Revival

TECHNICAL**MONOGRAPH** 2

Adaptive thermal comfort and controls for building refurbishment

This technical monograph is one of a set produced as part of the 'REVIVAL' project – an EU Energie Programme supported demonstration project of energy efficient and sustainable refurbishment of non-domestic buildings in Europe. The monographs explore some of the main energy and comfort issues which arose during the Design Forums held with each of the six sites. The four monographs are entitled:

- Thermal mass and phase change materials in buildings
- **Adaptive thermal comfort standards and controls**
- Natural ventilation strategies for refurbishment projects
- High performance daylighting

Improving energy performance and comfort

Refurbishment almost always involves the installation of new plant and controls. This in itself is often an energy-saving strategy since, not only is heat (or cooling) produced more efficiently in modern plant, but improved controls also result in far higher utilisation – i.e. a reduction in wasted heating or cooling.

Another motivation for plant replacement could be to improve comfort where for various reasons existing plant is inadequate. This may be due to the degradation of the system and controls, or due to gradual increase in heating (or cooling) demand due to increase in the total built area. Caution is needed here when specifying the capacity of plant, since other measures may result in significantly reduced loads – hitherto inadequate plant may now be able to cope. Even if for reasons of technical efficiency the plant is to be replaced, then it can probably be much smaller.

▼ **Figure 1**
Ad hoc additions to existing air conditioning plant without improvements to the fabric, together with old and degraded heating systems can often lead to very low efficiencies.

Thermal Comfort Standards

Once the decision to replace plant and controls has been made, then the question of comfort standards arises. There tends to be a presumption that air-conditioned buildings always provide a superior level of comfort. However, it is often found that satisfaction levels are quite high in naturally ventilated 'poorly serviced' buildings – for example the database of Building Use Studies shows that occupants are about equally satisfied in air-conditioned and non air-conditioned buildings.

There will be some cases where new plant will lead to major improvements in comfort conditions, but may lead to an increase in energy consumption of the refurbished building, in spite of other improvements. This would be the case, for example, in warm climates where the original building may have had no heating or cooling system at all (Figure 2). In these cases, the added value of improved comfort has to be recognised in assessing the performance of the improved building. It may be appropriate to make a comparison of the refurbished building with the predicted energy cost of the old building if it were serviced to provide the same comfort standards.

In the case of refurbishment, there may be qualities in the original building that are lost. For example, openable windows are often removed when re-glazing or double skinning,

and views maybe compromised by the application of shading devices. There is some evidence that building features such as these make occupants more tolerant of temperature swings. And it may be just as satisfactory to allow some drift in temperature conditions as in the original building, rather than implement a close temperature control strategy at considerable energy cost.

In order to achieve an informed solution to this question, it is necessary to understand the basic principles of conventional comfort standards and the more recent understanding of how *adaptive behaviour* can also influence overall satisfaction. Adaptive behaviour is where the occupant interacts with the environment in order to improve it, or changes their own state to improve their heat balance. This is an elaborate way of saying for example – "opens the window or takes their jacket off". There are also psychological factors that may influence the occupant's response to a given thermal condition. Commonplace though these responses are, conventional comfort theory has virtually ignored this aspect; in particular the extent to which it is influenced by building design.

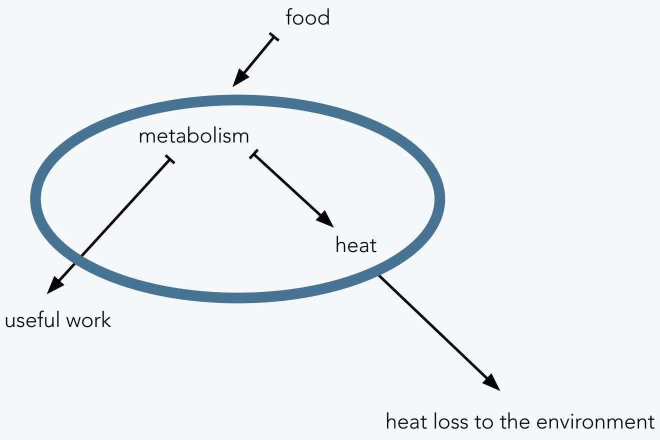
Conventional Comfort Theory and Heat Balance

Figure 3 illustrates the energy balance of the human body – or indeed any warm-blooded animal. Chemical energy is taken in the form of food, converted to mechanical energy and heat by the process of metabolism. The heat is an essential 'bi-product' in this conversion. This 'waste' heat production is found in other instances of energy conversion – e.g. the engine of a motorcar or at a power station.

However, in warm-blooded creatures nature has put this heat to good use, by maintaining the body at a steady temperature above that of the surrounding environment. This allows chemical processes such as enzyme action, to be optimised and independent of external conditions. This gave a huge advantage to warm-blooded creatures compared with cold-blooded animals. The problem is that this steady temperature has to be controlled to within +/- about 1^{o}K. In humans this is achieved by a series of responses some of which are physiological (e.g. shivering, sweating) and some of which are behavioural (e.g. putting more clothes on).

▲ **Figure 2**
The refurbished Meyer Hospital administration block is to be air-conditioned, and although it will be a highly efficient system, it will lead to an increase in energy consumption since the original building had no heating or cooling services.

▶ **Figure 3**
Metabolic heat is generated as a bi-product of the conversion of food energy to useful work.



Heat balance is the key to the process – if the heat loss to the environment is less than the metabolic heat gain, the person will go on getting hotter and hotter, and if heat loss is more than the heat gain, the person will get colder and colder. In both cases the ultimate result will be death. Feelings of discomfort are to give us early warning of this serious outcome.

Conventional comfort theory, as pioneered by P.O. Fanger, focuses on the need to provide this heat balance at all times by controlling the environmental temperature. In order to establish these 'ideal' conditions, subjects were placed in a climate chamber where the temperature was varied until the consensus response (the mean vote) was of zero thermal sensation. This was correlated with various parameters, such as metabolic activity level and the total heat loss (calculated from the person's temperature and clothing insulation level).

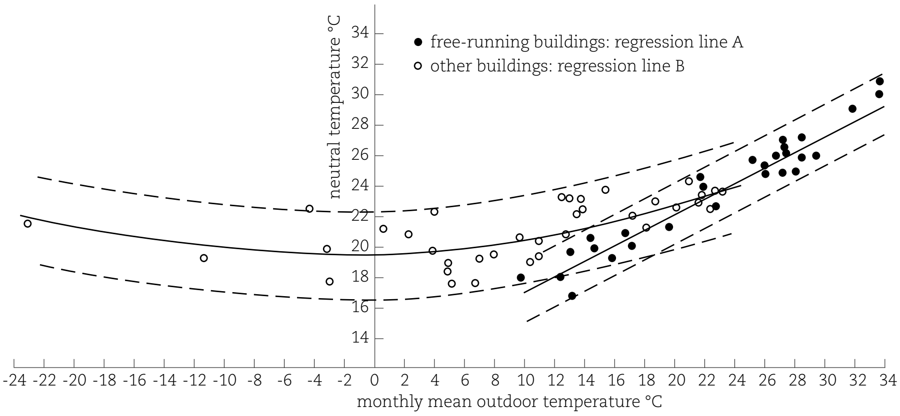
It is easy to see that this produces a universal figure – an office worker dressed in a suit operating a computer in Stockholm would need the same thermal environment as one similarly dressed in Calcutta. The internationalisation of standards through bodies such as ISO and ASHRAE has resulted in the global growth of the air-conditioning industry, and has contributed to the ever-increasing use of fossil fuel.

Adaptive Comfort Theory

The reality is however, that millions of people are satisfied with environments that fall a long way outside the limits prescribed by Fanger. Humphreys in his 'survey of surveys' carried out in 1974, showed that using the data from many surveys taken all over the world, the neutral temperature at which people reported satisfaction bore a positive relationship to the outside monthly mean temperature as shown in Figure 4. How can we explain this?

It's not that the physics of Fanger's analysis is wrong, rather it is the extrapolation of the subject's responses, from the steady state climate chambers, to normal living and working conditions that is inappropriate. This is because in real life, the body is not in steady conditions, and has at its disposal the use of many behavioural mechanisms, as well as physiological ones, to achieve a long-term thermal balance.

Furthermore, psychological factors influence our *interpretation* of non-neutral thermal sensations – for example, if we are a bit chilly, the warm spring sun can be a delight; if we are already sweating from insufferable heat, that same thermal sensation would certainly not be.



▲ Figure 4
The open circles are for surveys carried out in buildings that are air-conditioned, the solid circles are for free-running buildings. It shows that the comfort temperature bares a linear relationship with the monthly mean outdoor temperature. Fanger's equation would conclude that the comfort temperature would follow a horizontal line. The increasing comfort temperature is explained by the effect of adaptive actions by the occupants. It is not a physiological adaptation as often suggested. Humphreys derived the equation

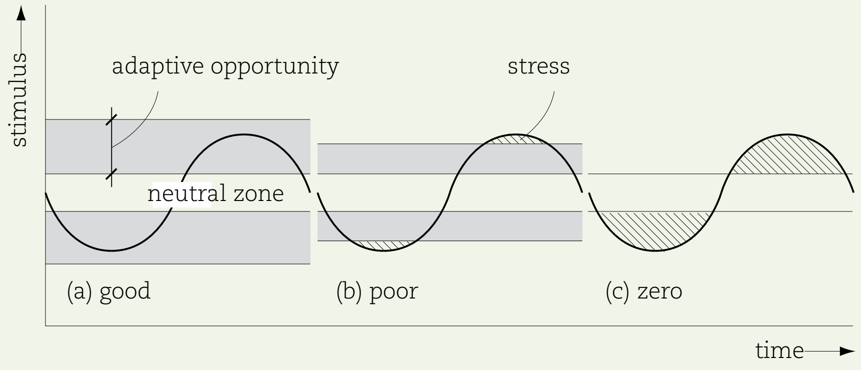
$T_n = 11.9 + 0.534 T_m +/- 2.5^{\circ}K$
where T_n is the neutral temperature and T_m is the mean monthly temperature

We are sensitive to the degree of risk of long-term heat imbalance. The momentary feeling of chill when we run out of a heated building to fetch something from the car, is interpreted very differently from feeling only slightly chilly in the middle of an open-plan office where we have no control over the temperature.

Adaptive actions, and the interpretation of the long term situation, are then, a key factor in satisfaction with the environment. It follows that a vital quality of an environment is the opportunity to make adaptive actions. This is illustrated in Figure 5 which shows an acceptable 'comfort zone' within hypothetical varying stimulus, (which could be temperature). Note that with good adaptive opportunity (a) the zone widens to include the extreme values, that in the intermediate case (b) the subject is stressed only when the adaptive zone is exceeded, whilst where there is no adaptive opportunity (c), any departure from neutrality results in stress.

It is important to note that conditions of zero adaptive opportunity are those prevailing in the climate chambers. This accounts for the far more demanding conditions for comfort resulting from climate chamber work.

▼ Figure 5
The neutral zone is, in effect, extended by adaptive opportunity. In the case of poor adaptive opportunity, the swing in the stimulus (e.g. temperature) exceeds a value with which the adaptive opportunity can cope leading to stress. In the case of no adaptive opportunity, any departure from the conventional comfort zone leads to stress. This is the situation in the climate chamber.



▲ **Figure 6**
Office environments in Portugal showing good (left) and poor (right) levels of adaptive opportunity

Application of adaptive comfort theory

What does this mean for designers and specifiers? How do we provide an environment with good adaptive opportunity?
We can identify three kinds of adaptive opportunity:

- Personal
- Building
- Systems and controls

Personal refers to the freedom of an individual to take actions that affect their own heat balance. Some of these are almost involuntary, such as the way one sits or moves. An important adaptive opportunity relates to clothing – the freedom of an individual to choose a clothing ensemble and/or to make adjustments that alter its insulation value.

For example the insulation value (measured in Clo units) for a pair of shorts and tee-shirt is 0.3 whilst that of a business suit is 1.0. By adopting the former, the comfort temperature will increase by about 3°K – this clearly may be sufficient to avoid air-conditioning with significant energy implications. There is no doubt that the ubiquitous business suit has been a major stimulus to the growth of air-conditioning in office buildings world-wide, even in temperate climates.

Dress code is not an area normally covered by the architect! However, the concept of the space in a broad social sense is often a matter for discussion in design meetings and it could be that informed input from the architect or engineer might influence the client in this respect.

Access to cold or hot drinks is also an adaptive opportunity that can have a significant effect.

Building refers to more familiar elements such as openable windows, occupant controllable blinds, flexible furniture layout and spatial freedom. Due to the variation in personal requirements, it is easier to satisfy occupants in cellular buildings than in open-plan.

It is also found that people are much more tolerant of variation in environmental conditions (for example temperature), if they are close to a window. There is also growing evidence that the provision of good outdoor views affects the overall well-being of occupants, which in turn influences their response to internal conditions in a positive way.

These issues are more familiar territory for the architect and can effect the design of the building from its most fundamental massing and planning, to the detailed specification of elements such as blinds and furniture.

Systems and controls refer to the provision of mechanical systems such as heating, lighting and ventilation, and the access of the occupant to their control. Because mechanical systems offer the possibility of high levels of automatic control, and with IT intelligence, it is often believed that this is preferable to manual control. However, it is now widely accepted, that local personal[1] manual control should be provided wherever possible.

This is not to say that intelligent controls have no role. Ideally, systems should have a *caretaker function*, i.e. they allow personal, manual control, but after a period of time they return the status of the controlled service back to a low-energy standby.

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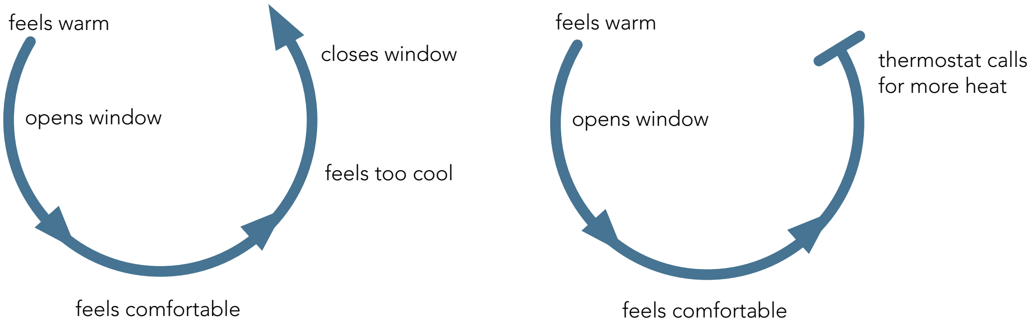
[1] 'Personal' implies a control which ideally would influence a single occupant. This has been provided in some hi-tech workstations, and is the norm in cars and aeroplanes. In buildings it is less common and may inhibit flexibility in room layout. However, controls should be as local as reasonably possible – the fewer occupants affected, the more the control will be used, and appreciated.



▲ **Figure 7**
The control feedback loop is broken by the intervention of the thermostat

Feedback loops

For example, in the case of heating controls, the normal setting might be in the lower half of the 'comfort zone'. However, an occupant might temporarily require more heat and adjust the setting higher. After a period of higher temperature, the control system would gradually return the temperature to its standby value.

This approach is particularly valid where feedback is weak. A good example of this is lighting. The occupant arrives in the morning in poor daylight and switches on the lights. Later during the day, the sky brightens and daylight alone is sufficient. However, the added illuminance of the artificial light is insufficient to make the room *uncomfortably bright*. Thus there is no incentive for the occupant to turn the lights off. The caretaker control would test if there was sufficient daylight available and then dim out the artificial lights.

In other circumstances, automatic controls 'sabotage' the natural feedback loop.

Consider the case shown in Figure 7 where an occupant, denied access to local temperature controls, opens a window. Instead of the room temperature dropping, thereby prompting the occupant to close the window, the thermostat calls for more heat. This not only frustrates the occupants intentions, but is also very wasteful of energy. It is this kind of conflict between the user and automatic control that has led engineers to develop hard line attitudes to occupant control.

What is needed, is a control system in which occupant action is not ignored or prevented, but becomes part of the system. In the example above, by simply disabling the thermostat when the window is opened, the natural feedback loop is restored. Further energy saving could be achieved by setting the heat demand to a lower or even zero level. This approach is to be incorporated in the KAT hospital refurbishment (Figure 8) where a micro-switch in the sliding doors to the balcony, switches off the room air-conditioning.

Intuitive interface design

The visual and ergonomic design of the control interface is important. Much attention is paid to this in other design areas such as motorcars. In the IT area, the issue of the degree to which the use of an interface is intuitive has become important in software design. Rather less attention has shown to this in building controls.

Controls to passive elements, such as blinds or windows, are naturally intuitive because the user understands the mechanics and interacts directly with the element; opening a window obviously connects the inside with the outside and therefore the outside air. This is often not the case with controls to mechanical systems. If anything, the situation has worsened with

▼ **Figure.8**
Micro-switches sense the opening of the large windows onto the balcony and switch off the air-conditioning. This prevents the feedback loop from being broken and prevents wasted energy

Positive adaptive attributes:

Relaxed dress code
Occupant mobility – access to hot/cold drinks
Openable windows
Adjustable blinds
Desk fan or locally controlled ceiling fan
Local heating/cooling controls
Workstation/furniture flexibility
Shallow plan (minimizing distance from windows)
Cellular rooms (reduces mutual disturbance)
Surface finishes appropriate to visual task
Daylight and task lighting backup
Good views (external and internal)
Transitional spaces (verandahs, atria etc)
Good access to outside areas

Negative adaptive attributes:

Uniformity of physical environment (temperature, lighting, colour)
Deep plan, reduced access to perimeter
Dense occupation with restricted workstation options
Sealed windows
Views obstructed by fixed shading devices
Central mechanical services control

growth of IT and digital control – multi-function buttons and touch-screens are a long way from a control knob with an arrow and HOT – COLD scale.

Finally, even if the control interface is intuitive, it must also be ergonomically satisfactory. A window catch that can only be reached by standing on the desk, or a radiator thermostat valve at floor level behind a filing cabinet, will not be used frequently. Another related matter is the importance of providing modulation control where required. For example, an opening window that is either closed of wide open, or a blind that cannot be partially deployed, is unsatisfactory, and will be used far less. The detailed design of control systems is beyond the scope of this monograph, but the four key principles are

- anticipating occupant interaction
- maintaining feedback to the occupant
- caretaker function
- intuitive and ergonomic control interfaces

How effective is the provision of adaptive opportunity?

The impact of providing adaptive opportunity is diffuse. There seems to be a general improvement in well-being indicated by higher scores in overall satisfaction in post occupancy evaluations (POE). This carries benefits to the building operator of higher productivity and low absenteeism rates.

However, it would be useful to be able to quantify the effects on specific environmental parameters such as temperature, i.e. by how much does the provision of adaptive opportunity affect the acceptable temperature limits. If this question could be answered, then conventional and internationally accepted temperature standards, derived from non-adaptive comfort theory, could be modified in response to the degree of adaptive opportunity.

Relatively little work has been done in this area although in a pilot study for CIBSE values of 'adaptive increments' for various adaptive opportunity attributes were tabulated, as shown below. Though the temperature increment is easy to specify quantitatively, the adaptive attribute has to rely on verbal description.

The adaptive opportunity table above can be used as follows:

1. look up the conventional comfort standard
2. select the adaptive opportunities that are present.
3. judge the degree to which the opportunity is present and modify the increment/decrement accordingly.
4. sum the modified increments/decrements and use this figure to extend the upper comfort limit.

Adaptive opportunity	Comfort temperature **decrement/increment** on standard comfort zone width (+/- 2.5°K from neutral)
Personal	
• free dress code	
• – 0.3 Clo	+ 2.5
• – 1.2 Clo	- 1.5
• Non-upholstered chair	+ 0.5
• Access to cold/hot drinks	+ 0.75 (- 0.5)
• Metabolic rate and posture	+ 1.0 (- 0.5)
Building	
• Desk fan or ceiling fan	+ 2.5
• Openable window	+ 1.5
• Operable blinds	+ 1.0
• Spatial variation	+ 1.25

Metabolic rate and Posture describe the tendency for people when overheated to move more slowly and efficiently, thereby lowering their metabolic rate. People also sit in a more extended posture, exposing a larger surface area than when under heated.

Spatial variation describes the ability of an occupant to seek out the position that is more comfortable than the room average. This could involve a small movement into a moving air stream or a better-shaded part of the room.

There are more opportunities for raising the upper temperature limit than for lowering the lower limit. It is almost universal to provide mechanical heating in cool climates although in some areas of southern Europe heating equipment is not installed. The most noticeable effect is the raising of upper limits, and this may permit the avoidance of air-conditioning.

Example. An architect's office in Athens has openable shaded windows, a cold drinks machine and a free dress code (occupants often wear shorts and tee-shirts). Seating is on open mesh steel chairs.

All adaptive opportunities are available except 5 and 6. Opportunity no.7 has the problem that when the louvre blinds are deployed they inhibit the ventilation and view so we will reduce that to 0.5. This gives a total increment of 8°K.

Taking a 'normal' neutral temperature for offices as 21 +/- 2.5 °C gives an upper 'conventional' limit of 23.5 °C. Adding the increment of 8°K gives us an absolute maximum of 31.5 °C.

In a study, actually carried out in an office in Athens during the PASCOOL project, it was found that the average satisfaction reported was 83% for a spatial mean room temperature of 30.5°C.

Summary Conclusions

There is now widespread support for the adaptive thermal comfort model. Both ASHRAE and CIBSE have recognised the adaptive model, and ISO standards are becoming more flexible in response to data from many EU funded research activities.

It remains difficult to quantify the benefits and the adaptive attributes of a design. This means that it is all too easy for the engineer when faced with a client's need for assurance, to resort to a conventional performance specification, met exclusively by an engineered solution.

However, good adaptive design can emerge from a well-integrated design team, where client, architect and engineer share the problem and approach the design solution together.

Refurbishment offers both constraints and opportunities. Whilst major re-modelling maybe economically impossible, many European buildings of 30 – 50 years old were designed in an era when relatively low servicing was the norm. This often means that shallow plans and generous floor-to-ceiling heights prevailed. Although detailed design, along with 'building abuse' in the form of alterations and 'improvements', may have rendered them currently poor performers, there remains a potential for good passive rehabilitation, which is usually closely compatible with good adaptive design.

The benefits of avoiding heavy servicing in refurbishment projects are considerable – apart from the reduction in capital costs, maintenance and energy, fitting ductwork and plant into existing buildings is often difficult and expensive in terms of space.

Developments in IT can also make a contribution in good adaptive design. Wireless controllers, occupancy detectors and local zonal control all help to give back "power to the people".

Prepared by Nick Baker the Martin Centre University of Cambridge