A Comparison of Structural and Behavioural Adaptations to Future Proofing Buildings against Higher Temperatures

David Coley[1], Tristan Kershaw[2] and Matt Eames[2]

1. Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK

+44(0)1225 385531, d.a.coley@bath.ac.uk

2. Centre for Energy and Environment, University of Exeter, UK

Corresponding Author: David Coley

The uncertainty surrounding projections of climate change has left the building design community in a quandary. Should they assume a worst case scenario, and recommend adaptations to designs that might prove to be unnecessary and quite possibly costly? Or should they increase the risk to the occupants by selecting a less pessimistic vision of the future? It is well known that structural adaptations, such as additional thermal mass, can help moderate internal conditions as can behavioural adaptations, such as opening windows. Here the relative magnitudes of structural and non-structural (behavioural) adaptations are reflected upon, with the specific intent of discovering whether non-structural adaptations might have a great enough effect to offset any errors from selecting what proves to be (in 40 years time) an erroneous choice of climate change projection. It is found that an alteration to how a building is used is as equally important as common structural adaptations, and that the risk of choosing what turns out to be an incorrect climate change projection can be dealt with by seeing non-structural adaptations as a way of nullifying this risk.

1. Introduction

Predictions of the world's climate point to an increasingly warmer world, with greater warming across land and away from the equator [1]. Predictions contained in the IPCC's fourth assessment report indicate mid-latitude mean temperature rises over land of ~4°C (under the A1FI scenario) [1]. However, recent research [2] shows that current emission trends imply that the actual temperature increase could be far higher than the A1FI scenario predicts, and hence A1FI can no longer be considered a worst case. This implies that several highly populated regions not used to high temperatures will be exposed to a very different summertime experience. As the events in Paris in 2003 showed, temperature rises and reductions in the diurnal cycle within the built environment can have life-threatening consequences and require a substantial response from emergency services [3,4]. In the absence of any human modification of climate, temperatures such as those seen in Europe in 2003 have been estimated to be 1-in-1,000 year events. However modelling by the Hadley Centre shows that, by the 2040s, a 2003-type summer is predicted to be about average [5] and this will clearly have a great impact on the energy consumption of air conditioned spaces and the thermal comfort within non-conditioned ones.

Not all adaptation strategies add cost. While ones to do with altering the structure of the building are likely to (termed *hard* adaptations), behavioural strategies (termed *soft* adaptations), for example opening windows earlier in the day, typically do not. Such behavioural strategies have been much less studied. Here, a comparison is made of the benefits of a small number of well tried hard adaptations with some example soft changes,

with the aim of seeing whether they are of comparable magnitude. The work does not aim to identify particularly good adaptations, or suggest that any one will be successful in all settings, but rather to have a first look at the potential of such, zero-cost, adaptations to reduce the risk of selecting the wrong climate change projection. Two building types are considered, a house and a school.

Within the built environment, the term behavioural adaptation most often arises in connection with the issue of thermal comfort, with the term meaning manipulation of clothing, body movement or objects in ones' immediate surroundings to create a more satisfactory state [6, 7]. In the climate change literature adaptive capacity, the property of a system to adjust its characteristics to expand its coping range, is used to similar effect [8,9]. Both have been considered by Kwok et al. with reference to climate change and buildings [10].

It is self evident that many designers will consider that a building that relies solely on behavioural change to combat climate change is not truly resilient, and this would seem a reasonable position. They will aim to produce a robust solution that relies on physical changes to the building to reduce any propensity to overheat, for example additional thermal mass. However if, behavioural adaptations are then added on top of these, it might well be possible that the result is a building that is still seen as acceptable even under the assumption of a more aggressive prediction of climate change. The use of such an extreme projection should engender confidence in the design from the perspective of both the design team and the client, and reduce the risk all parties are exposed to. In essence we are asking whether non-structural adaptations might have a great enough affect to offset any errors from selecting a lower climate change projection. (Given the probabilistic nature of recent projections, it unlikely the correct projection will be chosen by any modeller.)

2. Future Weather Years

Building simulation is a common practice in the design process of new buildings and even for the refurbishment of existing buildings. When using building thermal modelling packages there is the need to provide the model with a time series of weather data for the location where the building is to be located. For many countries it is common to use a file of example weather created from an analysis of many years of observations from a weather station. These reference years consist of data files that contain a list (usually on an hourly time step) of measured common weather parameters such as atmospheric pressure, temperature and wind speed. Reference weather years are published for many parts of the world, with the exact detail depending on the professional body or national institute that has assembled them; however, in all cases they attempt to represent many years worth of weather with a single year. In the UK these take the form of the Chartered Institute of Building Services Engineers' (CIBSE) [11] Test Reference Year (TRY).

The TRY is a composite year comprising of the most average months drawn from ~23 years worth of data typically spanning 1982-2004. A full methodology detailing the creation of these files can be found in the paper by Levermore [12]. The use of a single reference year would seem a sensible approach as it greatly reduces the computational effort required in modelling a building and hence the cost of the design process. Since this approach was first used, computers have become a lot faster but models and codes more complex, thus the approach has remained the standard way of assessing building performance.

Due to the nature of the models used to produce climate change projections there is a level of uncertainty in the possible levels of future climate change. In the UK this uncertainty has been represented in the latest set of future climate projections UKCP09 [13] released by the UK Climate Impacts Programme (UKCIP). These projections are probabilistic because multiple runs of climate models from several different countries were used to create a range of possible climatic futures. The results were then used to create probability density functions (PDFs) for a variety of climatic variables. These PDFs can be sampled at will to produce a large number of possible climatic futures. These can be used to create future weather years for a series of different statements of future world carbon emissions. These projections are probabilistic and are reported in terms of percentiles representing the fraction of climate model runs producing a level of climate change at least as large. This leaves the building designer or modeller needing to make a choice of which percentile to pick. Other work [14] has shown that the choice of climate change scenario and percentile will have a large impact on the scale of any adaptation strategy that will successfully mitigate against rising temperatures, and hence the choice of percentile is intimately entwined with build cost and the design teams attitude to risk.

UKCIP have not provided guidance on which percentile the building design community should select, believing that the probabilistic nature of the projections give the user the opportunity to reflect upon the needs of their client and the specifics of the situation. This has left clients, architects and modellers in a difficult position: do they simply opt for a precautionary approach and model with a high percentile projection, potentially increasing the cost above what might prove necessary by, say 2050, when projection becomes reality, or given the commercial setting, pick a less aggressive, lower, percentile? Clearly this is a question of risk: risk that will ultimately be borne by the occupant.

3. Method
Two buildings have been studied: a school and a large house. For both buildings a base case was established. These were calibrated such that their annual heating and electricity consumption was approximately typical for such naturally ventilated buildings. For the school, the consumption, in terms of energy per unit floor area was taken from CIBSE guide F [15]; for the house from national statistics [16]. Both base case buildings were constructed under the assumption of UK 2006 Building Regulations, and could be termed light weight (see the appendix for a list of constructions).

The following adaptations were applied, each classified as hard or soft, or both: increased thermal mass (hard); introduction of night cooling (hard if done by additional vents, soft if done by the opening of windows); external shading above windows (hard), solar-control glass (hard); reduced lighting and other electrical gains (hard if done by more efficient items, soft if done by better housekeeping); closing windows when the external air temperature is greater than the internal (soft); starting and finishing the school day two hours earlier (soft) and opening windows at a lower set point (soft). These are applied initially separately, then as a basket of measures. (See the appendix for the heavy weight constructions.)

In all cases the buildings were modelled using the current climate and projections for 2050. Future test reference year climate files were produced from the probabilistic outputs given in UKCP09 using the method given in Eames et al [14]. (These files are available for many UK locations from www.ex.ac.uk/cee).The 10th, 50th and 90th percentiles were used for a high emissions (A1FI) scenario. The buildings were assumed to be located in London (Islington). All buildings were assumed to be on an infinite plane that offers no

topographical shading. In the case of increasing the thermal mass of external elements, the thickness of insulation was adjusted to ensure the U-values remained constant. Simulations were made over the period 1st April to 30th October. A greater number of building types, constructions, or locations were deemed unnecessary as the work is not concerned about the precise benefits of particular adaptations to particular buildings, but in studying the broad context of adaptation and climate change prediction when the predictions are made in terms of probabilities.

Rather than use TRY files, the modelling could have been completed using future design summer years (DSYs). Traditionally, such summer years represent the third warmest summer within a data set of around twenty years. DSYs were not chosen because the statistical basis behind them is less robust, with the current (observed) DSYs being cooler than the TRYs for several UK cities.

4. Results

As figures 1 to 2 show, and as expected, the base case school building warms under the three projections of climate change, with the higher percentile projections giving rise to higher mean and maximum temperatures, and occupied hours greater than 25 and 28°C. In the case of the school (figure 1), peak temperatures are found to rise from a present day 31.9°C to 32.8°C when using the 10th percentile, to 37.3°C under the 50th percentile, to 39.5°C assuming the 90th percentile. It is clear from just these numbers that the scale of the challenge is proportional in some way to the percentile selected and thus the recommendations a design team are likely to suggest are also likely to be a function of the percentile. A similar pattern was found for the house (figures 3 and 4).
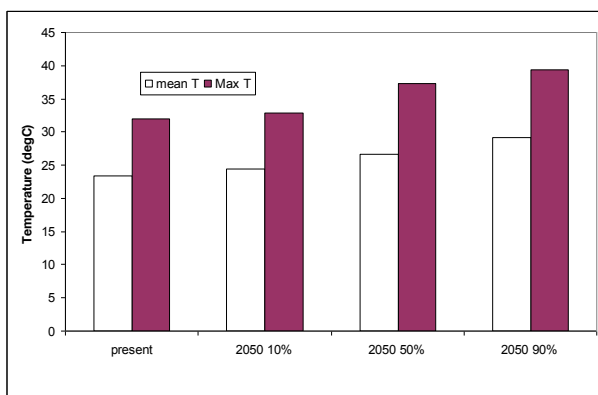

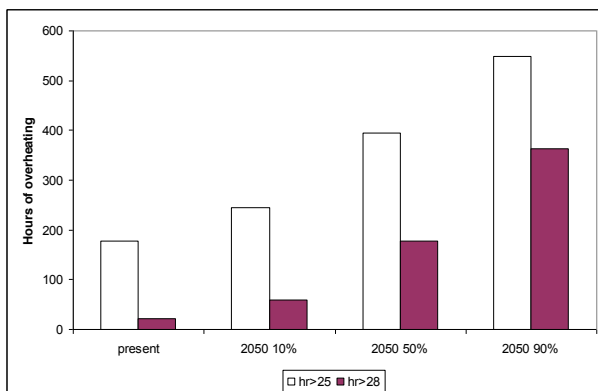Figure 1 Building averaged temperatures for the base case school.

Figure 2 Building averaged occupied hours of overheating for the base case school.
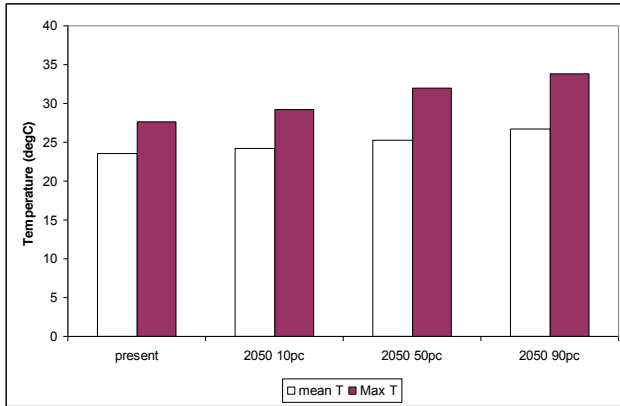
Figure 3 Building averaged temperatures for the base case house.
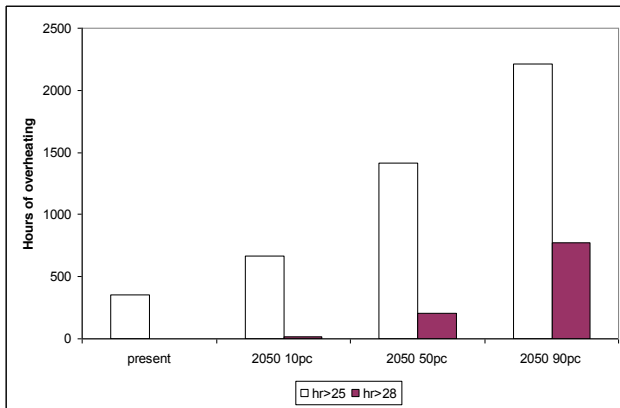
Figure 4 Building averaged occupied hours of overheating for the base case house.

The result of the various adaptation strategies are presented in terms of the change to the base case (indicated by lw, or light weight) the adaptations make to the mean and maximal (building averaged) internal temperatures, and to the number of occupied hours over 25 and 28°C as shown by figures 5 to 12. Although the effectiveness of any of the strategies depends on the future time period and the statistic chosen, it is clear that the behavioural adaptations are as least as effective as the structural ones, particularly when it comes to hours of overheating. This is true for both the school and the house.

Change in Mean Temp from LW Case (degC)

	lw shade	hw	lw solar glass	lw ealier day	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
present	-1.02	0.27	-1.02	-0.11	-0.75	-4.71	-0.1	-7.03
2050 10pc	-1.06	0.08	-1.05	-0.2	-0.81	0.48	-0.07	-4.5
2050 50pc	-1.25	0	-1.23	-0.45	-0.9	0.1	-0.03	-4.8
2050 90pc	-1.3	0.06	-1.28	-0.49	-0.93	-0.2	0	-4.96

Figure 5. Change in mean internal temperature from the base case school.

Change in Max Temp from LW Case (degC)

	lw shade	hw	lw solar glass	lw ealier day	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
present	-1.23	-3.27	-1.28	-0.55	-1.51	-1.73	-0.01	-3.52
2050 10pc	-1.28	-3.57	-1.26	-0.88	-1.21	0.1	-0.03	-1.12
2050 50pc	-1.54	-2.96	-1.52	-1.35	-1.58	-0.37	0	-2.26
2050 90pc	-1.51	-2.88	-1.52	-1.08	-1.52	-0.39	0	-2.29

Figure 6. Change in maximum internal temperature from the base case school.

Change from LW Case in Hours over 25 degC

	lw shade	hw	lw solar glass	lw ealier day	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
present	-54	-57	-54	-153	-53	-89	-4	-168
2050 10pc	-54	-34	-49	-96	-47	52	-3	-104
2050 50pc	-63	11	-60	-233	-58	43	0	-138
2050 90pc	-32	38	-32	-209	-44	19	0	-131
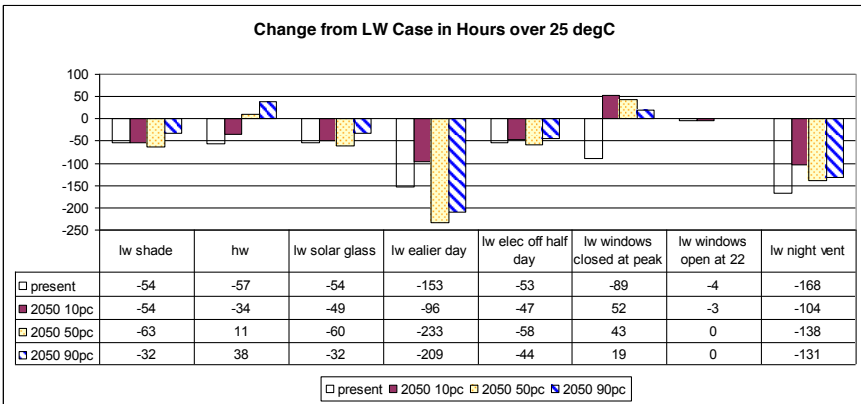
Figure 7. Change in occupied hours over 25°C from the base case school.

Change from LW Case in Hours over 28 degC

	lw shade	hw	lw solar glass	lw ealier day	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
present	-15	-20	-15	-21	-15	-16	0	-20
2050 10pc	-21	-42	-18	-36	-20	-1	0	-27
2050 50pc	-44	-22	-43	-144	-44	-13	0	55
2050 90pc	-65	8	-62	-228	-60	-28	0	-266
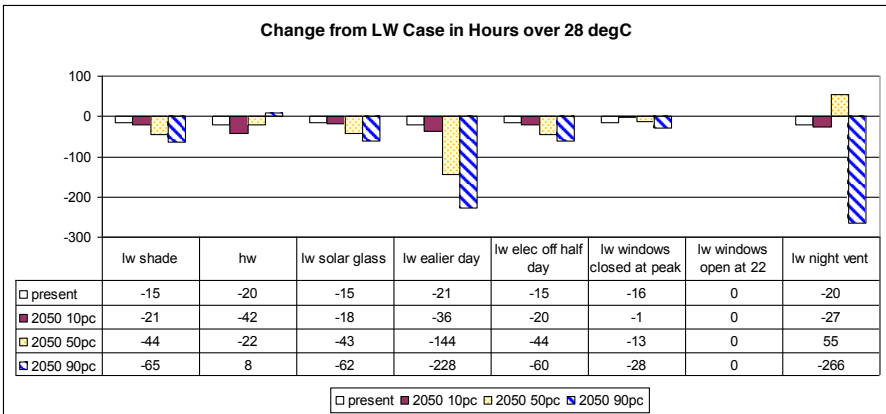
Figure 8. Change in occupied hours over 28°C from the base case school.

Change in Mean Temp from LW Case (degC)

	lw shade	hw	lw solar glass	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
present	-0.67	0.46	-0.62	0.03	0.04	-1.07	-0.17
2050 10pc	-0.58	0.24	-0.54	0.04	0.04	0.5	-0.28
2050 50pc	-0.57	0.1	-0.53	0.12	0.03	-0.9	-0.6
2050 90pc	-0.64	0.19	-0.59	0.14	0.01	-0.52	-1
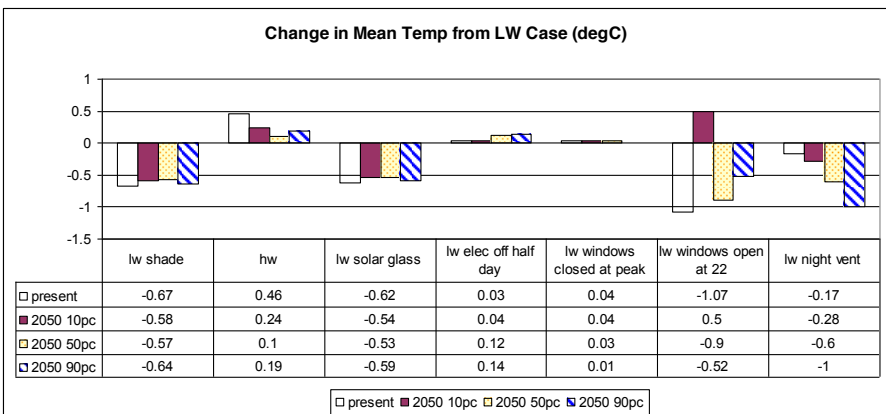
Figure 9. Change in mean internal temperature from the base case house.

Change in MaxTemp from LW Case (degC)

	lw shade	hw	lw solar glass	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
☐ present	-0.54	-0.95	-0.54	0.17	-0.02	-0.5	-0.13
■ 2050 10pc	-0.9	-1.23	-0.85	0.46	-0.1	1.7	-0.56
☐ 2050 50pc	-0.87	-1.12	-0.83	0.36	-0.13	-0.08	-1.09
◪ 2050 90pc	-1.1	-1.16	-1.05	0.44	-0.04	-0.02	-1.32

☐ present ■ 2050 10pc ☐ 2050 50pc ◪ 2050 90pc
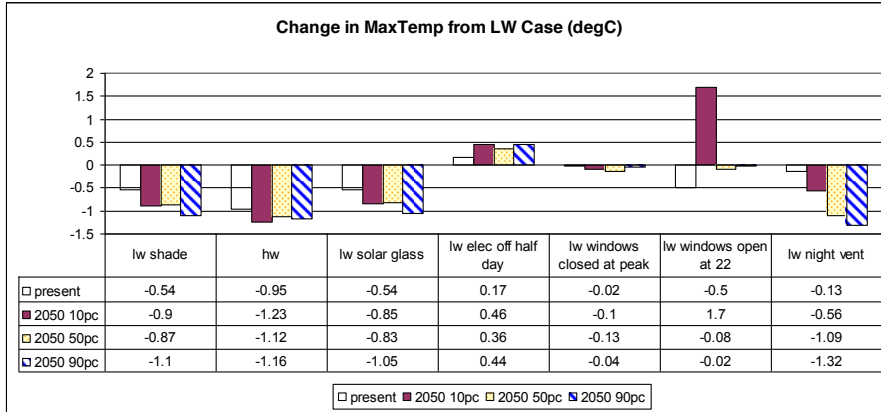
Figure 10. Change in maximum internal temperature from the base case house.

Change from LW Case in Hours Over 25 (degC)

	lw shade	hw	lw solar glass	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
☐ present	-234	-66	-224	102	12	-250	-104
■ 2050 10pc	-322	-58	-299	60	13	319	-202
☐ 2050 50pc	-450	203	-415	72	21	-480	-430
◪ 2050 90pc	-310	179	-284	5	-2	-349	-592

☐ present ■ 2050 10pc ☐ 2050 50pc ◪ 2050 90pc

Figure 11. Change in occupied hours over 25°C from the base case house.

Change from LW Case in Hours Over 28 (deg C)

	lw shade	hw	lw solar glass	lw elec off half day	lw windows closed at peak	lw windows open at 22	lw night vent
☐ present	0	0	0	0	0	0	0
■ 2050 10pc	-14	-18	-14	18	-1	63	-12
☐ 2050 50pc	-116	-89	-115	49	-2	-41	-125
◪ 2050 90pc	-284	56	-271	76	-3	-74	-374

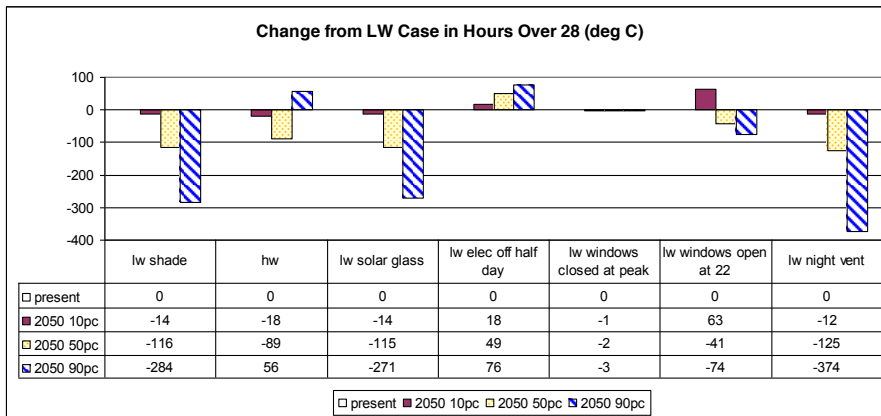☐ present ■ 2050 10pc ☐ 2050 50pc ◪ 2050 90pc

Figure 12. Change in occupied hours over 28°C from the base case house.

5. Discussion

One possible way of interpreting these results for real buildings is that, given the potential of soft adaptations, risk could be mitigated by modelling with a median projection (i.e. the 50th percentile) of climate change, and ensuring that hard adaptations are used to meet any thermal comfort or overheating criteria, then using soft adaptations as a response to greater than expected climate change. This would allow designers not to always design to the worst case prediction, but to walk a sensible line between responding to the question of

climate change in a constructive manner, and unnecessarily increasing the cost and complexity of buildings.

To test this approach, a combination of simultaneous hard adaptations were applied to both buildings and the affect on hours of overheating estimated for both the 2050 50th percentile and 2050 90th percentile projections of climate change. A combination of hard and soft strategies was then applied to the two buildings and the overheating caused by the 2050 90th percentile re-estimated.

For both buildings it was found (see Table 1 and Figures 13 to 16) that the inclusion of soft adaptations reduced the overheating back to approximately that found with the 50th percentile projections.

Table 1. Combined adaptation strategies. (S = behavioural; H = hard.)

Adaptation	School	House
Window shading (H)	•	•
Solar control glass (H)	•	•
Earlier day (S)	•	
Night ventilation (S)	•	•
Windows open at 22°C (S)		•

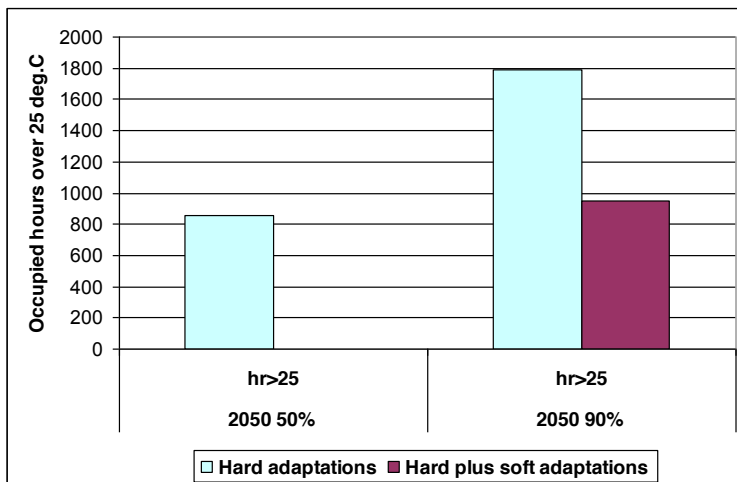

Figure 13.Combined adaptation of the house. The addition of behavioural adaptations is seen to bring the number of occupied hours over 25°C when modelled with the 90th percentile projection back to that given by the 50th percentile and only structural adaptations.
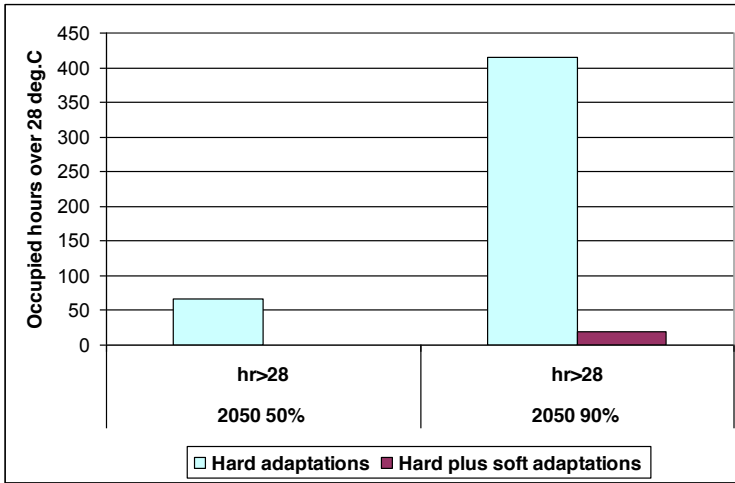
Figure 14. Combined adaptation of the house. The addition of behavioural adaptations is seen to bring the number of occupied hours over 28°C when modelled with the 90th percentile projection back to (and lower) than that given by the 50th percentile and only structural adaptations.
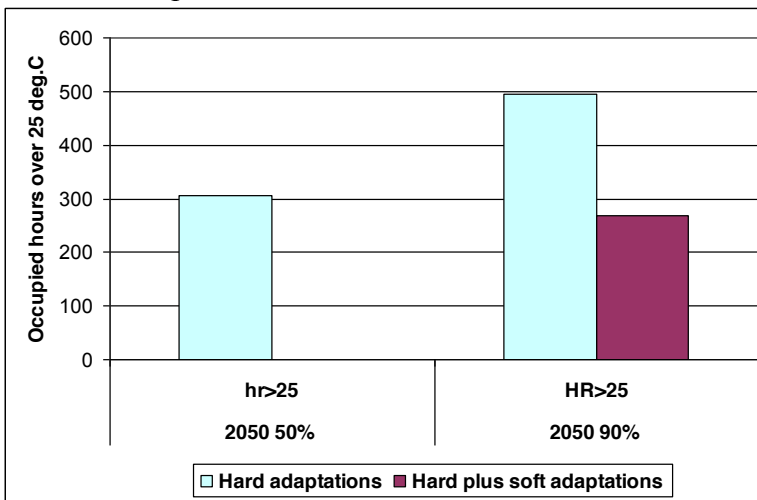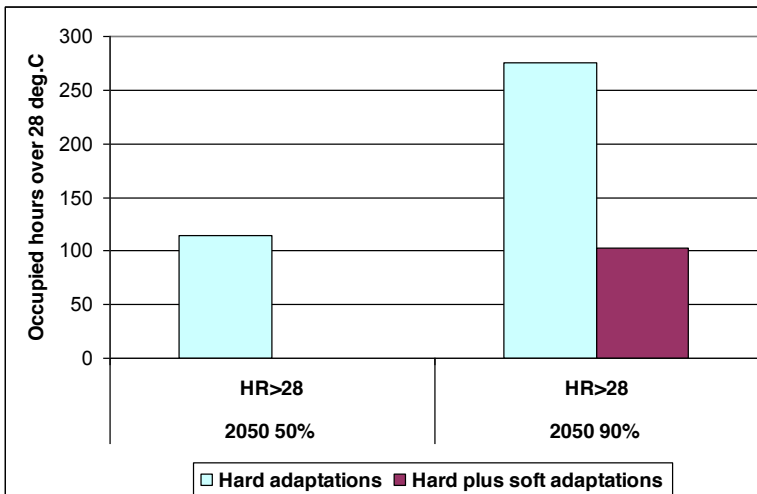

Figure 15. Combined adaptation of the school. The addition of behavioural adaptations is seen to bring the number of occupied hours over 25°C when modelled with the 90th percentile projection back to that given by the 50th percentile and only structural adaptations.

Figure 16. Combined adaptation of the school. The addition of behavioural adaptations is seen to bring the number of occupied hours over 28°C when modelled with the 90th percentile projection back to that given by the 50th percentile and only structural adaptations.

6. Conclusion

In has been shown that soft adaptations can be expected to be as useful a tool in the adaptation tool box as hard ones, in that they can both lead to similar reductions in temperatures and hours of overheating. Only two building have been studied, and only a small selection of adaptations has been considered. However, this is probably a reasonable approach as the aim is not to make categorical statements about any particular strategy, but to reflect on the relative magnitudes of the two categories of adaption: hard and soft.

It would also appear, within the bounds of the UKCP09 projections, soft adaptations are capable of offsetting any errors caused by selecting what, in future, turns out to be an incorrect prediction of climate change, thereby greatly reducing the risk to all.

This is not to suggest that designers should rely only on behavioural adaptations and ignore structural ones. That would invite additional risk. It is however clear that by considering behavioural adaption in addition to structural adaptation, modellers can be given free rein to investigate the performance under higher predictions of climate change, without necessarily suggesting more expensive or complex design solutions. It is worth considering whether behaviour adaptations are in general more or less robust in terms of the likelihood of realisation. For example would people consistently open windows to allow additional cooling, or close them when the external temperature is greater than the internal? This is at present unknown, and the answer in part lies in the future education of the occupant. However, physical changes to the building at design stage to make the space more adapted to climate change might well be value-engineered out before construction. This makes it difficult to know whether physical or behavioural adaptations will prove the more robust. Although, it is evident that if behavioural change is to be considered as an adaptation strategy, the building must allow, or possibly even encourage the strategy: this might prove to be fertile ground for future research. In addition, there are a plethora of other possible behavioural strategies that could be investigated including: clothing level, reducing other electrical gains, flexible working in summer, move the term dates of schools and the use of personal fans.

It would also be worth considering other climate change related impacts on buildings and how behavioural change might sit alongside physical changes (such as green roof) so to generate even more robust solutions.

7. References

[1] Fourth Assessment Report. Intergovernmental Panel on Climate Change, http://www.ipcc.ch/.
[2] Anderson, K., Bows, A. Reframing the Climate Challenge in Light of Post-2000 Emissions Trends. Phil. Trans. R. Soc. A **366** 3863-3882 (2008).
[3] Vandentorren, S., Suzan F., Medina S., Pascal M., Maulpoix A., Cohen J. and Ledrans, M., Mortality in 13 French Cities During the August 2003 Heat Wave. American Journal of Public Health, **94,** 1518-1520 (2004).
[4] Bouchama A. Heatstroke: A New Look at an Ancient Disease. Intensive Care Med., **21** 623–625 (1995).

[5] Stott, P.A., D.A. Stone and M.R. Allen. Human Contribution to the European Heatwave of 2003. Nature, **432**, 610–614 (2004).

[6] Humphreys MA, Nicol JF. In: Nicol F, Humphreys MA, Sykes O, Roaf S, editors. An adaptive guideline for UK office temperatures in standards for thermal comfort – indoor temperature standards for the 21st century. London: E & F Spon; 1995.

[7] de Dear Richard, Schiller Brager G. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions 1998;104(1a):145–67.

[8] Brooks N, Adger WN. Technical paper 7: assessing and enhancing adaptive capacity. In: Lim B, et al., editors. Adaptation policy framework: developing strategies, policies, and measures. Cambridge: Cambridge University Press. p. 165–81.

[9] Schneider SH. Abrupt non-linear climate change, irreversibility and surprise. Global Environmental Change 2004;14:245–58.

[10] Kwok AG and Rajkovich NB. Addressing climate change in comfort standards Building and Environment 45 (2010) 18–22.

[11] Chartered Institute of British Service Engineers, www.cibse.org/

[12] Levermore GJ and Parkinson JB. Analyses and algorithms for new Test Reference Years and Design Summer Years for the UK. Building Serv. Eng. Res. Technol. **27**, 311-325 (2006).

[13] UK Climate Impacts Programme. UKCP09 available from: http://ukclimateprojections.defra.gov.uk/

[14] Eames M, Kershaw T and Coley D. On the creation of future probabilistic design weather years from UKCP09. Building Serv. Eng. Res. Technol, **32**, 127-142 (2011)

[15] CIBSE Guide F, Chartered Institution of Building Services Engineers, London, 2004.

[16] Energy Consumption in the UK: Tables. Department of Trade and Industry, London, 2002. Available from: www.dti.gov.uk/energy/inform/energy_consumption

8. Appendix: Constructional Parameters

	Base case building	
	School	House
Wall construction	Block/insulation/plasterboard/plaster	Brick/insulation/ plasterboard/plaster
Glazing construction	Double glazed	Double glazed
Floor construction	Insulation/wood flooring	Insulation/wood flooring
Roof construction	Steel/insulation/plasterboard	Steel/insulation/plasterboard
Wall U-value	0.35	0.35
Glazing U-value	2	2
Floor U-value (W/m^2K)	0.25	0.25
Roof U-value	0.25	0.25

(W/m²K)		
Foor area (m²)	887	288
Storeys	1	2
Glazed fraction	19%	10%
Internal partitions	Block	Block
Infiltration	0.25 ac/h	0.25 ac/h
Lighting gains W/m²	13	5
Other electrical gains W/m²	2	2
Occupancy m²/person	3.46	48
Windows opening	24°C when occupied	24°C when occupied (but ground floor windows closed at night)
	Heavy weight alternative	
	School	House
Wall construction	Brick/insulation/block/plaster	Brick/insulation/block/plaster
Floor construction	Concrete/insulation/concrete	Concrete/insulation/concrete
Roof construction	Chippings/waterproof layer/insulation/concrete	Chippings/waterproof layer/insulation/concrete