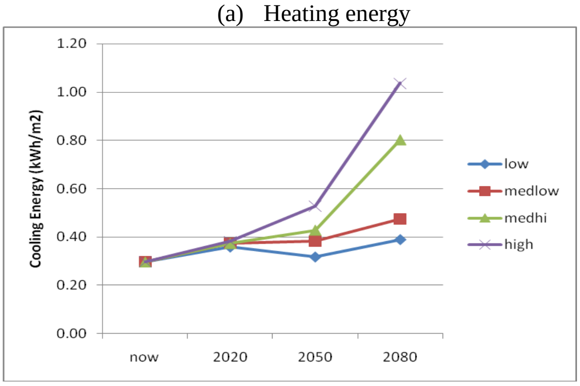
The heating energy used in 2050 office does not decrease greatly, since internal heat gain will be reduced significantly due to more energy efficient office equipment. This also causes a slight increase in cooling energy and overheating hours as shown in Figure 2b and 2c.

The histograms in Figure 3 illustrate the tabulated frequencies for heating energy use of all four climate change scenarios, in which the same scale for horizontal and vertical axes in two figures is used for comparison. As expected the shift from 2050 to 2080 confirms a reduction in heating energy per year. However, it is interesting to note that the standard deviation does not seem to increase over this time span. It is thought that this effect is due to the fact that while uncertainties in a number of effects like internal heat gain increase, absolute values decrease.

Table 5 shows the estimated first and second order coefficients based on the least square method. The T-value is the statistic variable for testing the hypothesis that the coefficient for the corresponding variable is zero. The P-value is the probability for testing the null hypothesis. The larger the magnitude of the T-value and the smaller the P-value, the more significant is the corresponding coefficient. Using these indicators, heat gains from equipment and lighting have a significant effect on heating energy use and overheating hours.

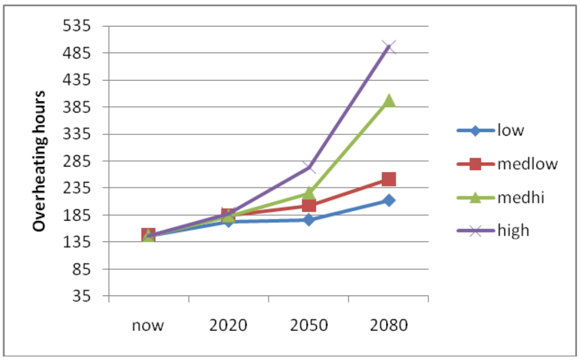


(a) Heating energy



(b) cooling energy

Figure 2a, b: Predicted energy use for four different emission scenarios under zero coded levels (see Table 3)



(c) overheating hours

Figure 2c: Predicted overheating hours for four different emission scenarios under zero coded levels (see Table 3)

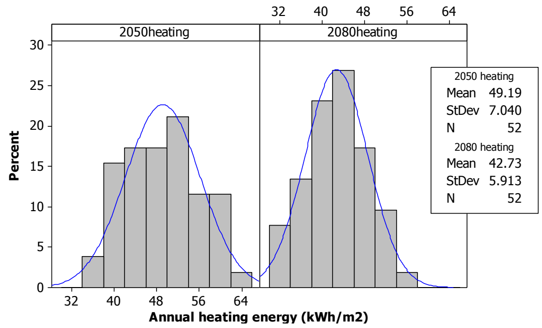


Figure 3: Histograms of predicted heating energy for 2050 and 2080

CONCLUSIONS AND REMARKS

This paper presents a research project that employs building performance simulation to quantify the risks of predicted changes in climate conditions for crucial thermal building functions.

An initial experiment is described that shows how a complex range of factors needs to be considered that, apart from climate change, also relate to changes of the building (for instance intervention/renovation) and changes in the operational scenario (for instance internal heat loads). These factors need to be clustered in change scenarios that feed into probabilistic building performance simulation.

The initial trial reported in this paper only considers a limited set of change factors. Further research is needed to map the full set of factors that impact on the future building performance, and to gain insights in reasonable trends for the changes that are expected to take place for each of these factors. Advanced statistical approaches will need to be employed to prevent explosion of the input space representing these factors and their trends.

Table 5 Estimated Regression Coefficients for 2050 with high emission scenario based on coded levels

TERM	HEATING		
	COEF	**T-VALUE**	**P-VALUE**
Con	46.29	711.54	0.000
X1	4.36	189.49	0.000
X2	-6.69	-290.70	0.000
X3	2.03	88.46	0.000
X1*X1	-0.46	-10.80	0.002
X2*X2	0.32	7.49	0.005
X3*X3	0.07	1.56	0.216
X1*X2	-0.26	-8.14	0.004
X1*X3	0.19	5.94	0.010
X2*X3	-0.29	-9.04	0.003
TERM	**OVERHEATING**		
	COEF	**T-VALUE**	**P-VALUE**
Con	273.17	468.73	0.000
X1	-5.63	-27.31	0.000
X2	36.46	176.94	0.000
X3	0.00	0.00	1.000
X1*X1	-0.88	-2.28	0.107
X2*X2	1.79	4.65	0.019
X3*X3	-0.63	-1.63	0.203
X1*X2	-2.92	-10.01	0.002
X1*X3	0.00	0.00	1.000
X2*X3	0.00	0.00	1.000

Interestingly, the initial work seems to indicate that long term predictions (2080) do not necessarily have to involve more spread – uncertainty - than medium term predictions (2050). This might be due to a downwards trend in a number of important input parameters like internal gains; while uncertainties increase over time, the absolute impact becomes smaller in the long term. In general, it is not a surprise that more attention should be paid to the change of internal heat gain because more insulated building envelope and efficient HVAC systems become available. Although more energy efficient office equipment and lighting would lead to less reduction in heating energy consumption in the future weather, it will provide more opportunity for passive cooling, free cooling and efficient active cooling systems to minimize overheating risk under global warming, as less heat gains mean less cooling load.

Future work will cover a deeper study of energy use and overheating risk, and their consequences for critical building functions like occupant performance and health. It is noted that new, probabilistic, climate change scenarios for the United Kingdom are expected to made available during 2009; these will be employed in later stages of the project.

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