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BUILDING PERFORMANCE SIMULATION FOR THE MANAGEMENT OF THERMAL PERFORMANCE RISKS IN BUILDINGS SUBJECT TO CLIMATE CHANGE

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ABSTRACT

This paper reports on research that uses building performance simulation and uncertainty analysis to assess the risks that projected climate change poses to the thermal performance of buildings, and to their critical functions.

The work takes meteorological climate change predictions as a starting point, but also takes into account developments and uncertainties in technology, occupancy, intervention and renovation, and others. Four cases are studied in depth to explore the prospects of the quantification of said climate change risks.

The research concludes that quantification of the risks posed by climate change is possible, but only with many restrictive assumptions on the input side.

INTRODUCTION

Within the building science and construction communities, there is an increasing interest in the impact that predicted changes in climate conditions will have on building performance. In general, global warming will result in a shift from heating energy to cooling energy. However, there is a need to address system sizing for changing peak loads as well as the operational range of natural and passive systems.

Initial work in this area, for instance the seminal report CIBSE TM36: "Climate change and the indoor environment: impacts and adaptation" (Hacker et al, 2005) has approached the issue through deterministic simulations, which give a good first indication of likely impacts. Other recent articles covering the subject are for instance Crawley (2008), Holmes and Hacker (2008), Lomas and Ji (2009) or Chow and Livermore (2010). The research reported in this paper expands the earlier work with an attempt to quantify the risks that climate change poses for thermal building performance, taking into account the many uncertainties that are inherent in the long–term (50 to 100 years) time horizons on which climate change takes place.

The overall methodology underlying the project is the quantification of risks in terms of a risk factor RF, which can be defined as the product of probability of failures (Pf) and the consequences of failure (Cf), RF = Pf x Cf. For quantification of Pf, the project looks at various change scenarios for both the building and its operational conditions. This is not just limited to climate change trends, but also looks at changes in occupancy, intervention and renovation, and others. For consequences of failure Cf it looks at implications of climate change for building performance. Prime targets are energy use, greenhouse gas emissions and overheating; however the project also looks at more complex issues like office work productivity.

Four case studies are analyzed in depth to explore how building simulation can support the management of the thermal performance of buildings subject to climate change. These four cases represent four very different building types (domestic property, office building, educational building and retail unit). They also range from notional reference schemes to actual existing buildings, allowing a connection with the earlier theoretical work as well as a comparison with real life monitored data. Finally, these four different cases all come with different key functions and hence different performance metrics, which benefits the investigation of handling climate change impact studies via building performance simulation.

This paper reports on the overall project, but with an emphasis on the use of building performance simulation as a tool to assess the risks that climate change poses to the thermal performance of buildings. Further detail on the separate case studies is available in other publications as indicated in the result section.

METHODOLOGY

Any building performance analysis study requires the careful definition of the object under investigation (a building and its (sub) systems), the experimental conditions under which this object is studied (climate conditions, occupancy behaviour, control settings), and the data collected during the experiment and the way that data is processed (performance indicators). Since this paper deals with climate change impact assessment studies, this paper starts with discussing climate change predictions and their application to simulation studies. This is followed by an overview of the cases studied, other assumptions needed plus inherent uncertainties, and the general computational approach.

Climate predictions

A prerequisite for any climate change impact assessment study is the availability of information on the future climate conditions. This information can be obtained from two main approaches: extrapolation from historical data, or prediction by complex physical models, mainly Global Circulation Models or GCMs. Typically the information is provided by meteorological and climate change researchers working outside the realm of building science. In most cases, their climate change predictions are not directly applicable for transient building simulation: climate change is typically described in terms of changes to annual averages for a series of different greenhouse gas emission scenarios, whereas most transient simulation tools need this information to be translated into an hourly weather data file. This translation is not undisputed in terms of data continuity and interrelation between various weather parameters. For detailed papers on this subject, see Crawley (2008), Jentsch (2008), and Guan (2009).

The work in this research paper makes use of two key climate change prediction datasets: UKCIP02 and UKCP09. UKCIP02 provides climate change predictions for various locations in the UK under four main emission scenarios. The more recent UKCP09, which became available while the project was ongoing, is more comprehensive as this is probabilistic data, which takes into account the natural variation in the climate. Figure 1 provides a flavour of the complexity of UKCP09 data. For one location in the UK, this shows probability distributions for four 30-year time slices. Note that these distributions still only show the annual mean temperature; for most building simulation tools this needs to be translated into an hourly climate file.

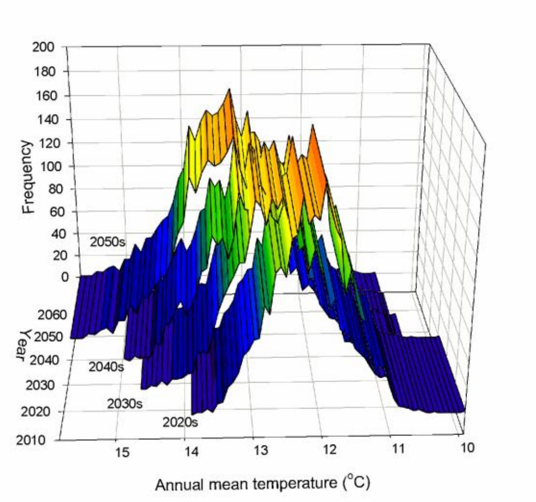

Figure 1. Representation of UKCP09 climate change predictions for Plymouth, UK

Contrary to previous datasets the UKCP09 predictions can be directly applied to building simulation. This is possible through a Weather Generator (WG) which creates synthetic hourly time series (Jones et al, 2009).

Building case studies

Climate change impact assessments have been carried out for four different buildings. These have been selected with various objectives in mind. They represent different building types, in order to cover fundamentally different uses and key sectors of the overall building stock. Furthermore, the cases target specific building services (HVAC systems) and building shell properties. Descriptions and some key specifics are presented below.

In all four cases risk has been studied in terms of the probability of building performance (or lack thereof, giving Pf) and likely consequences for the main functions of the buildings. The performance metrics selected reflect the consequences of not meeting key criteria, thereby giving Cf).

CIBSE TM36-O2 Reference Office

The initial case study for this research stems from the earlier work of CIBSE TM36. Case O2, representing a modern office with a mixed-mode ventilation system, has been taken forward to align the studies. Figure 2 depicts the O2 Office. The choice for the mixed-mode system, which combines natural and mechanical ventilation, is made due to the concerns that climate change might affect the operation range of natural and passive systems; a building that combines natural and mechanical modes allows tracking such changes.

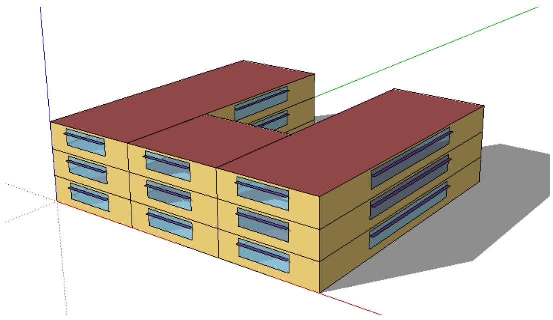

Figure 2: CIBSE TM36, Case O2

House with GSHP and PV

In order to cover the domestic building stock, a case study representing a modern two storey, four bedroom detached home is studied. The building has a total floor area of 148 m^2, and again is in line with the CIBSE TM36 case studies; see Figure 3. It is equipped with HVAC systems that at present are increasingly popular in Western Europe and the UK: a ground source heat pump (GSHP) and a photovoltaic (PV) array.

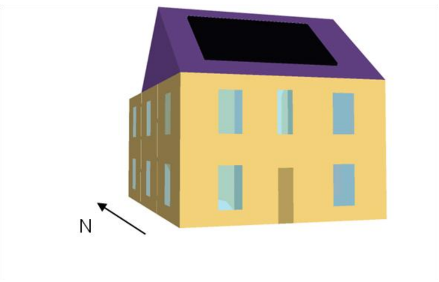

Figure 3: Four bedroom home with PV and GSHP

EnergyPlus benchmark Supermarket Building

A supermarket building is studied in order to investigate the changes in predicted building performance over time. Supermarket buildings are a good candidate for this type of work since they have a high degree of repetition, and hence have a relatively deep insight in performance degradation over time. As retail units they consists of extremely market driven structures and HVAC systems. Most HVAC systems in supermarkets are renewed after about 20 years. The model is largely based on the EnergyPlus benchmark model, ensuring compability with general assumptions; see Figure 4.

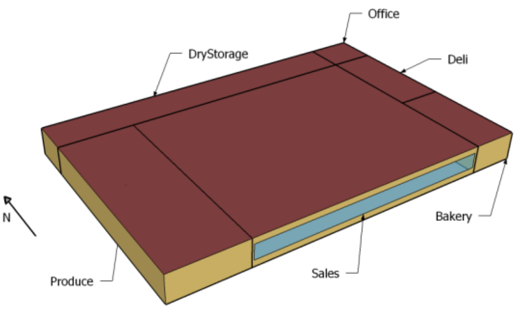

Figure 4: Supermarket (EnergyPlus Benchmark)

Roland Levinsky Building

The Roland Levinsky Building is a real building, located at the author's campus. Since this is an existing facility, it provides a case study where the researchers have access to the building design team (architect, engineers, and contractors), the facility management team, as well as end users. A model of the building is presented in Figure 5. Note the highly complex geometry of the building.

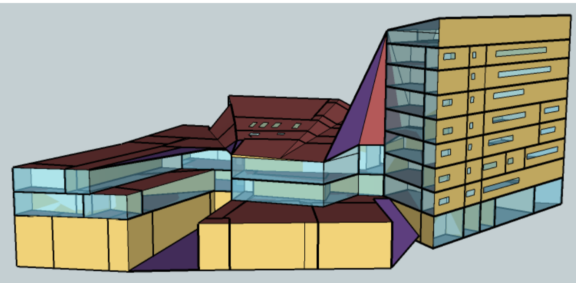

Figure 5: Roland Levinsky Building

The Roland Levinsky Building is a multi-purpose educational flagship facility, providing space for students, staff and the general public. It is home to the local Faculty of Arts and comprises teaching space, theatres, office space and a café. The building is nine storeys high and offers about 13,000 m^2 of floor space. It has a reinforced concrete frame and a striking copper cladding that forms both the roof as well as two facades. The north and south facades are entirely glazed. Since the buildings sits an inner city urban environment with corresponding noise and pollution it is mechanically ventilated.

Generic modelling assumptions and uncertainty

While the four cases are closely defined, a series of further assumptions is needed to develop thermal models. Whenever possible, additional information on material properties, occupancy schedules and control set points is based on information from key sources like the ASHRAE Handbook of Fundamentals (ASHRAE, 2009), CIBSE Guide A (CIBSE, 2006) and the UKs National Calculation Method (NCM, 2009).

Throughout the studies various scenarios have been considered and reflected in the models. This includes various occupancy schedules for the domestic property, maintenance and system upgrade scenarios for the supermarket building, and changes in office equipment for the Roland Levinski Building.

Obviously, the definition of the building model adds further uncertainties to those inherent in the climate change prediction. Various factors have to be taken into account. Between any buildings as-designed versus as-build, there are uncertainties due to natural variation in component dimensions and material properties. There also is a spread in occupant behaviour and control settings. Where possible these have been taken into account via probability distributions, building on previous work by Macdonald and Strachan (2001). Table 1 and Table 2 give a simple example of some of the assumptions for one of the case studies only.

Table 1: Initial parameter setting for some parameters of the CIBSE TM36 O2 Office model

VARIABLE	UNIT	BASE CASE
Wall U-value	W/m^2 K	0.3
Floor U-value	W/m^2 K	0.22
Roof U-value	W/m^2 K	0.22
Window U-value	W/m^2 K	2.0
Infiltration rate	ACH	0.25
Equipment peak heat gain	W/m^2	12
Lighting peak heat gain	W/m^2	12

Table 2: Probability distribution of said parameters of the CIBSE TM36 O2 Office model

VARIABLE	DISTRIBUTION	VALUES
Wall U-value	normal	μ* σ (10%)
Floor U-value	normal	μ* σ (10%)
Roof U-value	normal	μ* σ (10%)
Window U-value	normal	μ* σ (10%)
Infiltration rate	normal	μ* σ (50%)
Equipment heat gain	normal	μ* σ (15%)
Lighting heat gain	normal	μ* σ (20%)

Where μ = mean value from Table 1, σ = variance (standard deviation, x% of mean value). Specific values depend on the building element, room or zone of the building.

Other uncertainties are more difficult to capture. Performance degradation of systems and components is one of these, and has been investigated via the supermarket building case; for more detail see de Wilde et al (2011). Even more difficult is the prediction of interventions in the building systems and fabric (renovation), as this requires predicting the moment of intervention as well as the specific intervention action. For some of these an estimation of likely interventions can be attempted; for instance one can extrapolate trends in building shell U-values from past data, or analyse trends pertaining to system efficiencies. However, other interventions are almost impossible to predict; for instance, an existing gas fired boiler might be replaced with future heat pump technology, or even newer systems that are not yet 'on the radar'.

Performance metrics

Further complexity relates to the performance metrics used in the climate change impact assessment studies. Typical performance indicators like the annual energy use for heating and energy use for cooling, as well as the associated carbon emissions, have been studied. Similarly, analysis of peak heating and cooling loads and overheating risk in summer are logical targets. However, in order to obtain these key figures from building simulation further assumptions are needed, for instance regarding the fuel mix that underpins electricity production, or the spatial/zonal resolution and potential need to use adaptive rather than static thermal comfort models when analysing overheating. Assumptions and findings in these areas can be found in de Wilde and Tian (2010a, 2010b). Similarly, specific systems sometimes call for specific performance indicators. For instance the PV and GSHP in the domestic building require data on the coincidence between electricity production and electricity consumption, in order to establish the dependency of the building on the electricity grid. This again drives the modelling approach and system simulation resolution needed for the climate impact assessment study.

Computational approach

All four case study buildings have been modelled in subsequent versions of the transient thermal building simulation tool EnergyPlus (V.3.0 – V.5.0).

The probabilistic approach taken in this study is based on the propagation of uncertainties. This requires a range of assumptions on factors that are of relevance, translation of these factors into probability distributions, and then sampling from these distributions. Since there are many parameters to be considered, which sometimes are even further complicated by the need to study various intervention scenarios, this is a non-trivial issue. Figure 6 conveys this for one of the building cases. In Figure 6 one can see various probability distributions as well as alternative scenarios (base case, and scenario A, B and C) which represent the building in the original state as well as after a minimal, average and aggressive intervention in terms of making the building more energy efficient. The process therefore has been automated using the SIMLAB package, using Latin Hypercube sampling.

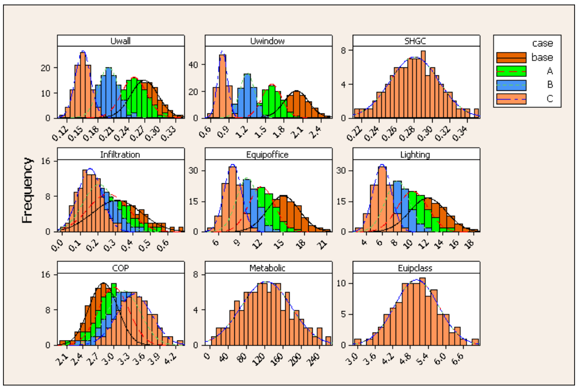

Figure 6: Parameter sampling in order to deal with probability distributions

The sample size needed for analysis of the case studies ranges from several hundred EnergyPlus input files for the relatively simple domestic building, to several thousand input files for the complex university campus building. As all EnergyPlus simulations are stand-alone simulation experiments, parallel computation can be used to speed up the analysis. To this end, simulations have been carried out in a Condor Grid, which provides access to 200 PCs. This allows to carry out studies that would cost up to a month on a single machine to be conducted within a single weekend. Figure 7 shows usage statistics of the local grid.

Sensitivity analysis of the computational results from the simulations has been conducted with various statistical techniques, specifically SRC (Standardized Regression Coefficients), SRRC (Standardized Rank

Regression Coefficient), MARS (Multivariate Adaptive Regression Splines), and ACOSSO (Adaptive COmponent Selection and Smoothing Operator). For further detail on these methods see Helton et al (2006) and Curtis (2009).

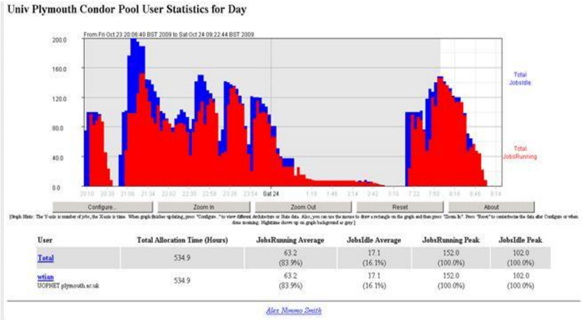

Figure 7: Grid Computing Statistics

The overall complexity of the analysis work undertaken is conveyed by Figure 8, which shows the individual EnergyPlus simulation runs done for the university building, demonstrating combinations of parameters, intervention scenarios, and climate files. The total number of models (in terms of combination of building model with climate data file) studied here is 2400.

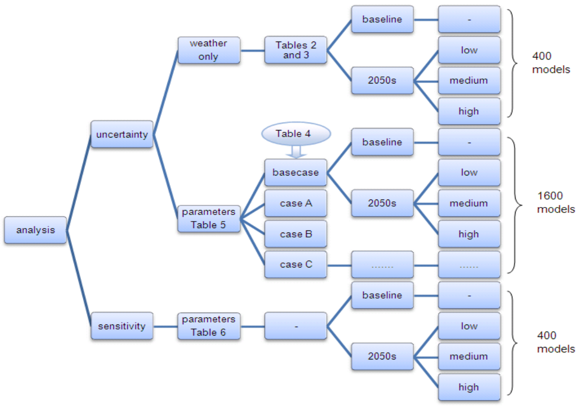

Figure 8: Modelling approach

COMPUTATIONAL RESULTS

A selection of results is presented in this section. These have been taken from the extensive dataset of simulation outcomes resulting from the project with a view of illustrating key points that are of relevance to the overall project and from a building simulation point of view. Note that risk, as a product of probability and consequences of occurrences, is implicit in all results.

Results for the CIBSE TM36-O2 Reference Office

The simulations on the CIBSE TM36 Case O2 reference building confirm the expected trends, where over time energy use for heating is decreasing while energy use for cooling is increasing.

Sensitivity analysis, in this case via SRC and SRRC, allows identifying key factors that cause a spread in simulation results. On the heating side of the equation, infiltration, lighting gains and equipment gains are prime sources of uncertainty. Interestingly, as overall heating energy reduces with a warming climate, over time the overall uncertainties in predicted heating energy become smaller as well. On the cooling side of the equation, climate conditions, lighting gains and equipment gains are driving factors; here uncertainty increases over time.

As noted, the O2 Office is also a case that points out the need to closely study the definition of performance indicators in terms of underlying assumptions like zonal resolution. As described in detail in de Wilde and Tian (2010a), adaptation of a different zoning model (simplified one zone model or detailed room-by-room modelling) can cause differences of up to 28% in the predicted overheating risk. A similar effect pertains to underlying assumptions regarding thermal comfort conditions. Figure 9 shows predictions made using both approaches. The base case, A and B scenario represent the building in the original state as well as after a minimal and aggressive intervention in terms of making the building more energy efficient.

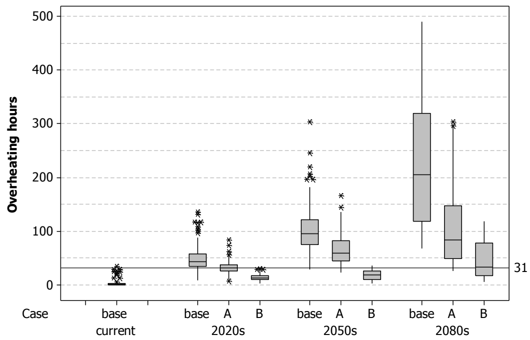

Figure 9a: Static comfort assumption

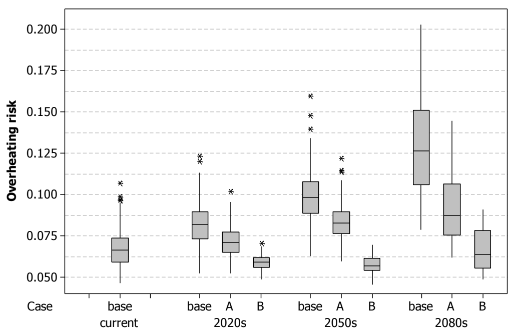

Figure 9b: Adaptive comfort assumption

Figure 9. Overheating risk for current state, 2020s, 2050s, and 2080s for different building intervention scenarios

Looking at overheating criteria as stipulated in CIBSE Guide A (CIBSE, 2006), a building under static assumptions will need to be fitted with an additional active cooling system somewhere between the 2050s and 2080s. However, the same building with adaptive assumptions does not require this intervention.

Results for the house with GSHP and PV

The simulation work carried out for the domestic property with GSHP and PV again show the typical trends, with a decrease of annual heating energy but an increase in overheating risk. A key factor as identified by the uncertainty analysis is the carbon emission factor for electricity; obviously this one has a highly political dimension and therefore is extremely hard to predict.

Interim results carried out on this case demonstrate the need to keep alert regarding analysis models that are applied. Figure 10 shows the relation between annual cooling degree days and the percentage of hours over 26°C in a room. Clearly, at lower threshold values for the cooling degree days this relation is non-linear, whereas at higher values it becomes linear. This has implications for the sensitivity and uncertainty analysis methods that can be applied.

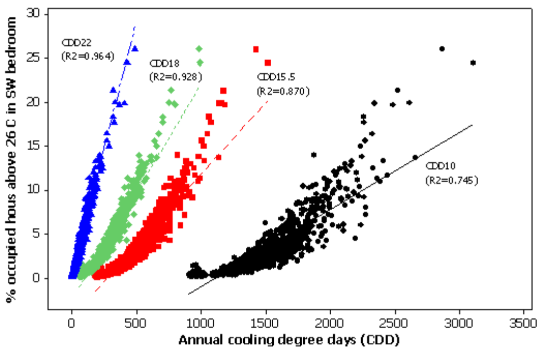

Figure 10. Relation between overheating risk and annual cooling degree days (CDD), Southwest bedroom

Results for the E+ Supermarket Building

The study on the supermarket building shows the feasibility but also the limitations inherent in attempts to predict changes in thermal behaviour of buildings over the years – in other words, in a longitudinal view of building performance. Figure 11 shows the gradual increase in cooling energy for this building over the years, under two different maintenance scenarios.

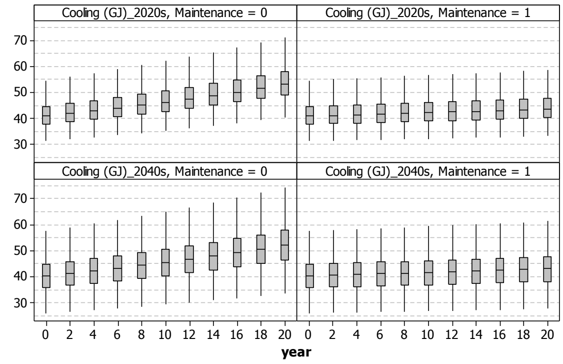

Figure 11: Longitudinal prediction of annual energy use for cooling for a supermarket building over a time span of 40 years.

Apart from a change in climate conditions the underlying simulations take into account that there will gradual decreases in things like thermal insulation provided by the building shell, gas burner efficacy, COP of the cooling system, fan efficiencies and others. For more details, see de Wilde et al (2011). While the maintenance procedure of course will have a significant impact, a crucial assumption in this longitudinal prediction of building performance is the moment of building renovation/upgrade. This supermarket building is assumed to be 40-year life expectancy, with an intervention after about 20 years for HVAC system. However, the exact year is in fact very hard to predict, yet causes a step change in the predicted performance. Overall, it is found that there is a lack of information about HVAC system and building material life times and performance degradation, making this type of prediction difficult for less standardized buildings like offices, schools etcetera.

Results for the Roland Levinsky Building

The final case study analyzed in this project is an operational, real building.

Figure 12 shows some typical simulation results, in this case presented as cumulative distribution functions (CDFs) for annual cooling energy per square meter floor space.

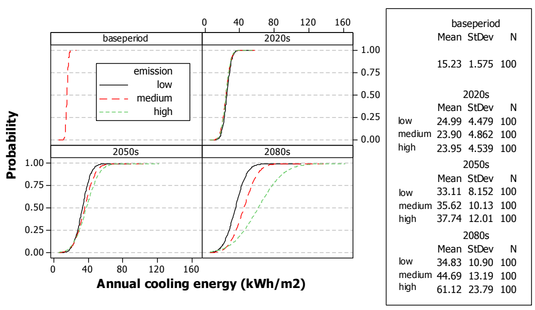

Figure 12. Cumulative distibution functions of annual cooling energy

The study of an actual building brings in a number of interesting points by itself; for instance it became obvious that the brief of this building was not concerned with climate change adaptation at all. Furthermore, it provided a sobering view on building simulation efforts by establishing some hard realities about system optimization; typically it made it very clear that system sizing is much less an issue than often assumed by building simulationists, since the building is equipped with dual systems for back-up and servicing purposes; each of these is sized at 75%, yielding an in-designed overcapacity totalling 150% from inception. In this light any concern about slight increases in cooling load can easily be accommodated. Finally, the building is presently being monitored; initial energy use surveys indicate that the actual operation is rather different from many typical mechanical engineering stage and building performance simulation assumptions. Another interesting point raised from this study is that of validation of probabilistic results with actual meter readings; values obtained over the first years of operation of the Roland Levinsky Building of course fall on the CDF, but say little about the accuracy of the predictions made. Finally, discussions with the local Estates department made it clear that some of the questions underlying this project are only on long-term horizon; with constrained budgets the focus of facilities managers is on operating their buildings efficiently today, within the financial room available. Questions about interventions due in 15, 20 years do not rank high on the priority list.

CONCLUSIONS AND REMARKS

Regarding the overall objectives of the project on management of thermal performance risks in buildings subject to climate change, the following conclusions have been drawn:

(1) With building simulation tools it is possible to carry out probabilistic predictions of the future thermal behaviour of buildings. However, various issues limit the usability. The most difficult factor is the need to predict both the time and impact of interventions, like building fabric and HVAC systems upgrades. This limits our capability to truly calculate the probability of failure as intended in the outset of the project.

(2) The consequences of failure are a moving target. For the reference buildings studied there are no clients or owners that can be consulted on their priorities. However, involvement with an actual building and its facilities managers shows that climate change adaptation in general is low on the priority list.

(3) Quantification of risk, in terms of a risk factor that is the product of probability of failure and consequences of failure, can be done with today's technology. However, this is only possible within a frame of stringent restrictions, like assuming that the building is maintained in exactly the same state from commissioning to end of life, or that moments of upgrades and effect of such upgrades are known a priori. Additionally one needs to assume that key performance indicators studied, like for instance overheating risk, are indeed crucial to the building operator.

(4) Given these conclusions it appears that risk acceptance and risk abatement studies presently are not yet viable options in the domain of climate risk impact studies for individual buildings.

In terms of the building simulation discipline, this project leads to a number of specific observations on available information, simulation methodology, tools and software environments, and data aggregation and analysis:

(a) Overall there still is a serious lack of information on building system properties needed for probabilistic analysis. This concerns the natural spread in material properties, service life, and performance degradation over time. Without further work to expand our knowledge in these areas, efforts to simulate future performance of buildings will by nature include relatively large uncertainties.

(b) In terms of simulation methodology, further work is needed in order to increase the handling of fundamental assumptions, like the use of static versus adaptive thermal comfort assumptions or building zoning assumptions, and the way these are communicated. This relates to a general need to further strengthen the definition of performance indicators in terms of 'repeatable virtual experiments' with a universally understood context.

(c) It appears that the current generation of building simulation tools is at best equipped with a batch processing function. Further work in uncertainty and sensitivity analysis would benefit from tools that can actually handle parameter ranges and distributions. Workarounds via external environments is of course possible but might limit this type of analysis from going mainstream. On the plus side, there is no need to change the 'internal' mechanics of the simulation process; given structured outside handling the present functionality gives plenty of room to explore various research questions in the realm of climate change impact analysis.

(d) Existing simulation programs like EnergyPlus are set up to deal with single year climate files; typically one climate data file can be selected from their input menu. Work that takes a longitudinal view, connecting various climate years, normally is not accommodated. Again this can be covered by external workarounds, but it seems that a fundamental change to multi-year simulation as well as data aggregation and presentation might benefit future tools.

(e) Simulations that deal with sampling from larger search spaces are excellent candidates for parallel computing. This can be efficiently done in research institutions that have Grid computing in place. It is worth investigating whether similar approaches can be transferred to cloud computing, especially with a medium-term transfer of this type of analysis to small size consultancy practice.

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