21st Century Standards for Thermal Comfort: Fostering Low Carbon Building Design.

Paul Tuohy*, Sue Roaf, Fergus Nicol, Mike Humphreys and Atze Boerstra

*Energy Systems Research Unit, University of Strathclyde, Glasgow, G1 1XJ, 00 44 141 548 5765, paul.tuohy@strath.ac.uk.

Abstract

The urgent need to reduce anthropogenic greenhouse gas emissions in a bid to meet increasingly aggressive targets has focused attention on energy use in the built environment. Nearly 50% of all energy consumed in the developed world is consumed in buildings. While the theoretical trend in regulations is towards better buildings in reality many new buildings are energy profligate.

Modern thermal comfort standards have been in part responsible for these increased levels of energy consumption. A partner paper (Roaf et al, 2009) described the historical evolution of the current standards and some problems inherent in the buildings they shape and serve, and proposed two new methods of regulating thermal comfort with the aim of reduced energy demands. These methods recognize human adaptation in their heating and cooling set-points. The new methods incorporate this human adaptation either through fixed heating and cooling thresholds (similar to the Japanese Cool-Biz approach) or through heating and cooling set-points calculated based on outdoor conditions (using CEN standard equations).

In this paper the viability and potential impact on energy demands of these new approaches are investigated using simulations of a typical London office and of the same office upgraded to ‘passive’ standards, both for a current climate and a predicted 2080 climate. The impact on energy demand of other factors such as set-back temperatures, internal gains and ventilation rates are also investigated.

Adopting either of the new adaptive control strategies gives a reduction of some 50% in heating and cooling energy for the simulated office. Further significant reductions through reduced set-back temperatures, more effective ventilation strategies and higher efficiency equipment are also predicted and a potential scenario developed where energy demand for heating and cooling is close to zero.

A comparison between the two new adaptive approaches is made, strengths and weaknesses of each identified, and possible implementation methods discussed. Recommendations for future regulations, design and operation of buildings are proposed.

1. Introduction:

The recent trend particularly evident in non-domestic buildings has been for increasing adoption of HVAC systems, the trend being in part driven by the wide acceptance of the PMV(Predicted Mean Vote) criterion for indoor comfort. However the PMV criterion has been found to under-predict the range of comfortable temperatures found in field studies, particularly in buildings where occupants have some opportunity to adapt themselves and their environment to maintain comfort. Here we investigate the potential of two new approaches alternative to PMV which are based on the adaptive comfort criteria currently included in the CIBSE Guide [ref] and in the ASHRAE and CEN standards [ref, ref]. The historical background and rationale for these two new approaches was described in a partner paper (Roaf et al, 2009).

The application of adaptive criteria has so far been restricted by these standards to free-running buildings where occupants can adapt their dress, behavior and local environment to maintain thermal comfort, and the criteria have primarily been used for naturally ventilated buildings in summer. There is however some justification for using adaptive criteria more widely; the survey data used in the formulation of the CEN adaptive standard included several buildings where the occupants had the use of local heating and cooling appliances [ref]; surveys of German buildings with centrally controlled Thermally Active Building Systems (TABS) have suggested that adaptive criteria best represent occupant comfort in these circumstances [ref]; the recent 'Cool-Biz' initiative in Japan successfully applied fixed threshold temperatures for cooling of Government offices and occupant adaptation by changing to less formal dress was encouraged [ref].

In this paper we illustrate the potential reduction in energy use that could be realized if buildings were designed and operated so that the adaptive criteria were applied. The impacts of other measures such as reduced setback temperatures during unoccupied hours, reduced energy use by equipment and lighting and the use of free cooling through enhanced ventilation are also analyzed. The analysis includes likely future building standards for new or retrofit designs and the analysis is repeated for both a current climate and a predicted future climate.

The aim of the analysis is to provide input to: the definition of future regulations, to design guidance and to operational guidance that will assist in realizing robust comfortable low energy buildings in practice.

2. Comfort temperatures and climate.

Adaptive comfort criteria for buildings have been incorporated in the CEN and ASHRAE standards and CIBSE guidance. In this study we will use the adaptive comfort criteria of the CEN standard [ref] and CIBSE guideline [ref] which defines the comfort temperature (Tcomf) and running mean outdoor temperature (Trm) and relates them as shown in equation 1.

$$\text{Tcomf} = 0.33\ \text{Trm} + 18.8 \qquad (1)$$

In our study we have chosen to investigate the predicted impact that use of the proposed approaches to building control which incorporate adaptation would have on energy use for an example London office using dynamic simulation analysis. The analysis tool used in this study is ESP-r [ref].

There are various sources of current and future climate information for London: CIBSE recently published current and future UK climate datasets for use in building simulation based on the UKCIP02 projections [ref], there has also recently been a revised and probabilistic UKCIP09 set of projections. Dru Crawley of US DOE recently defined algorithms for incorporating both climate change and urban heat island effects in climate files for building simulation [ref]; we have chosen to use 2005 and 2080 London climate files from this dataset as the basis of our analysis.

The running mean outdoor temperatures (Trm), and the indoor comfort temperatures (Tcomf) calculated using equation 1, are shown in figure 1. The shift between 2005 and 2080 in the annual average running mean temperature is +3.3 degrees while in the summer period the average shift is larger at +5.5 degrees. The corresponding shifts in indoor adaptive comfort temperatures are +1.1 for the annual average and +1.7 degrees for the summer average respectively.

3. Approaches to thermal comfort in buildings

The partner paper described in more detail the rationale behind the proposed two new approaches based on adaptive comfort criteria. The first of these is to impose a heating setpoint of 18 degrees and a cooling setpoint of 28 degrees (label: h18c28), this approach is somewhat similar to that taken in the Japanese Cool-Biz program where a fixed cooling threshold was applied. The second new strategy (label: Adapt) is based directly on the CEN adaptive comfort criteria; in this case the heating and cooling setpoints are calculated based on the running mean temperature using equations 2 and 3.

$$Tcool = Tcomf + 3 \quad (2)$$

$$Theat = Tcomf - 3 \quad (3)$$

A base case scenario representing existing typical practice was to impose a fixed heating setpoint of 21 degrees and a fixed cooling setpoint of 23 degrees (label: h21c23). This h21c23 scenario was chosen to represent operation in accordance with the REHVA guideline which suggests a constant 22 degrees as the optimum temperature (Plocker W, Wijsman A, 2009). All three control methods are illustrated in figure 2. The adaptive control (Adapt) is derived from the running mean temperature and so will be different for the 2080 and 2005 climate cases while the h18c28 and h21c23 approaches are climate independent. One observation is that in 2005 the Adapt and h18c28 cooling thresholds are both around 28 degrees in July and August but that in 2080 the Adapt cooling threshold is around 29.5 degrees, it would of course be feasible to adjust the h18c28 setpoints through time in order to synergize with a change in climate. A second observation is that the h18c28 thresholds are much wider than the Adapt thresholds although the differences between heating setpoints during times of peak heating and differences between cooling setpoints during times of peak cooling are not so pronounced.

4. The example office.

To illustrate the impact of the different control strategies a simulation model of a London office was used. The model represents a 180m^2 mid-floor section of a larger office building with windows facing north and south. The section analyzed includes both cellular and open plan office areas. Two versions of the office building were used; one representing a typical 1990s construction; a second representing more advanced construction with insulation and infiltration close to Passive House standards and incorporating some simple over-window shading and some exposed thermal mass (exposed lightweight concrete ceiling etc). Figure 3 gives some sketch images of the office and tables 1 and 2 give construction and operation details. The analysis output includes the indoor and outdoor environmental conditions on a sub-hourly time step and the heating or cooling energy required to be supplied into the space. The analysis presented here does not take account of heating or cooling system efficiencies or auxiliary energy for any pumps and fans associated with heating, cooling and ventilation.

Details of internal gains, setback temperatures and ventilation rates are given in tables 3 to 6 and are discussed in more detail later in this section. The ventilation during occupied hours (as explained in Table 6) for the office is assumed to be sufficient to maintain fresh air but could be supplied by mechanical systems or through window opening or by other passive means. The infiltration outside of occupied hours is set to be appropriate for the construction standards applied.

The construction and operation of the building assumed for this example office are set deterministically and do not represent the variations and uncertainties in construction, building use or occupant behaviors that would be experienced over the life of a real building. We have taken this simplified approach here in order to clearly illustrate the potential impacts of the new approaches to comfort. To fully explore the robustness and capability of a building design these variations and uncertainties should be incorporated in a probabilistic analysis as outlined elsewhere [ref].

5. Impact on heating and cooling energy demands

The performance of the typical 1990s version and the Advanced version of the office was analyzed with each of the three control strategies applied (h21c23, h18c28, Adapt) for the 2005 and 2080 climates. Figure 4 shows the calculated total heating and cooling energy demand for each of the combinations of building, climate and controls.

The Advanced office performs significantly better than the typical 1990s office for all the combinations of climate and controls in terms of overall energy demand for heating and cooling however both the typical and advanced versions perform significantly worse in the 2080s climate. The new control approaches (h18c28 and Adapt) both perform significantly better from an energy perspective than the baseline h21c23 control with the h18c28 performing the best.

Figures 5 and 6 show the heating and cooling energy demand separated. Heating demand is close to zero for the Advanced building while there is a general trend towards reduced heating in 2080. Cooling is increasingly dominant in the Advanced building type or 2080 climate.

The scenarios analyzed so far have included the baseline setback conditions i.e no setback with the h21c23 control and heating and cooling setpoints of 18 and 30 degrees with the proposed h18c28 and Adapt control. The effect of setback was investigated by running the model with the range of setback temperatures as described in tables 3 and 4 with the results as shown in figure 7. Results show significant benefits of reduced setback temperatures in the typical 1990s version but much smaller benefit in the advanced case. The reduced effect in the Advanced case is due to the higher stability of the indoor environment due to the improved insulation and air-tightness and the higher thermal mass in this version of the building.

Another parameter with high uncertainty which can have a high impact on overall energy use in buildings is the energy consumed in lights, equipment and appliances. There are various current projections for future equipment and lighting energy use and associated internal gains in offices, initiatives such as the IT White Paper [ref] and EU Lighting and Equipment Directives etc. promise reduced energy demand. However increased density of electronic equipment in offices may act to offset these improvements. In order to evaluate the impact of internal gains three scenarios were analyzed as outlined in table 5. The effect of higher gains from energy consumption on the 1990s building did not show a large change, this was due to increased gains causing reduced heating and increased cooling in similar amounts or vice-versa, while for the reduced gains case the net effects on total energy demand for heating and cooling are approximately neutral. The situation in the Advanced building is not the same as the energy demand for heating is close to zero. For the Advanced office the impact of increased internal gains from equipment would be to significantly increase the cooling energy demand and the total for heating and cooling. Similarly, reduced internal gains caused a reduction in the total energy demanded for heating and cooling. Internal gains have a very large impact in this case.

The cooling load is increased and dominates the energy performance of the advanced building. This effect is caused by the reduction in free cooling available through conduction and infiltration due to the improved insulation and infiltration characteristics of the Advanced envelope. This effect can possibly be offset if opportunities that exist for free cooling with outdoor air can be realized. Several ventilation scenarios were investigated (table 6) for the proposed new controls (h18c30 and Adapt) and the results shown in figure 9. The first enhanced free cooling ventilation scenario which was investigated was the opening of windows during occupied hours to establish cross-flow ventilation achieving an assumed 5 air changes per hour, the second enhanced ventilation scenario investigated is the use of secure night ventilation in summer in combination with daytime cross flow ventilation, the assumption being that these night time ventilation paths allow the 5 air changes per hour to be maintained throughout unoccupied hours. It should be stated that while these deterministic assumptions for air flows used here are well established assumptions given in guidelines [ref, ref] in practice more detailed consideration of ventilation openings, occupant behavior and other uncertainties is recommended to achieve a robust building design [ref]. Where these cross ventilation and night cooling air change rates can be achieved in practice then cooling demand is greatly reduced to around zero for the 2005 climate and an 80% reduction is predicted for the 2080 climate case. In combination with low internal gains the enhanced ventilation can almost eliminate the calculated requirement for cooling even for 2080 climate.

For the example office the new control strategies in combination with the advanced fabric, shading, low internal gains and effective summer ventilation are predicted to achieve close to zero energy demand for heating and cooling.

6. Impact on internal temperatures.

The impact of the different approaches to building controls on the internal temperatures experienced in the office space is significant. Figure 10 shows the monthly average, maximum and minimum indoor resultant temperatures predicted for the typical 1990s office space and the 2005 climate for baseline office of figure 4 with the h18c28 and ADAPT controls applied. Figure 11 shows in more detail the calculated resultant temperatures during occupied hours for an example week in April 2005. This example week is one where outdoor conditions are cooler at the beginning of the week but become significantly warmer as the week progresses. The typical 1990s building has a higher daily and monthly range of indoor temperatures than the advanced building - illustrating the effect of the external shading in limiting gains and the thermal mass in moderating temperatures (although only a very simple shade was used in this example). The advanced building is generally warmer than the typical 1990s building which could be expected due to the higher insulation levels and the reduced infiltration rates of the advanced building construction.

There are significant periods of the year when the h18c28 controls result in conditions which are outside of the adaptive comfort range (Tcomf +/- 3 degrees) and would be predicted to result in some discomfort (cool in spring, summer and autumn in the typical 1990s building, warm in the shoulder months for both buildings). These warm discomfort periods could potentially be reduced or eliminated where opportunities for free cooling through enhanced ventilation exist as described in the previous section however the cool periods would require occupants to adapt beyond +/-3 degrees of the comfort temperature (Tcomf).

7. Discussion

The human species is inherently resilient and adaptable. However, adaptive comfort standards although well established are currently cautiously interpreted and viewed as only being applicable in occupant controlled naturally ventilated buildings during periods when they are in free-running mode (no heating or cooling). The partner paper to this one [ref] explores the history behind the current situation and proposes much more widespread application of the adaptive comfort standards as a mechanism for significant reduction in unnecessary energy use. The proposal is that people can and do adapt themselves and their immediate surroundings in order to be comfortable across a range of indoor conditions. This approach is in contrast to the approach provided in guidance by commercial building service engineering organizations which generally advocate much tighter temperature tolerances or fixed setpoints and require systems intensive solutions.

Before the middle of the 20th Century many buildings were constructed with high thermal mass, deep set windows and optimized natural ventilation schemes which resulted in a stable internal environment. The trend since has been away from these methods in part driven by higher internal gains from equipment but also driven by increasing reliance on automated systems. The typical 1990s building in this study gives an example of a building which does not by itself provide a stable internal environment while the advanced building results in a more stable environment but is prone to overheating or a high cooling load unless it is operated to take advantage of free cooling.

The study carried out in this work is a parametric analysis aimed at clearly demonstrating the effects of each of the investigated factors. For building design the authors advocate a more detailed probabilistic approach to realizing a building that is robust to future variations e.g. patterns of use and local climates etc [ref]. This work focuses on the energy required to be delivered to the indoor environment to maintain the required heating and cooling setpoints, the input energy to the systems (including system efficiencies and losses, pumps and fans etc) used to deliver this energy to the space is not addressed here but current and probable future system performance is discussed in another paper [ref] (It is increasingly the case that energy for heating and cooling is delivered by the same system with similar efficiencies).

The underlying assumption here is that the building occupants find their environment acceptable and they feel that they are able to adapt to maintain their personal comfort e.g. more clothes in winter, less clothes in summer etc. A key point may be that the occupants are confident that the building will maintain comfortable conditions even in extremes, either through robust passive design and operation or through available systems.

Both of the proposed methods for incorporating human adaptation in building operation (h18c28 and ADAPT) resulted in over 50% reduction in calculated energy demand for heating and cooling across all combinations of construction type and climate. The h18c28 approach has the advantage of being very simple to communicate but resulted in indoor climates that were at times outside of the Tcomf +/- 3 degrees range with an associated increased risk of discomfort. The ADAPT approach is more complex to communicate and implement but gives better comfort performance. Possible future implementation of an ADAPT scheme could involve a link with weather forecasting services (such as already in use for pre-charging electric storage heaters etc).

Further operational factors were found also to have a significant impact on building energy performance. The setback temperatures applied outside of the occupied periods was found to have a large impact for the typical 1990s building with high heat losses but not be so important for the advanced building. Internal gains from equipment gave significantly increased cooling demand in the advanced office but this effect was offset by reduced heating demands for the typical 1990s office (in fact the increased electricity used for appliances may still give an increase in input energy for all cases where a high efficiency heat pump is used for heating and cooling).

The more advanced building construction has almost no heating demand but increased cooling demand due to the lower unintended free cooling (heat losses to the environment) of the advanced construction. This effect could be offset and the cooling load of the advanced office reduced to almost zero even in the 2080 climate if effective ventilation strategies could be implemented to achieve day and night free cooling.

Public awareness of the approach being taken and the reasons for doing so may be important to gain acceptance for a change to the proposed new standards. Feedback mechanisms such as public display of the current setpoint temperatures and the buildings current and cumulative energy use would increase awareness as well as ensure that any problems were detected.

8. Conclusions

There is great opportunity for reduction in the energy used in buildings. This study suggests for the example office a combination of strategies could achieve close to zero energy demand for heating and cooling for the 2005 and predicted 2080 London climates.

The combination of measures recommended as the basis of future standards are:

- Design or retrofit buildings passively to provide intrinsically robust internal environments with low heating and cooling energy demands.
- Provide opportunities for adaptation by building occupants through the building design and operation regime including dress codes etc.
- Apply adaptive standards to heating and cooling system controls.
- Minimize setback temperatures outside of occupied periods.
- Minimize internal gains.
- Maximize opportunities for free cooling.
- Maximize heating, cooling and ventilation system efficiencies or eliminate the requirement for them.
- Publicize the approach being taken to reduce energy use and provide performance feedback mechanisms.

9. References

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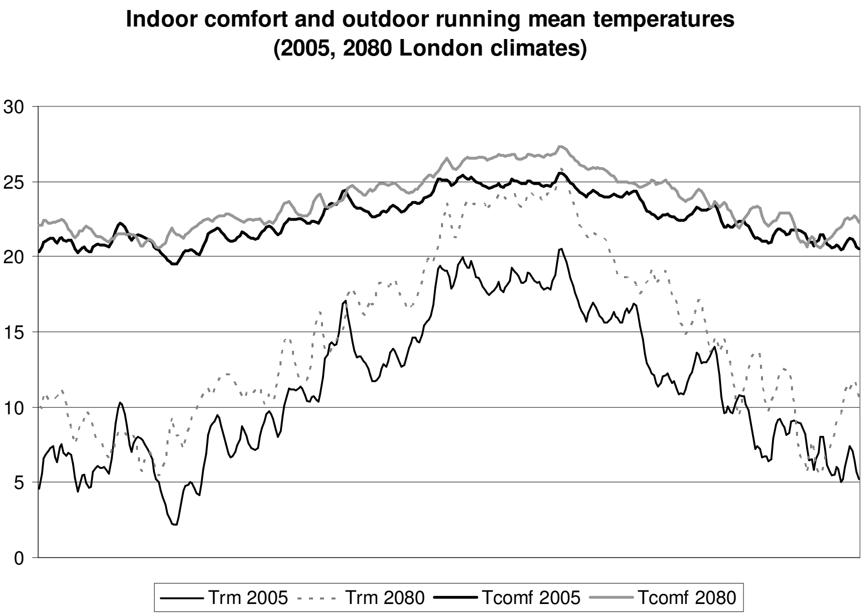


Fig 1: Outdoor running mean temperature for the 2005 (Trm 2005) and projected 2080 climates (Trm 2080). Indoor adaptive comfort temperatures for the 2005 (Tcomf 2005) and projected 2080 (Tcomf 2080) climates.

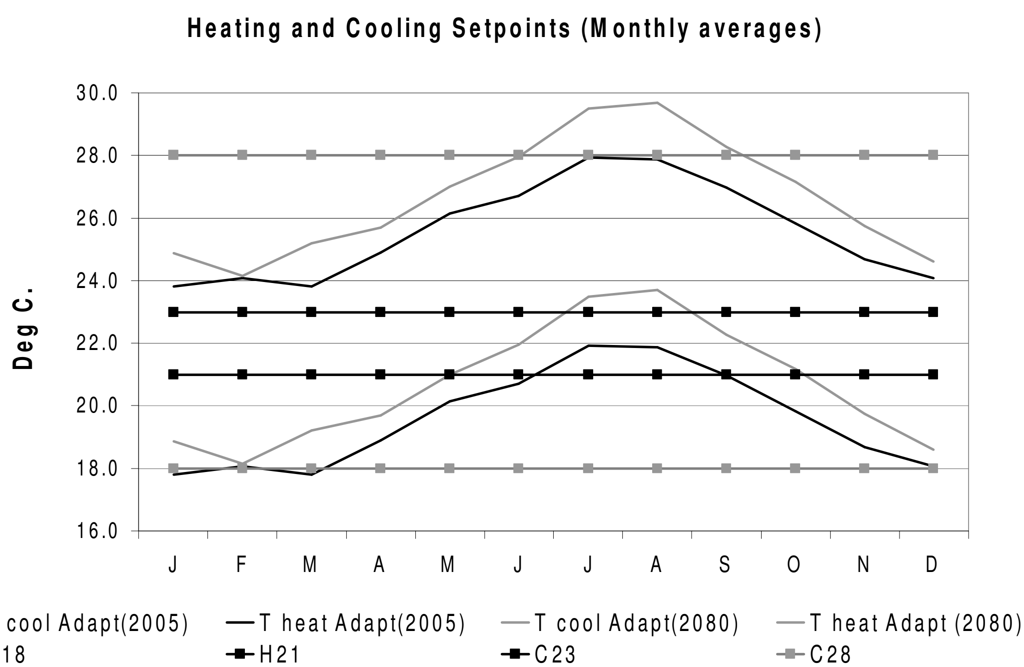


Fig 2: Illustration of the three approaches to control of indoor comfort for the London 2005 and projected 2080 climates.

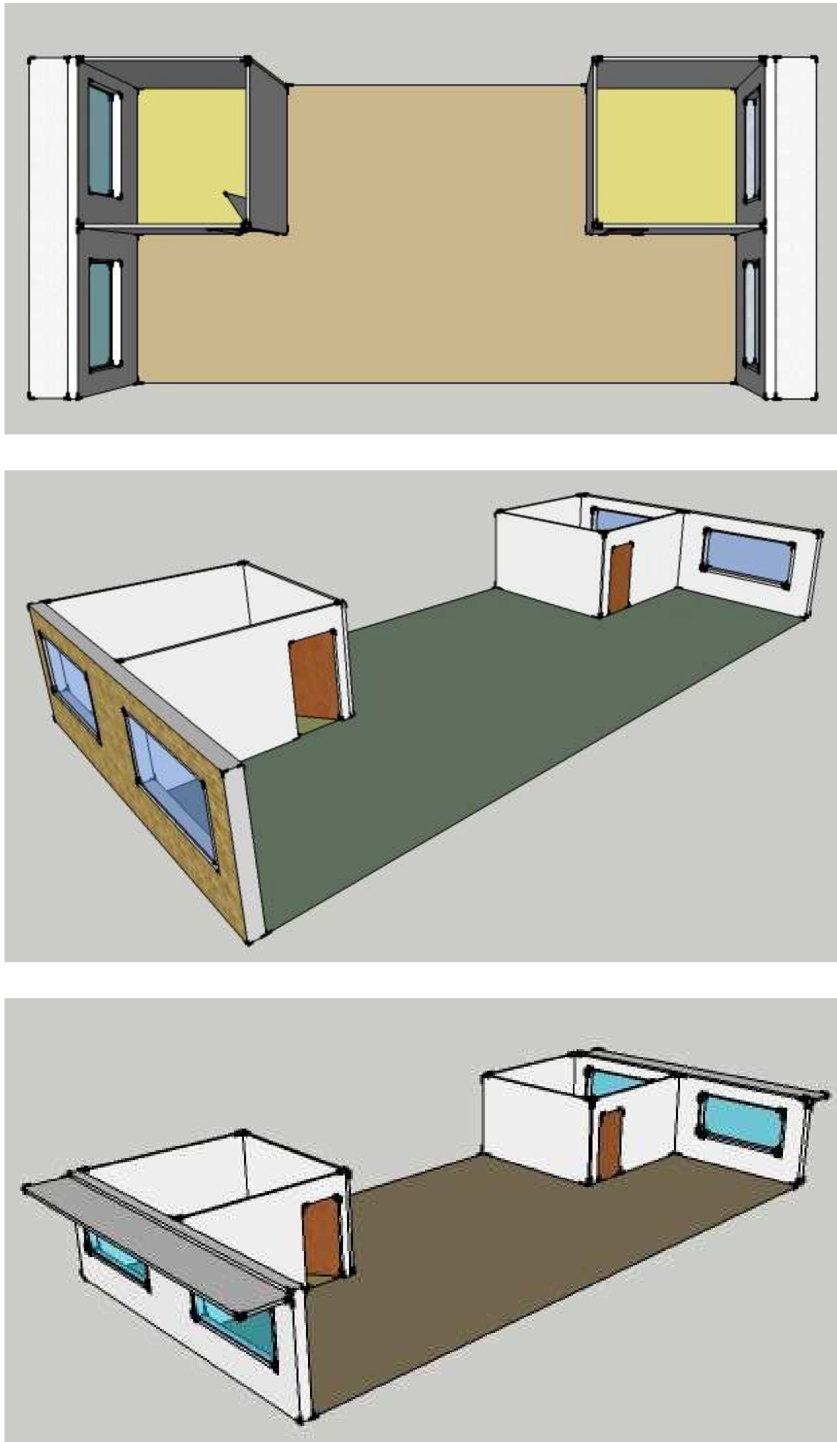
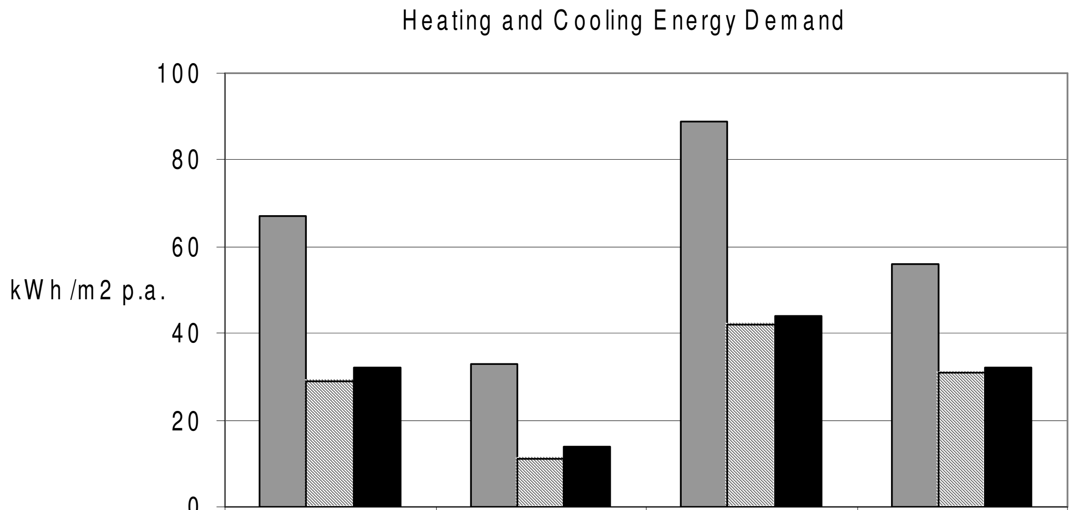
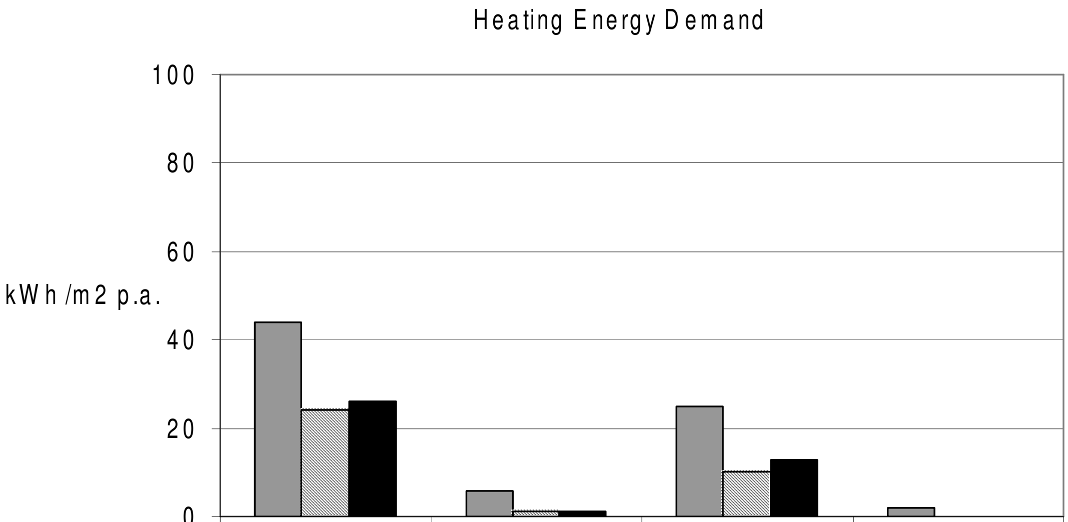


Fig 3: Three sketches illustrating the simulated office; a plan view (top image), a view of the typical 1990s version (middle image) and a view of the Advanced version (lower image).



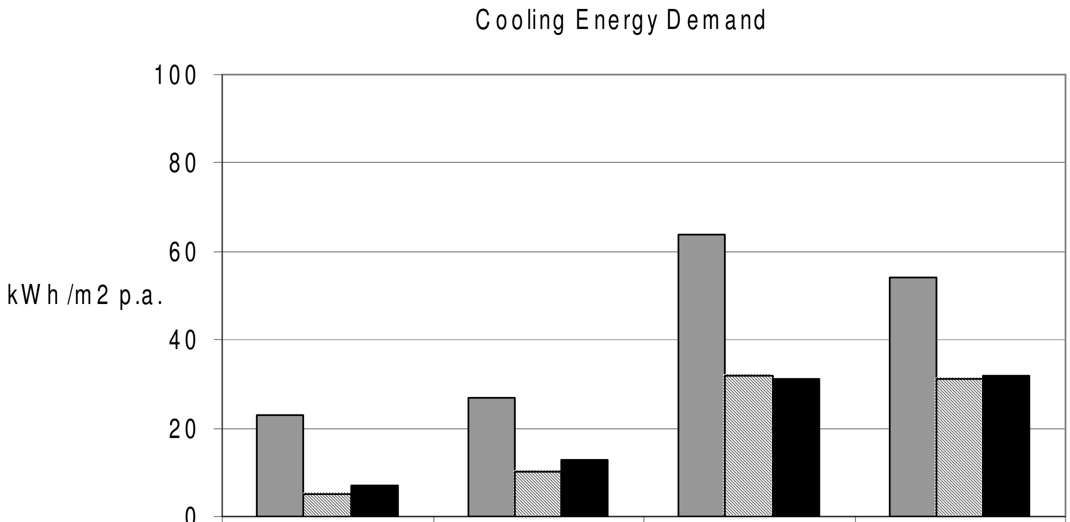
	typical building, 2005 climate	advanced building, 2005 climate	typical building, 2080 climate	advanced building, 2080 climate
h21 c23	67	33	89	56
h18 c28	29	11	42	31
adaptive	32	14	44	32

Fig 4: Calculated total heating and cooling energy demand for each of the combinations of building, climate and controls.



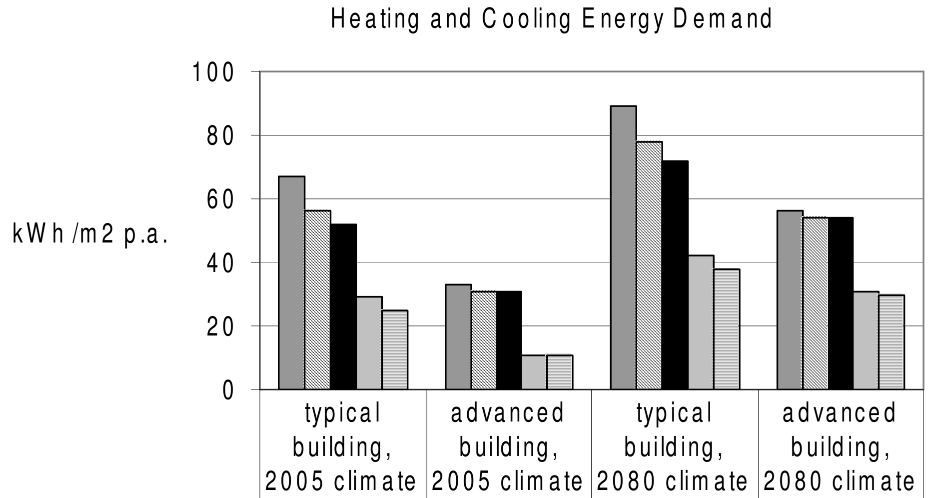
	typical building, 2005 climate	advanced building, 2005 climate	typical building, 2080 climate	advanced building, 2080 climate
h21 c23	44	6	25	2
h18 c28	24	1	10	0
adaptive	26	1	13	0

Fig 5: Calculated total heating energy demand for each of the combinations of building, climate and controls.



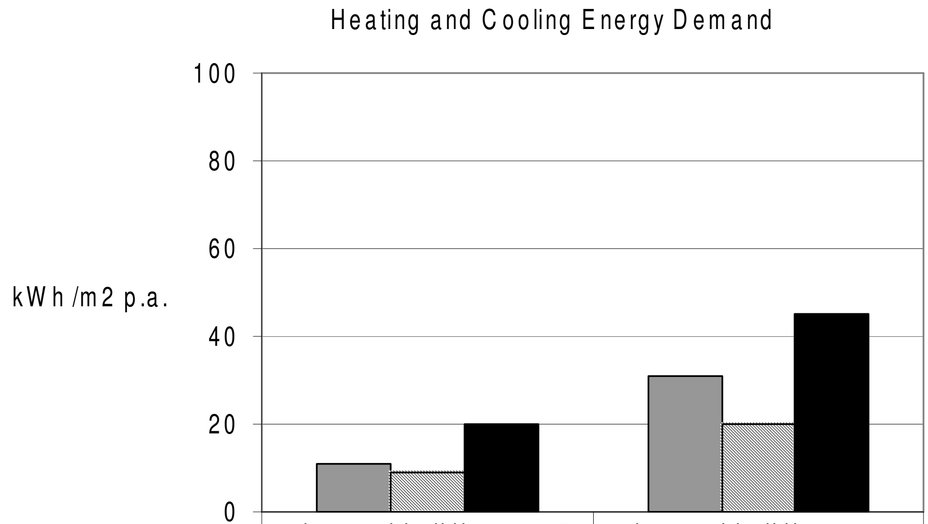
	typical building, 2005 climate	advanced building, 2005 climate	typical building, 2080 climate	advanced building, 2080 climate
h21 c23	23	27	64	54
h18 c28	5	10	32	31
adaptive	7	13	31	32

Fig 6: Calculated total cooling energy demand for each of the combinations of building, climate and controls.



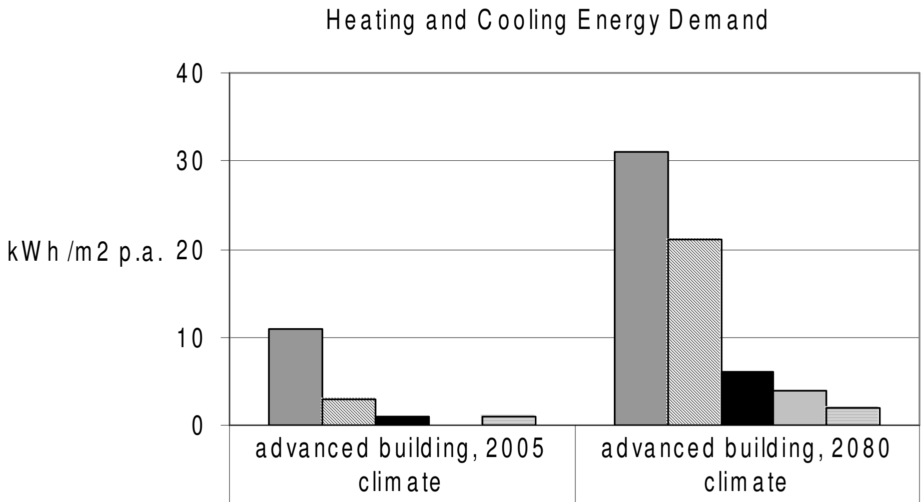
	typical building, 2005 climate	advanced building, 2005 climate	typical building, 2080 climate	advanced building, 2080 climate
h21 c23; no setback	67	33	89	56
h21 c23; 18-26 setback	56	31	78	54
h21 c23; 15-32 setback	52	31	72	54
h18 c28; 18-30 setback	29	11	42	31
h18 c28; 15-32 setback	25	11	38	30

Fig 7: Calculated impact of setback temperature on heating and cooling energy demand for combinations of building, climate and controls.



	advanced building, 2005 climate	advanced building, 2080 climate
h18 c28; baseline gains	11	31
h18 c28; low gains	9	20
h18 c28; high gains	20	45

Fig 8: Example of the impact of internal gains the on the calculated heating and cooling energy demand for the Advanced office with the h18c28 controls.



	advanced building, 2005 climate	advanced building, 2080 climate
h18 c28	11	31
h18 c28; XV 5 AC/H	3	21
h18 c28; XV+NC	1	6
h18 c28; CV+NC+LG	0	4
ADAPT; CV+NC+LG	1	2

Fig 9: Calculated impact of various ventilation (Cross vent: XV, Cross vent plus night cooling: XV+NC) and gains combinations (Low gains: LG) on heating and cooling energy demand for the Advanced building, climate and controls (h18 c28 and Adapt) scenarios.

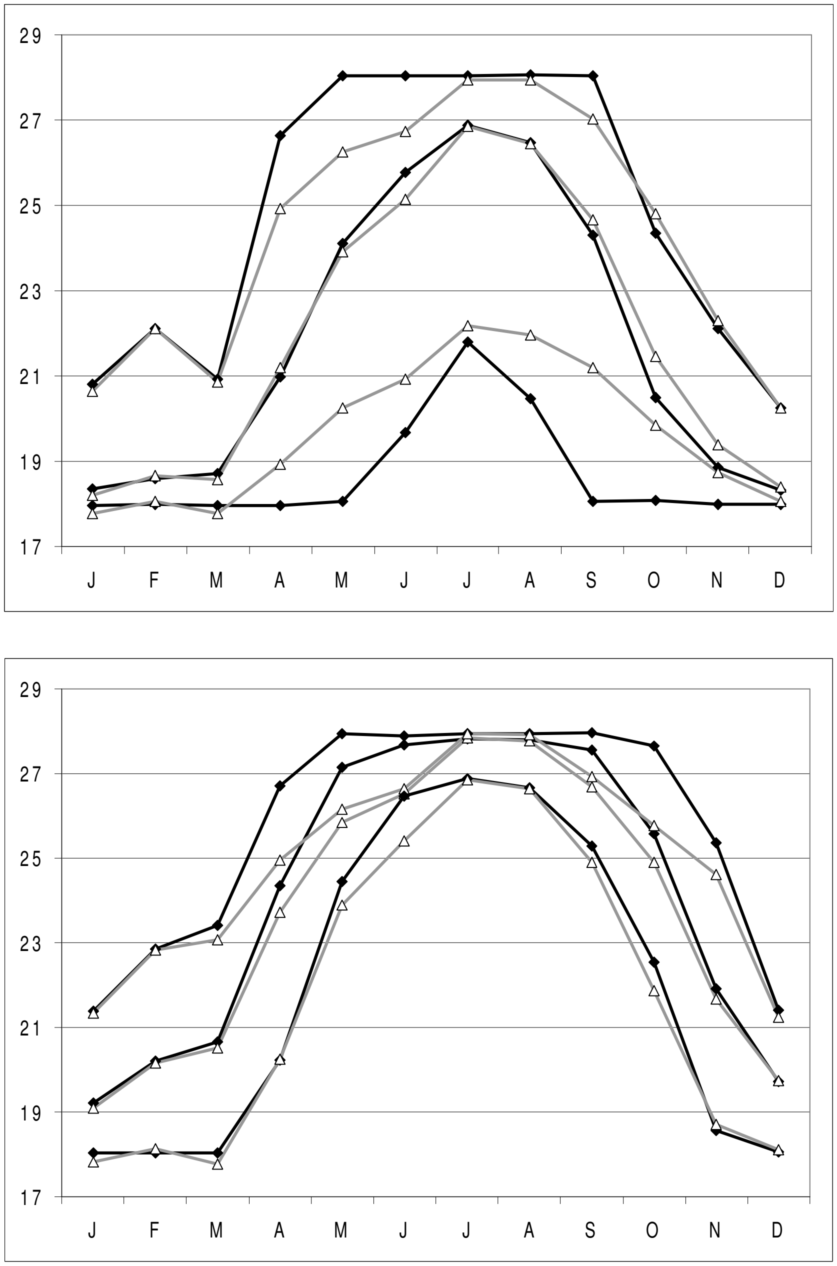
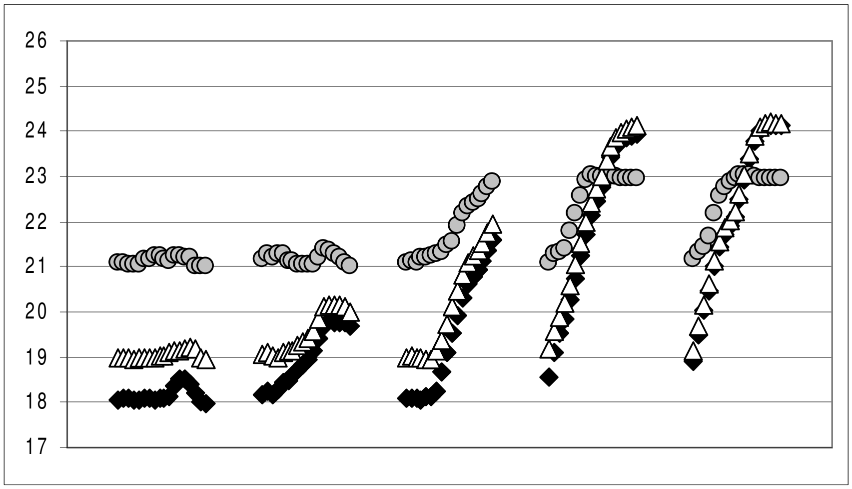


Fig 10: Monthly mean, maximum and minimum indoor resultant temperature (degrees C) for the h18c28 (white triangles on grey line) and ADAPT (black diamond on black line) control options for the 2005 climate. The top graph is for the typical 1990s construction the bottom graph is for the advanced construction.



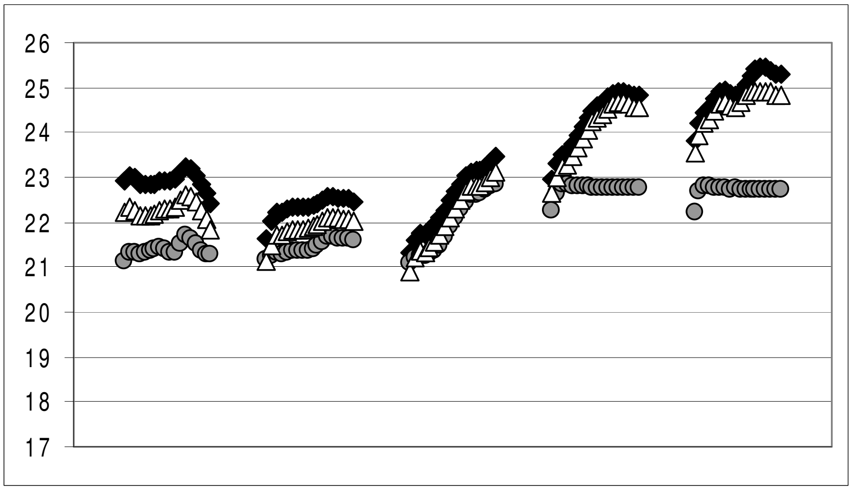


Fig 11: Indoor resultant temperature (degrees C) during occupied hours for a week in April 2005 for the h18c28 (white triangle), the ADAPT (black diamond) and the h21c23 (grey circle) control options. The top graph is for the typical 1990s construction, the bottom graph is for the advanced construction.

	1990s	Advanced
walls	masonry; internal insulation; plasterboard; U=0.6.	external insulation; conc block; plaster; U=0.13.
floor	insulation; wood board; carpet.	light concrete; carpet.
ceiling	insulation; plasterboard.	light concrete.
glazing	double; U=3.3.	triple; U=0.8.
partitions	plasterboard; insulation; plasterboard.	plasterboard; insulation; plasterboard.
external shade	no	shaded

Table 1: Construction details for the typical 1990s and the advanced versions of the office (construction layers are listed from outside to inside).

Occupancy	8.30 - 6.30 (Mon - Fri)
Heat/Cool period	6.00 - 19.00 (Mon - Fri)
Set-back period	All except Heat/Cool period
Control point	Resultant temperature (0.5MRT, 0.5AT)
Systems	Ideal

Table 2: Operational details for the office model. Note: the Resultant temperature is made up of 0.5x the Mean Radiant Temperature (MRT) and 0.5x the Mean Air Temperature (AT).

	Baseline	setback 1	setback 2
H-C setpoints (occ)	21-23	21-23	21-23
H-C setpoints (setback)	21-23	18-26	15-32

Table 3: Three setback conditions for the h21c23 control: the baseline has no setback, setback 1 includes heating and cooling setpoints of 18 and 26 degrees respectively in the setback period, setback 2 has setpoints of 15 and 32 degrees.

	Baseline	setback 2
H-C setpoints (occ)	18-28/Adapt	18-28/Adapt
H-C setpoints (setback)	18-30	15-32

Table 4: Two setback conditions for the h18c28 and Adapt controls, the baseline includes heating and cooling setpoints of 18 and 30 degrees respectively in the setback period, setback 2 has setpoints of 15 and 32 degrees.

	Baseline	Low Gains	High Gains
Gains (occupied)	15	12	20
Gains (not occupied)	4	1	4

Table 5: Internal gains scenarios. Gains are given in Watts per m2 floor area.

	Typical building	Advanced building	Advanced with X-vent	Advanced Xvent + NC
Airchange (occupied)	1.6	1.6	5	5
Airchange (not occupied)	0.25	0.1	0.1	5

Table 6: Ventilation scenarios: The ventilation rate of the baseline office during occupied hours is 1.6 ac/h which corresponds to 10 liters/second/person, outside of occupied hours the air-change rate is due to infiltration. A scenario is created for the Advanced office case where cross flow ventilation (X-vent or XV) can be achieved with a ventilation rate of 5 ac/h during occupied hours, a second scenario is where this can also be achieved during unoccupied hours (Xvent+NC).