CLIENT-DRIVEN SENSITIVITY ANALYSIS OF THE ENERGY CONSUMPTION OF A WELSH OFFICE BUILDING USING PROBABILISTIC CLIMATE PROJECTIONS

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ABSTRACT

Climate change will affect the performance of our building stock. As buildings can have a lifespan of 50-100 years, designing for this condition is now a key challenge for the building industry.

This study focuses on predicting current and future behaviour of a fully air-conditioned office building in Wales. UK probabilistic climate projections are used to predict its annual heating and cooling energy consumption. The main aim is to identify the effects of interventions to the building envelope and the behaviour of the occupants. The difference to other studies in this context is that the type and range of paramters changed were chosen by the client. They had the final decision as to which what was finally would be implemented. One of the key findings for the client was that even in a fully air-conditioned building, exposing the thermal mass reduces the annual energy consumption.

INTRODUCTION

There is now a general agreement that climate change is inevitable (CIBSE 2005; Jenkins et al. 2009) and that anthropogenic greenhouse gas emissions are part of the cause for the rising temperature and sea levels (Jenkins et al. 2009; IPCC 2007). Globally, this can result in flooding and an exacerbated heat island (Shimoda 2003). In the UK extreme events are predicted to occur, such as periods of high temperatures and heavy winter precipitation (Beniston et al. 2007).

Trends such as a rising average temperature and a changing distribution of rainfall throughout the year are already changing (Jenkins et al. 2009). Trends such as average temperatures are predicted to continue rising globally as a result of climate change (CIBSE 2005; IPCC 2007). These changes will affect the performance of buildings. In the building industry, there are differing opinions on the adequacy of current design practices addressing climate change. In a survey by Morten et al. (2011), most participants agreed that current design practises are inadequate. Those who disagreed generally held senior positions within an organisation. De Wilde et al. (2012) identified another problem; parts of a design are occasionally ignored on site. This leads to unexpected problems: omitted chillers and ductwork for example has led to overheating.

Many research activities exist which try to predict how climate change will affect buildings (De Wilde & Tian 2012; Radhi 2009; Jenkins et al. 2011). Building performance simulation (BPS) tools can indicate how a building will behave. A buildings behaviour can be described using different performance metrics, of which a critical review is given by De Wilde et al. (2011). Conclusions drawn from this review include 1) future behaviour prediction is feasible and 2) a lack of research exists that uses a probabilistic approach 3) a typical performance metric for a climate change study is annual energy consumption.

BPS can analyse a range of systems in a building and associated parameters. Radhi (2009) claims that building systems, occupants and the design of a building's envelope can have a significant effect on energy consumption. Some systems are more influential than others on the energy consumption of a building. Over a buildings lifecycle, a study has demonstrated that the HVAC and electricity systems can be the cause of up to 94.4% of the primary energy consumption (Scheuer et al. 2003). These systems could significantly influence the energy consumption of a building if the average temperature will rise in the future. It is also important to check if existing technologies such as the HVAC system will be suitable for higher outside temperatures. Overheating can occur even in air conditioned offices in the future (Guan 2009). Research on similar topics as above has led to a range of guidance on the effect of climate change on buildings (Hacker et al. 2005; CIBSE 2005).

BPS can also be combined with uncertainty analysis to examine future behaviour (Tian et al. 2011) and robustness (Hopfe et al. 2011) in more detail . A sensitivity analysis can further lead to the derivation of possible adaptation measures (Guan 2012). The opportunity to make a difference with such adaptation strategies and new technologies is before a building is constructed (Camilleri et al. 2001; Granadeiro et al. 2012). The validity of analysing the performance of a building using data from the planning stage is supported by Korjenic et al. (2012). However, the reliability of results has been questioned when predictions of technologies and efficiencies of systems are involved (De Wilde et al. 2011; De Wilde et al. 2012).

The above highlights cooperation between academia and industry is important. Research on existing or planned buildings could support industry to make informed design choices. This paper is an example of close cooperation between academia and industry. It was part of a Technology Strategy Board (TSB) competition "Design for Future Climate: Adapting Buildings". The aim of this competition is to support the development of adaptation strategies of UK buildings to climate change. Therefore, the purpose of this paper is to examine the future performance of a planned building at the detailed design stage in order to help informed decision-making. It is important to note that the client makes the final decisions, and feasibility plays an important role. Probabilistic climate data is used to develop an adaption strategy based on behavioural and physical design parameters.

The paper will first analyse existing research on climate change and building design. This is followed with details on the climate projections used. A methodology and case study is presented, detailing the sensitivity analysis. The analysis examines behavioural and fabric design parameters. Finally, results and an adaption strategy are discussed.

CLIMATE CHANGE AND BUILDING DESIGN

Dynamic building simulation tools and climate projections can be combined so engineers and architects can design a building with a more robust design to future performance. Many studies have looked into simplifying this process.

(Coley & Kershaw 2010) predicted the future resilience of a building using a method that calculates its climate change amplification coefficient (C_T). It is unsuitable for a sensitivity analysis, as a new C_T is needed each time a model parameter was changed.

Another study (Christenson et al. 2006) used the method of degree-days based on monthly temperature data to determine the impact of climate warming on buildings. One of the conclusions from this study is that it was important to continuously update weather data used for building design, otherwise cooling demand will be underestimated and heating demand overestimated. The chosen method is described as fairly accurate as long as the internal temperature, thermal gains and building properties are relatively constant. As a result, this method is not suitable for some applications.

Regression models have also been developed to assess the future performance of buildings (Wan et al. 2011; Jenkins et al. 2011). These simplified models are based on specific buildings and climates. Their usefulness is therefore limited.

A common trend found in studies in this field is in the future heating energy demand will fall and cooling energy demand will rise (Christenson et al. 2006; CIBSE 2005; Cartalis et al. 2001). The latter can almost have a linear correlation to the rise in average temperature (Guan 2009).

When predicting such a change in the performance, a sensitivity analysis can identify which parameters have the greatest impact on future performance. (Tian & De Wilde 2011) undertook an uncertainly and sensitivity analysis on thermal behaviour of an existing air-conditioned university building in Plymouth, UK. It is shown that more than 80% of the output uncertainty in annual heating energy is linked to the window U-value, infiltration rate and window solar heat gain coefficient (SHGC). For the annual cooling energy, the variables were the window SHGC, window U-value and cooling degree days which have a base temperature of 18º C. (De Wilde & Tian 2010) have shown that the orientation of a building is also important, as office productivity can differ between elevations. The limitation of using such data is it is only applicable to similar buildings, and one characteristic may be enough to render results unsuitable. For example, Guan (2012) discusses that adaptability measures suitable for heating load dominated buildings may not be suitable for cooling load dominated buildings. Such a characteristic is divorced from weather, location, orientation etc.

Another physical design parameter that has been identified as significant in literature is thermal mass (Rodrigues et al. 2013). Buildings that have a higher thermal mass (Hacker et al. 2008) and which use low energy design techniques (Holmes & Hacker 2007) have been shown to produce lower CO_2 emissions. This is supported by Peacock et al. (2010), who claim that some low thermal mass dwellings will be likely to overheat in the future.

A selection of the physical design parameters mentioned above is included in this study. One main exception is the study uses a window G-value instead of a window SHGC, as this is more common practise in the UK. In addition, some behavioural parameters are tested, as studies such as (Coley et al. 2012) have shown they are also important.

UKCP09 AND PROMETHEUS

Information on the first UK probabilistic climate projections 2009 (UKCP09) is available in Murphy et al. (2009). Part of the UKCP09 project is a weather generator. This uses baseline climate data (1961-1990) to calibrate its rainfall model, and calculates future weather files for 30 year time periods. The baseline climate data originates from historical observations to take into account local topology and has a 5km spatial resolution. Change factors then amplify baseline precipitation data to resemble a chosen future period, from which other weather variables can be derived. These change factors differ on a 25km resolution. As the UKCP09 is based on probabilistic information, there are 10000 possible change factors for each location, emission scenario and decade. The weather generator will output 100 samples of climate data per year, based on randomly selected change factors. This results in 3000 equiprobable future climate files for each time period. Using this tool to generate future climate data does have some limitations: 1) processing the significant amount of output data is computationally expensive and 2) the data lacks certain variables necessary for thermal simulations (Eames et al. 2010), such as wind direction.

In order to promote the use of the UKCP09, projects have been set up such as "The use of probabilistic climate data to future-proof design decisions in the buildings sector" (Prometheus). The outcomes of this project are baseline and future weather files for three time periods. These files include the missing variables (Eames et al. 2010). Thermal simulations using these weather files have been shown to be consistent with models using CIBSE future weather years and UK Climate Impacts Program 2002 climate data (Hulme et al. 2002). Additionally, they have been found to produce similar results to using the equiprobable weather files in less computational time (Kershaw et al. 2010).

The Prometheus files are decadal, and are currently available for the present, 2030, 2050 and 2080 time periods. Each time period encompasses 30 years of data. For example, 2020 actually contains data from 2010-2039. The methodology of their derivation has been published and peer-reviewed by Eames et al. (2010). The files differ in three ways: summer temperature, emission scenario and probability percentile. The summer temperature of the file is either average or higher, resulting in either a Test Reference Year (TRY) or a Design Summer Year (DSY) file. TRY are recommended for energy analysis (CIBSE 2006). There are three emission scenarios available in UKCP09: low, medium and high. Lastly, there is a choice in the cumulative density function (CDF) probability percentile. This can be 10%, 33%, 50%, 66% and 90%, with the 50% labelled as the central estimate of the likelihood of the change (Eames et al. 2010). Figure 1 shows a comparison of some of the variables between the present TRY and 2080 TRY in a medium emissions scenario, and with a 50% CDF. The location is Cardiff, Wales.

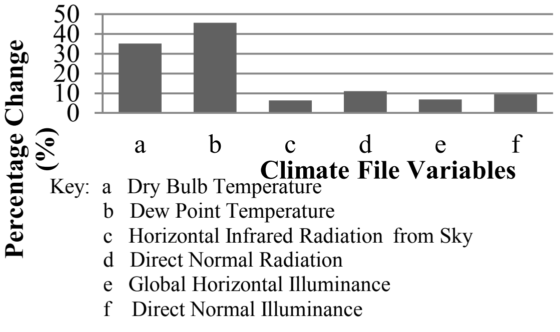

Figure 1 Percentage Change from Control TRY to 2080 TRY [medium emissions, 50 percentile]

The most significantly increased variable is the dew point temperature, followed by the dry bulb temperature. A building experiencing this change in external stimuli will have a lower cooling energy demand and face different challenges with condensation.

CASE STUDY AND METHODOLOGY

The new Admiral Insurance Headquarters will be built in the city centre of Cardiff, Wales. It is aiming for a BREEAM (BRE Global 2012) excellent rating. BREEAM is a sustainability design and assessment method. The building has 12 storeys and 22944 m^2 floor space, and at the time of writing was at the detailed planning stage. The ground floor will be retail and ancillary space, whilst the remaining floors will be office space for a telephone exchange centre. The occupancy density is $5.9m^2$/person, which is higher than the recommended average $10m^2$/person (BCO 2009). The top 11 storeys have an identical floor plan: an open plan office centred around a staircase. The building will use only mechanical ventilation to avoid the noise pollution of a city.

The methodology underlying this study is so-called action research (Oates 2006). The case study runs parallel to an industry project. Progress relies on meetings, workshops and feedback between different design team members. The initial model is from the design team, and it is based on client specifications. This includes geometry, material and HVAC descriptions, and internal gains. This forms the *'base'* case in this study. Cardiff University's role in this project was to analyse the buildings performance at different time periods, identify the main parameters which had a significant impact on energy consumption, and suggest adaptation measures. The BPS tool used for the energy analysis was IES-VE (version 6.4.0.7). Figure 2 shows a screenshot of the model.

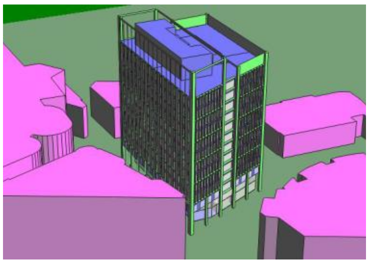

Figure 2 Model of the Admiral building and its surroundings.

Initially a *'base'* case was simulated under all time periods, then various physical and behavioural parameters were adjusted. The physical parameters of the '*base*' case and '*variation'* cases are listed in Tables 1 and 2. In each '*variation*' simulation, only one parameter differs to the 'base'. Table 1 contains internal gains and the boiler and chiller coefficient of performance (COP). Table 2 contains structural parameters.

Table 1
Details of the 'base' case for the Admiral Building

PARAMETER		MAXIMUM SENSIBLE GAIN
Internal Gain	People	73 W/person
	Florescent Lighting	10 W/person
	Equipment	23.5 W/person
Chiller COP		5.72
Boiler COP		0.88

The decisions on data use in this project were client-driven. The authors guided the choice of parameters, but the entire design team agreed on the values for the 'base' and 'variation' cases in order to mirror best and standard practice values.

Table 2
Physical parameters adjusted in derivative models.

PARAMETER	UNIT	BASE	VARIATION
Glazing G-value (G_g)		0.4	0.19, 0.55
Ground U-value (U_g)	W/m^2 K	0.2	0.1, 0.15
Roof U-value (U_r)	W/m^2 K	0.2	0.1, 0.15
Thermal mass (TM)		Suspended ceiling	Tm exposed by removing ceiling tiles
Wall U-value (U_w)	W/m^2 K	0.2	0.1, 0.15
Glazing U-value (U_g)	W/m^2 K	1.76	0.8, 1.8
Infiltration (I)	ach	0.25	0.044, 0.133
Glazing Ratio (GR)	%	40	30, 60
Shading (S)		No shading	With shading

The behavioural parameters studied were occupancy times and the cooling set point temperature. The cooling set point temperature is categorised as a behavioural parameter in this study, as changing it would affect the occupants and not incur any financial costs. The cooling set point temperature parameter (T) in the *'base'* and two '*variation*' cases is 24, 26 and 28°C respectively. The occupancy parameter (O) has two '*variation*' cases. The *'base'* case is occupied 7-10pm. The first '*variation'* is 6am -9pm, to see the effect of starting when there is a lower outside temperature. The second '*variation*' is 6am - 12pm, and 2-11pm. This attempts to minimise the cooling necessary during what should be the hottest part of the day by vacating the premises.

The *'base'* and *'variation'* cases were simulated with future weather files to test the buildings robustness. The Cardiff weather files used are from the Prometheus project. TRY files were used for the present (1961-1990), 2030, 2050 and 2080 time periods. To avoid extreme predictions, the medium emission scenario and the 50% probabilistic percentile was selected. Overheating is not considered as the case study relies on mechanical ventilation. Carbon emissions have also not been presented as it is expected that the HVAC system will be replaced many times with more efficient COPs as it has a shorter lifespan than the building.

RESULTS AND DISCUSSION

The Admiral building '*base'* and '*variation'* cases are simulated in the present, 2030, 2050 and 2080 time periods. The performance metric chosen is heating and cooling loads. CO2 emissions are not considered as the COP for the chiller and boiler have not been adjusted to take into account replacement with more efficient versions in the buildings lifetime. Such an estimate would also need to be tested for sensitivity, and this study focuses on structural and behavioural parameters only.

'Base' Case

The purpose of the *'base'* case is twofold. Firstly, it portrays how the planned Admiral building will react to climate change. Secondly, it is used as a control to which all '*variation*' cases can be compared. Figure 3 shows the heating and cooling energy use of the *'base'* case with different climate file periods.

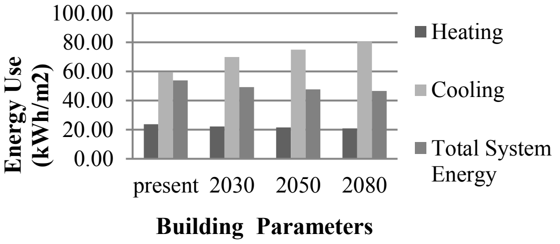

Figure 3 Future energy use of the Admiral building

Climate change will cause the cooling demand of the base case to rise by 36%, and the heating demand to decrease by 12%. This will be mostly due to the aforementioned average temperature rise. The overall system energy consumption of the building will decrease, mainly as these values take into account boiler and chiller COPs.

'Variation' Cases

The purpose of changing parameters in isolation is to determine their suitability for inclusion in an adaption strategy. The heating and cooling demand of the *'base'* case (labelled 'B') and '*variation*' cases are in Figures 4, 7-9. Changing parameters affects the building under all the time periods in the same way, the main difference is that the values of the figures increase from the *'base'* case to 2080. The observations below are therefore applicable to all the time periods.

The most influential change is to increase the cooling set point temperature. Although this is not currently a feasible strategy for the planned building, this could be a future option if peoples tolerance level rises because of the external temperature increasing.

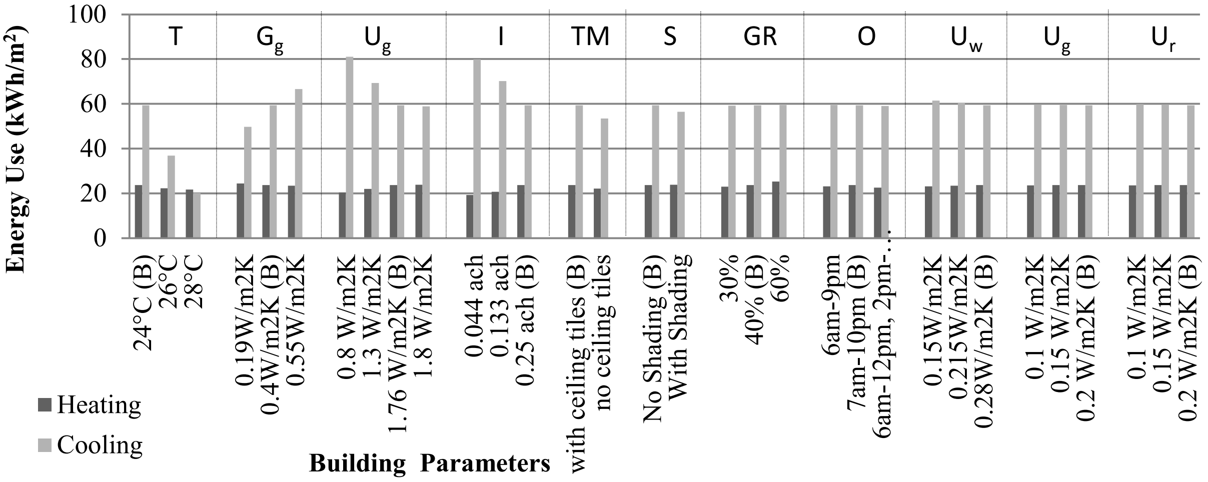

Figure 4 Admiral building performance in the present time period

Another measure is increasing windows U-values and decreasing their G-values. A penalty of decreasing the G-value is inside lighting conditions may be lowered too far. A daylighting analysis would have to be run to identify any problem areas. As a result additional electric lighting may necessary, which would increase the already problematic internal heat gain and also the energy demand of the building. This could be negligible in the future, if lighting is more energy efficient. The higher U-value could also have a negative effect on occupants, as if they are near the glass their exposal to a cold surface could result in their radiant heat loss.

As the building has high internal gains, increasing the infiltration significantly decreases cooling demand. The risks with such a strategy include the building may be uncomfortable to work in due to draughts and it is an uncontrolled measure: in the future it may leak too much heat. Suitable alternative strategies include night cooling or natural ventilation.

Although these measures were initially turned down due to fear of noise pollution, they could form part of an adaption strategy for the future when there is more data available on the actual use and occupancy of the building.

Natural ventilation could also augment the benefit of using the thermal mass of the building. Exposing the thermal mass is already an influential parameter to lowering the annual cooling demand. In this study, the ‘exposing’ mechanism is the removal of the ceiling tiles. Figure 5 supports this theory in the present time period. It shows the cooling demand of the building with and without ceiling tiles on the 21st July (peak cooling). The model with no ceiling tiles is penalized with a higher cooling demand at the start of the day. This will inadvertently cool the thermal mass and allow it to absorb heat during the day. This is shown with the reduced cooling demand during peak occupancy. It can exude this heat back when the temperature drops at night.

Thermal mass also has a positive effect on the heating season, which can be seen in Figure 6. This shows a reduction in the heating and cooling demand on the peak day of heating (Jan 1st) in an open plan office space in the building in the present time period. It also shows the building needs cooling even in the winter.

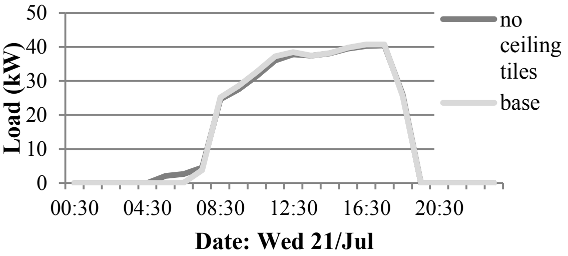

Figure 5 Effect of thermal mass on cooling demand

In comparison to other measures, changing the glazing ratio, wall U-value and occupancy were not as effective. This would differ in a warmer climate where an empty building during the warmest part of the day would noticeably lower the cooling demand.

In terms of the heating demand, none of the changes in parameter values had a significant effect. Savings from adaptation strategies lowering cooling demand will not be offset by the heating demand increasing drastically.

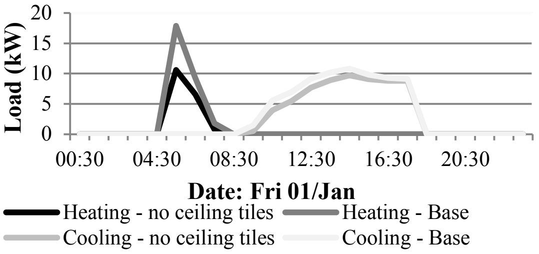

Figure 6 Effect of thermal mass on heating and cooling demand

A summary of a case which uses the most effective variations is given in Table 3. Missing variations are revealing thermal mass, using shading and the 6am - 12pm, and 2- 11pm occupancy.

Table 3
A summary of the most effective variations for lowering annual heating and cooling

PARAMETERS	G_g	U_g	U_r	T	U_w	U_g	I	GR
Values	0.19 W/m^{2}K	1.8 W/m^{2}K	0.2 W/m^{2}K	28°C	0.28 W/m^{2}K	0.2 W/m^{2}K	0.25ach	30%

CONCLUSION

A sensitivity analysis has been performed using BPS on the Admiral Insurance Headquarters building that will be located in Cardiff, Wales. Initial parameters and their upper and lower limits originate from the design team. As the building was in the detailed planning stage during this study, this client-driven approach enabled the simulation of realistic design interventions. Prometheus climate data was used for present and future simulations. Both physical and behavioural parameters were analysed for their impact on future heating and cooling energy use.

From the physical properties, the window U- and G-values have the greatest effect on cooling energy use. Their replacement should have priority in an adaption strategy, which could include measures such as shading. Another sensitive physical parameter of the building is infiltration. This is indicative that internal heat gains are high, and night or day passive ventilation should be reconsidered. In order for a client to accept this, they would have to be presented more information on noise pollution. Finally, the ability to reveal thermal mass in the future should be considered. It helps reduce both the heating and cooling demand, even in the absence of natural ventilation. Buildings with concrete frames with unexposed thermal mass have to potential to reduce their energy demand in the future. This information can be influential in the design stage as the structural frame cannot be easily replaced in later stages of the building's lifecycle. Regarding behavioural parameters, measures relating to lowering occupancy should have priority as they lower internal gains. These could include adding the possibility of working from home to company policy. Alternative measures include replacing equipment and lighting frequently with more efficient models. They contribute to the internal gains that cause the building to be cooling dominated.

A limitation of the research methodology is the initial base model received had to be changed over several meetings and emails in order to give a more accurate representation of the planned building. Using an approach such as Building Information Modelling would have simplified this and the model would be beneficial at later stages in the lifecycle, for example in facility management. In addition, the comprehensiveness of the study was limited as the client was only interested in changing certain aspects. Results of this study and adaptation measures were fed back to the design team. Each parameter was analysed in terms of practicality, energy and cost savings. Comments were made that the adaptation strategies are useful, especially the information about the window and the future benefits of using a concrete frame. The developer also expressed that they would be more likely to consider using concrete structures in future buildings. However, no change was made to the original building plans. This illustrates how even with time and money invested by the client, and sufficient information available on adaptation measures, the final decision is still client- and not performance driven. Research shows (Struck 2012) that the results from this study could have been more influential in the earlier design stages. However, based on the concern of the client that much of the data was not available at the conceptual stage, the research was conducted at the detailed design stage. In conclusion, this client driven case study shows the importance of BPS and modelling under a future climate, and how it can inform design decisions in the building industry. It shows in a cooling based building in a temperate climate 1) removing internal heat from a building is more important than adjusting the building envelope and 2) using a concrete frame in a building gives it the ability to use its thermal mass either currently or in the future to lower cooling demand.

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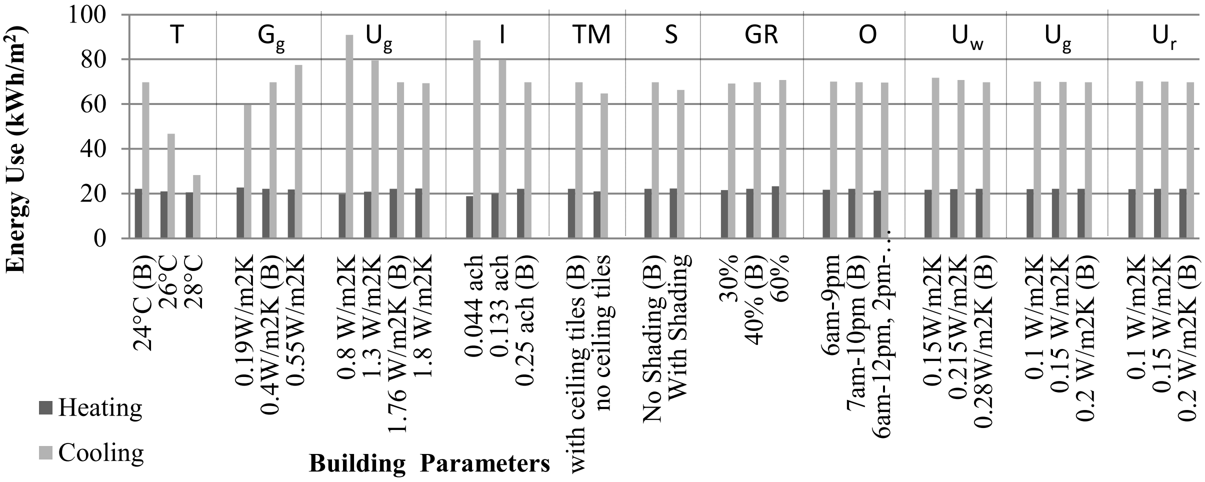

Figure 7 Admiral building performance under the 2030 period

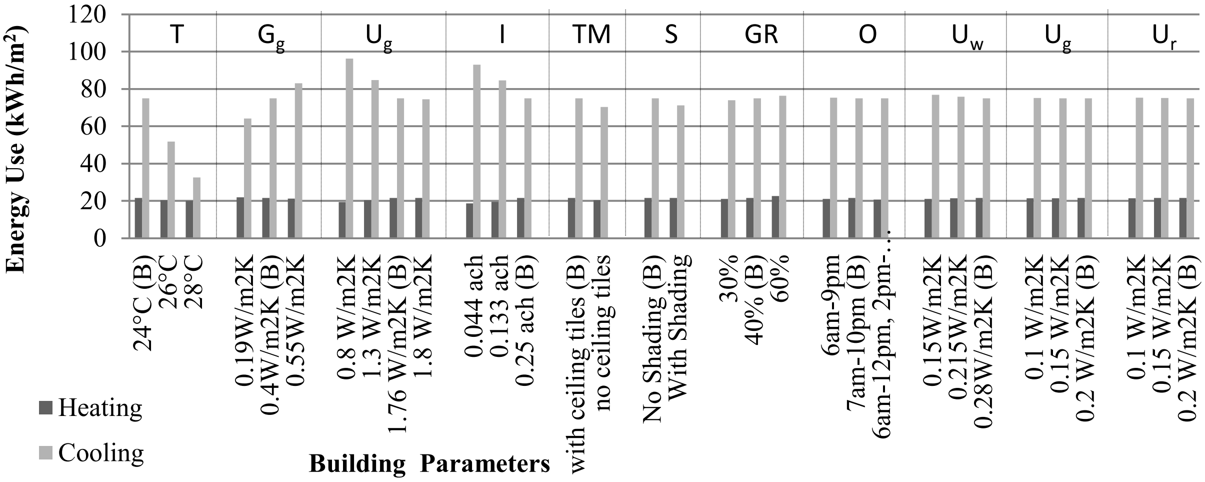

Figure 8 Admiral building performance under the 2050 period

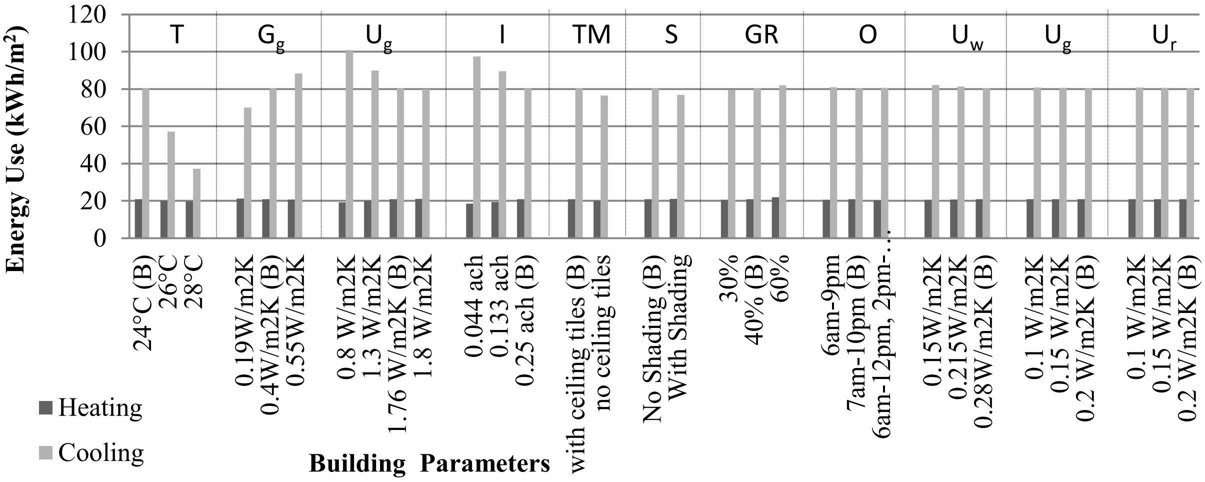

Figure 9 Admiral building performance under the 2080 period