Tyndall°Centre
for Climate Change Research

Establishing research directions in sustainable building design:

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Final Project Report

Establishing research directions in sustainable building design

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Section 2 - Technical report

Introduction

The following report is in part based on the many and varied discussions raised in this project. The minutes of the workshops and copies of the presentations made are available through the project website (contact Samantha Lawton sl285@cam.ac.uk for password). Rather than summarising the contributions made, the report that follows is an overview of the key issues and is written by the coordinator – Koen Steemers. As such, the views expressed and the emphasis given is that of the author and not of the many people who have contributed to the workshops (who are listed above). The author would therefore like to thank all of the contributors and simultaneously apologise for any misrepresentation. The report that follows is in part a draft of a paper that has been submitted to 'Building Research and Information Journal' for publication in 2003.

Abstract

The purpose of this report is two-fold: first, to review in generic terms the views, publications and research related to building design and climate change, and second, to raise a number of questions and potential research avenues. This paper primarily addresses the roles of building design and its implications for occupant behaviour in the context of the environmental performance of buildings and climate change. The emphasis is on the integration of adaptation with energy efficient design, both in

terms of how buildings can be designed to increase their adaptive potential but also in terms of the significance of occupant adaptive opportunities.

Background

Within the building professions, and populist environmental community more broadly, there are polarised opinions related to the implications of climate change, ranging from those proclaiming an "apocalyptic prospect of catastrophic climate change" (Smith, 2001) to others who claim that "we are actually leaving the world a better place than when we got it…: mankind's lot has vastly improved in every significant measurable field and it is likely to continue to do so" (Lomberg, 2001). What is interesting about both views is that there is an implied need for adaptation to the situation. The aim of this paper is not to discuss the detailed science of climate change, but to focus on the strategic research issues raised by adaptation to climate change in the context of the built environment. In particular, the interest is in identifying the links between how buildings and their occupants can adapt to climate change, and what research questions this raises.

The reason to emphasise adaptation, as opposed to mitigation, is twofold. Firstly, climate change is predicted to continue unabated for at least the next 40 years even in the light of the most effective mitigation strategies that can be implemented. Thus, whatever our successes regarding emission reductions, buildings will need to respond to an inevitable degree of climate change. Secondly, mitigation in terms of reduced energy consumption and thus reduced emissions associated with buildings, has a long track record in research, and, despite failings in practical impact, the emphasis is primarily now on transferring this expertise to practice. Energy efficiency, stimulated in modern times by the oil crisis of 1973, is a well-established research field. More recently this has been given new impetus by the environmental movement and the Rio and Kyoto Protocols. However, adaptation to climate change in terms of the planning, design, construction, use and maintenance of buildings is a burgeoning research area that requires greater emphasis than hitherto. This paper focuses primarily on two of the above issues: the potential role of the building user with respect to building design in the context of climate change. It aims to explore research questions related to climate change and its implications for building design and use, and the focus will be the environmental performance of buildings, as opposed to constructional or structural.

The Climate Change Messages

The IPCC Third Assessment Report (2001) outlined a number of global implications of climate change:

1. The predicted annual costs associated extreme weather events are in the order of 1000 million US Dollars.
2. The anticipated sea level rise between 1990 and 2100 is 49cm, and in Bangladesh alone 10 million people live within a 1-meter sea level rise contour.

3. Globally it has been predicted that by 2050 there will be 150 million refugees as a result of climate change.
4. The approximate cost of action to mitigate and adapt is between 1 and 2.5% of GNP.

These statements provide a broad-brush and rather negative impression of the wider financial, physical and social challenges that appear to confront us. Such sweeping and rather depressing prospects are echoed in publications that targeted at the building industry, often without addressing the particularities of local conditions and variations, let alone building-specific opportunities or possibilities.

Building oriented publications

The rather negative slant is echoed by numerous building design texts that have an almost religious tone – along the lines of "the end of the world is nigh". Such an approach is not unusual and can be found in any number of architectural treatises and articles. The argument typically to develops a moral imperative and then proposes the preferred solution. For example, 'sustainability' is frequently cited as the imperative and 'green architecture' – in any number of guises from hi-tech sophistication to what can be termed 'new primitivism' – as the solution. Occasionally, a rational critique of the issue – whether this refers to strategies for climate change or sustainability – is provided. Rarely do proposed solutions live up to or even address the issues raised in generic, demonstrable or measurable terms. This is perhaps as a result of the nature of building design – as opposed to many other industries – where prototyping, refinement, optimisation and mass production are rare. This is at least in part due to the lack of feedback, where the in-use performance is rarely evaluated in terms of performance objectives. However, the lack of a generic approach can also be seen as an advantage, in the sense that the specificities of the local context (whether micro-climatic, urban, social or other) can be addressed, as opposed to imposing a pre-determined 'optimum' solution.

More problematic is the lack of an agreed method of assessment that enables the necessary design flexibility to address the local climatic as well as the contextual aspects in a transparent way. Environmental modelling of buildings tends to offer answers to particular proposals, whereas what might offer more flexibility in design terms is to model the 'robustness' of design strategies in a specific context, or a range of detailed design opportunities – a 'solution space'. Understanding the robustness and scale of adaptive opportunities would seem to be a promising response to the challenges of climate change. However, research in this sector has tended to take a different approach.

A brief review of the existing climate change related material reveals that there are broadly four categories.

- Policy (e.g. DETR, 2000)
- Data (e.g. Hulme et al., 2002)
- Strategies / Discussion (e.g. Laing, 2001; Smith, 2001)
- Tactics (e.g. Graves and Phillipson, 2000)

For the purpose of this paper we shall focus briefly on the latter two categories, partly because there is an abundance of material on policy (typically in the form of political 'wish-lists') and climate change data (largely, though not totally, undisputed facts for given scenarios), and partly because strategies and tactics are more closely associated with building design implications.

Strategies

As mentioned earlier, the strategic discussions tend to be polarised between those who see action as imperative and those of a more 'wait and see' persuasion. The former views are by far the most predominant. As expressed by proponents of the latter view: "there is a plethora of … advice and guidance … all tending to overreact to an inherently uncertain situation" (Guldberg and Sammonds, 2001, p. 79). The case for sustainable design is made by architects and industry leaders, and supported by a range of opinions, facts and figures. For example, in financial terms Sir Martin Laing (2001) claims that the top 50 companies with environmental standards have outperformed FTSE 100 by 15% in 5 years; that increasingly pension and insurance companies require environmental credentials of construction companies; and that the UK Government – responsible for 40% of construction – is demanding change through for example the application of environmental assessment methods. Such high-level rhetoric ultimately has little to do with the actual building performance of buildings, and can all too easily be disputed.

Where one might expect greater relevance to building design is at the level of design guidance. Typically, existing environmental building design guidance ranges from resource efficiency strategies to renewable energy systems (e.g. Smith, 2001) – occasionally, occupant comfort and well-being are included as part of the debate (Baker and Steemers, 2000). The focus of this readily available material targeted at the design professions is almost exclusively on mitigation as opposed to adaptation. This is a point that will be raised again in this paper.

An argument that can be raised against a focus on building design is that the emphasis should be on energy supply as opposed to energy efficiency (this is discussed further with respect to the existing building stock and refurbishment below). For example, the move from coal to gas in the UK has reduced CO_2 emissions by 21% since 1990 – although this trend is unlikely to be sustained, particularly in the context of the anticipated increase in global gas prices. This argument is often coupled with the view that efficiency is relatively expensive and does not easily address the problem of the existing building stock – particularly when, as now, it is not generally integrated as part of normal refurbishment cycles. In the end, the received wisdom is that renewable energy supply and energy efficiency are both critical, and for designers this has extended to the challenge of integrating the two through design (e.g. building integrated photovoltaics).

Despite the widespread availability of information on energy efficiency and renewables in the context of building design, there is a distinct lack of discussion at the strategic level of how building design can adapt to climate change. This is particularly true for the environmental performance of buildings.

Information on structural and planning related aspects (e.g. in relation to flooding) are more widely available.

Tactics

Graves and Phillipson's document (2000) is an example of only a few publications that address tactical implications of climate change on the built environment. They tend to provide simple and straightforward guidelines on interventions that will pre-empt the effects of climate change, and are thus primarily focused on adaptation – to the detriment of considering mitigation. For example, design teams are recommended to:

- design for 5-10% higher wind loads
- design for more driving rain
- use materials that are UV resistant, heat stable and water tight
- increase foundation depths in clay by 0.5m
- avoid vulnerable flood plains and coastal areas
- consider water resources

As can be seen from the above list, some recommendations are specific whilst others are vague, and most focus on structural performance. Some mention is made of energy efficiency, through the use of natural ventilation, though the only link made between mitigation and adaptation is that climate change is anticipated to result in small winter heating savings in the UK, offset by increased use of air conditioning by 5-20% (Graves and Phillipson, 2000). Furthermore, the analysis is based on one climate change scenario – thus there remains a degree of uncertainty – and takes no account of potential synergies with mitigation strategies. These arguments have been made very convincingly in a comprehensive review of Graves and Phillipson's report by Lowe (2001).

Another tactical design implication of climate change scenarios relates to the potential for natural ventilation. In response to the anticipated increase in mosquitoes and other insects in some areas – in the UK this is predicted to include some southern areas – windows may be opened less when ventilation is most needed (i.e. warm summers). The use of insect screens is a simple adaptive tactic to overcoming such conflicts, although one would expect an increase in resistance to airflow and thus a reduction in the effectiveness of anticipated natural ventilation. Perhaps more importantly, the apparently inexorable rise in car use (partly as a result of climate change creating less comfortable external conditions) and the associated air and noise pollution (despite improving engine performance), will continue to constrain the potential for simple ventilation through openable windows. The consequence is likely to be an increasing the uptake of air conditioning systems – both in buildings as well as in cars – unless (or until) adaptation to climate change becomes a mainstream concern in building design.

It is evident that further research is needed to understand, develop and implement adaptive strategies and tactics. There are numerous research programmes in place which address climate change in the context of the built environment, some of which are outlined below.

Current Research

The research work being supported by the Tyndall Centre clearly represents a hugely valuable body of work, and is particularly strong on large-scale interdisciplinary activities. However, to date, only a small fraction of projects relate directly to buildings, and almost all have been in the Theme 2 (with mitigation as its primary remit). The focus on mitigation is perhaps understandable in the context of the UK where 50% of emissions are associated with buildings. However, the challenge of how the built environment – with buildings designed to last at least well into the current timescale of climate change scenarios, and cities being near-permanent – can adapt to climate change is as yet not extensively addressed within this consortium.

It is evident that despite the value of such projects, their emphasis is on mitigation - building adaptation, whether in new build or refurbishment, is not emerging as a primary activity in the buildings sector.

At a European level too (in terms of the EC funded research programmes) there has to date been a division between broad climate change research and the environmental performance of buildings and cities. Again, the emphasis of building research has been on renewable energy and efficiency with the aim of minimising carbon emissions, whereas climate change research tends to focus on scientific and policy issues. The forthcoming 6th research framework programme has recently been launched and it does not look hopeful that climate change and building design – not to mention adaptation – can easily be brought together. (Further information on the 6th Framework Programme is available on www.cordis.lu)

A number of other agencies have promoted and funded research. An example in the UK is the Construction Research and Innovation Strategy Panel (CRISP) which have commissioned a number of reports related to climate change (www.crisp-uk.org.uk). Although the emphasis is not to support fundamental research but rather to distil and provide an overview of existing knowledge and make it available to the construction industry. As a result, such work is very valuable, particularly at identifying gaps, needs and strategies.

In the context of this paper and its aims, two key areas for further research emerge: the performance of existing buildings and defining adaptive potential (both in terms of the adaptive building, but also the closely related issue of the adaptive occupant). Having provided a cursory overview of research, the second part of this project report will focus on these two aspects in more detail.

Existing buildings

A significant gap in the discussions regarding climate change adaptation relates to the existing building stock, which is currently one of the single biggest sources of CO_2 emissions in the world (50% in the UK, 41% in the EU and 36% in the USA). Even when considering the issue of mitigation alone the role of the existing stock is central – particularly for buildings that pre-date fuel efficiency regulations and are thus very inefficient by current standards. Unless either the rate of building replacement is radically increased or sustainable refurbishment is implemented extensively, building design and construction appears to have little role to play in tackling global warming. Unlike mitigation – where the alternatives to reducing energy demand through design and construction can be in part addressed by supply side – for adaptation there is no choice but to address climate change through design. This is the case for both new build but even more importantly in refurbishment.

Approximately three quarters of the building stock in the UK is pre-1980s, much of which may be vulnerable to changes in structural and environmental forces due to climate change. This raises the question to what extent and in which terms modern (say, since 1980) buildings might be more or less vulnerable to climate change. Clearly, in terms of energy use, older buildings designed to older regulations will perform poorly by modern standards. It may also be that older structural regulations and wisdom is outdated and of a lower standard, suggesting that new buildings are less vulnerable to climate change – at least at the level of structure and construction detailing. However, this may not be the case in terms of planning as it would appear that much relatively new development has taken place on flood plains. Perhaps more importantly, older buildings will have been subjected to corrosion, damp rot, infestation, etc., and are thus more likely to be vulnerable to changes in climatic conditions.

However, in environmental terms many older buildings – typified by 18th and 19th century buildings – have characteristics that make them potentially more resilient and adaptive, including: modest plan depths, high thermal mass, tall ceilings, narrow windows, etc. Clearly one could develop a typological classification as a function of use, form, construction and/or age, and assess each type in terms of environmental resilience or adaptive opportunities. This approach has already been, and continues to be, applied in the context of structural risk, where the vulnerability of a property (to wind damage, flooding, etc.) is mapped as a function of building type and location (Spence and Brown, 1998; Baxter et al., 2001 a and b). Clearly, such an approach is worth further research with respect to mapping the potential or priorities for adapting to climate change of existing buildings.

It is evident that existing buildings are a particular concern. However, it is worth noting that in the context of climate change scenarios – typically spanning this century – new buildings will have an increasingly important role as older buildings are replaced. Within the next 50 years one might expect half the existing buildings to have been replaced (assuming a replacement rate of 1% to 1.5% annually). Climate change is a gradual process that is anticipated to become increasingly noticeable over the next 50 to 100 years. Thus in the timeframe of climate change predictions new buildings will accumulatively account for an equal or greater fraction of the building stock (though probably not the energy demand or insurance risk) and should be designed to enable adaptation to climate change. However, all buildings within their lifetime will undergo shorter refurbishment cycles, during which time adaptive improvements can be implemented. These cycles range typically as follows (Mulligan and Steemers, 2002):

- Redecorate: <5 years for redecoration (which may include improved finishes or making-good superficial damage)
- Refit: 7-15 years for systems and appliances (which could enable improved controls and environmental performance)
- Refurbish: 15-50 years for non-structural building fabric (roof, wall cladding, windows, joinery and insulation could be upgraded to higher tolerance level)
- Rebuild: >50 years for rebuilding of structural elements (to higher specifications e.g. wind loading, raised floors to avoid flooding, etc.)

The stage in the refurbishment cycle that a building is in will have an impact on whether it is able to be adapted to the rate of climate change. For example, as summer peak temperatures increase and become more frequent, a building can exploit a ‘refit’ or ‘refurbishment’ cycle to implement adaptive responses (e.g. improved shading devices, controls, efficient lighting to limit internal gains, improved ventilation). If a building is not due for such a cycle, exceptional costs may be incurred (e.g. portable air conditioning units), or the building could be perceived as increasingly obsolete. Matching the rate of climate change with the implementation time of appropriate adaptive strategies - that also integrate mitigation - is a fruitful area for further research. Such an approach has been explored in a recent CRISP report (Lowe, 2001).

It would thus seem possible that existing buildings can progressively adapt to climate change, with greater or lesser ease (and cost) according to the building type. A review of generic building typologies that have survived over longer periods (centuries) reveals characteristics that make them particularly suitable to adaptation (though clearly some buildings, such as those of historic value, are conserved for cultural reasons). Following the principle of ‘survival of the fittest’ it follows that generic buildings that have survived over centuries – including periods of climatic extremes such as infamous storms, droughts and floods – and are still currently in use, would seem to possess valuable attributes. Without going into any detail here, such attributes will include design decisions related to choice of site, building form, materials, construction techniques as well as user interaction (occupancy type, maintenance, repair, etc.). A historical review would begin to highlight such adaptive attributes.

Adaptive potential

The adaptable building

What becomes evident from looking at the existing stock and refurbishment cycles is that there is a potential for buildings to adapt to climate change incrementally over time. Understanding this 'adaptive potential' of existing buildings by studying their refurbishment history will provide valuable insights – not only for the existing buildings, but also for new buildings. There will buildings that have the potential to adapt physically, through intervention in to the building fabric or services over time – this outlined below. However, first it is worth noting that there are 'hidden' design strategies that foster the potential of individual adaptive behaviour.

There is an increasing interest in adaptable buildings, primarily driven by market forces (i.e. a flexible building is seen as having greater market value than a bespoke design). However, to date the emphasis has been on perceived flexibility in planning terms, conforming to simple preconceptions (e.g. in the commercial sector: full air conditioning, clear floor plates, moveable partitions, etc.). The work of DEGW (Duffy, 1997) and others has responded more directly to changes in working patterns and technologies, such as tele-working, creating a number of working scenarios and plan arrangements. Although such developments are not primarily motivated by concerns for climate change, it is interesting to note that there is a parallel in the context of adaptability. For instance, a spatially flexible arrangement offers the occupant some degree of choice over where to sit, and this choice can be influenced by the environment (light, breeze, noise, etc.). It is well known that increasing an occupants' degree of control over their environment increases their comfort and perceived productivity. This increased tolerance, particularly when integrated with other building fabric design strategies, can enhance the adaptive potential of a building to climate change. Environmental diversity is thus seen as a possible advantage, as compared to the provision of a narrowly determined environment that is often beyond the occupant's direct control. This point is elaborated below under 'The adaptive occupant'.

A direct research avenue concerning adaptive potential and its implications for building design, use and refurbishment is presented in recent work by Fernandez (2002). Referred to as 'diversified lifetime' of buildings, the concept is to propose that buildings may be designed to be constituted from a number of different parts with different design lives (Fig. 1). Uncertainty about a building's long-term use is reflected in reduced permanence or investment in its construction or components, and an inherent potential to adapt spatially and functionally to change. Thus the aim is to anticipate changing market, business or – in this instance – climate conditions (or even a combination of all three). Only where there is certainty is it worth investing for the longer term. In environmental terms this may involve investing in a building services strategy for the key long-term part of the building that will be able to cope with predicted climate change. Conversely, short-term components can be designed for minimal climatic change and maximum flexibility.

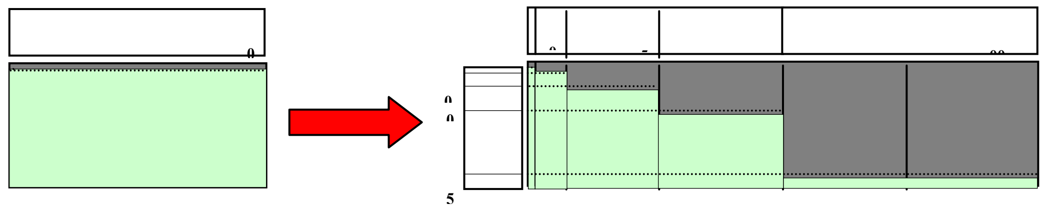

Fig. 1 – Homogeneous (A) and heterogeneous lifetime diagram (Fernandez, 2002). The diagram illustrates the principle of diversified lifetime using a simple graph of building areas in percentage of the total (vertical axis) and time (horizontal axis). The rectangle on the left is a building in which 100% of its space has been designated a 50 year lifespan. To the right of the arrow the building has been apportioned varying lifetimes by distinct areas,.

Diversified lifetimes depend on a number of technologies to enable the necessary changes required to provide flexibility. Fernandez (2002) describes these as follows: "Design for disassembly, separation technologies, materials reclamation and recycling, loose-fit detailing, lightly-treading foundations and other technologies, will all contribute to a suite of technologies necessary for building volumes to change over time."

The notion of diversified lifetime is a particularly interesting one in terms of infrastructural adaptation to climate change. Although not explicitly related to climate change, Fernandez has identified possible trajectories of generic and case study buildings. The purpose of the concept is to open up the range of trajectories available in response to anticipated or unforeseen future change, and to design in a way so as to maximise future diversity. It would in principle be possible to define the 'envelop' of these trajectories in terms of their response to climate change in order to define the adaptive potential of a design. Criteria which minimise adverse impacts, such as resorting to air conditioning, can be used to further exclude options in order to identify design opportunities that both mitigate and adapt to climate change.

Clearly this speculative outline warrants further research and development. Aspects of this research are currently being undertaken via a joint Cambridge University (UK) and MIT (USA) project in collaboration with BP. An important subset of the concept relates to the design of building services, which are discussed below with a particular reference to occupant control and behaviour.

Building services

There is an abundance of evidence to suggest that we as occupants, at least in cool and temperate climates, have not adapted well to the increasing use of air conditioning since its invention by Willis Carrier some eighty years ago. It has been argued that the long-term evolutionary responses to our environment have fine-tuned our senses to be stimulated by the natural environment and its vagaries

(Baker, 2000). We sense our thermal context through subtle or invigorating changes in conditions – a breeze through an open window, the radiant heat from a fireplace, etc. We see by sensing change in light and dark. Every sense suggests that we do not enjoy an excessively controlled, stable environment. However, since the invention of air conditioning a certain level of expectation and association with status has crept in to some parts of society. This is particularly so where the climate regularly swings above upper comfort conditions.

An extreme example of the controlled environment is sensory deprivation. Our buildings, since the advent of air conditioning, have become increasingly closely controlled and deep plan, whilst consuming significantly greater amounts of energy. Studies have shown that on average, despite wide variations, air conditioned offices consume twice as much energy as naturally ventilated ones (Baker and Steemers, 2000), though it is clear that new innovations and technologies can in theory provide more energy efficient solutions.

Some implications of close mechanical control are now becoming clear, through anecdotal evidence of absenteeism, sick building syndrome and reduced productivity (Bordass et al., 1995). Furthermore, poor performance, particularly in terms of indoor air quality, is associated with inappropriate and badly commissioned and maintained environmental building systems. The mismatch between user and system, and between building design and system, increases the risks of poor performance in systems that are insufficiently robust. Thus again the notion of robustness, as opposed to optimum performance, is raised as a key concern.

The move towards centralised control with Building Energy Management Systems (BEMS) risks leaving the occupants powerless over their own environment. However, increasingly sensors and controls enable a more localised occupant interaction over the systems (e.g. light dimming in favour of switching, but with occupant override; localised ventilation equivalent to task lighting, etc.).

When intelligent systems start to respond to, and enable, occupant interaction with the building fabric a new potential might emerge. At a simple level, the act of opening a window should turn off heating or cooling locally. The result is a more dynamic mixed-mode (both spatially and temporally) operation of buildings – one where the building serves the occupant. The building can still revert to an 'optimum' state (in energy and comfort terms) after a given time period or in response to occupancy sensors. An answer would appear to lie in combining robust climatic design (e.g. high mass, moderate glazing, etc.), with intelligent controls and components, in order to maximise adaptability. Although this would not totally eliminate the potential conflicts between occupant behaviour and 'optimum' performance, it offers an integrated approach to resolving occupant well-being and environmental impact. Such flexibility and adaptability gives the control back to the occupant and enables him or her to respond to climate change through their interactions and relationship with the building and its systems. Understanding what these adaptive opportunities are and how they relate to the occupant is discussed below.

The adaptive occupant

Numerous sources and examples can be quoted that demonstrate the way in which vernacular and even primitive architecture has responded to the climate. Perhaps the most revealing examples of this relationship between architecture and climate can be observed in the architecture of extreme climates. Here both the adaptation of design and the occupants demonstrate a number of possibilities that are relevant to the challenges presented by climate change in a more moderate climate. The question raised is thus: can adaptive opportunities increase the range of conditions for comfort in line with climate change without the need to resort to air conditioning? First, we need to briefly outline these adaptive opportunities.

Recent research by Merghani (2001) highlights the thermal comfort related experiences of living in traditional courtyard houses in a hot-arid climate. The work demonstrates that occupant behavioural patterns – notably spatial freedom - correlate closely to improving occupant comfort. Spaces offering improved comfort conditions were consistently used, and even locations within spaces which were cooler than average room temperatures were unconsciously sought out (Fig. 2).

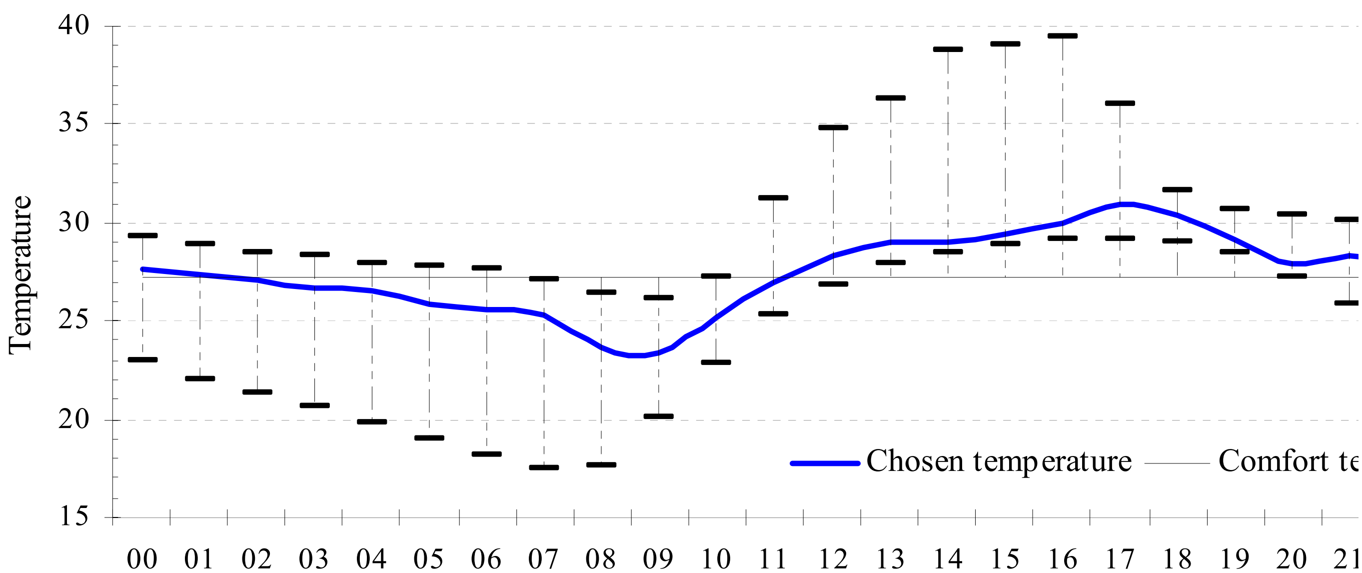

Figure 2 – The graph shows hourly temperature ranges available in the building and the temperature of the location chosen by the occupant. This data demonstrates that given spatial options, the user will tend to adapt to either low or high temperatures by choosing appropriate comfort conditions (Merghani, 2001).

The design of the traditional courtyard house offers a range of spatial conditions, varying from internal rooms to verandas and external courtyards, with various thermal characteristics (from slow to rapid response and from inside to outside). The design could thus be described as offering large spatial adaptive potential to the user, enabling him or her to maintain relative comfort in an extreme climate.

On the same basis as the spatial variables, a number of personable adaptive opportunities were also assessed. These include: changes to dress, activity level, posture, hot/cold drinks, showers, sprinkling the courtyard and use of fans. What is perhaps most significant is not so much the individual beneficial effect of each action but the consequence of combining these opportunities (Fig. 3). Thus the range and combination of adaptive opportunities available to the occupant will significantly improve their comfort. What is critical is that these opportunities should be made available through design, where possible, to maximise the adaptive potential.

	base case	**adapted case**
air temp	30.5	28.0
rad temp	30.5	28.0
air speed	0.1	0.2
clo	0.5	0.4
met	1.2	1.1
PPD	**68.4%**	**17.5%**

Figure 3 – A theoretical comparison of the impact of small adaptations, made in spatial terms and by adjusting clothing and metabolic rate only, on the Predicted Percentage Dissatisfied (PPD). The result shows that the adapted case has the potential to be significantly more satisfactory in thermal terms than the base case, which assumes average temperatures and air movement (rather than spatially improved ones) (Baker and Standeven, 1996).

Even more critical is that the adaptive potential needs to be recognised and framed in such a way so as to be able to assess adaptive design strategies. At the simplest level, there is a need to replace the simplistic temperature criteria for comfort with more real and sophisticated indices of comfort. This is not a trivial challenge, and one that needs further work. It is evident that the change from prescribing air temperature criteria from 20 degrees C plus or minus 1 degrees C, to between 18 and 27 degrees, reduces the reliance on systems and increases the climatic range within which these targets can be achieved. One would expect that developing adaptive comfort criteria beyond simple air temperature limits would provide further opportunities to accommodate climate change.

Adaptation, both through building design and occupant interaction, would thus appear to be a critical and feasible strategy to coping with climate change whilst limiting energy use. However, assessing a building's – and the occupant's – adaptive potential needs further research. Evidence suggests that there are broadly three categories:

1. Spatial: the ability to move and adjust workstation position (e.g. hot-desking) and location (e.g. home working), the provision of a variety of transitional spaces (quiet courtyards, sunspaces, cellular and open plan areas, etc.)

2. Personal: the ability to adapt clothing, change posture, take drinks, etc. (e.g. the provision of drinks, dress policy, etc.)
3. Control: the ability to interact with the building fabric and systems, and create a connection with the external climate (e.g. view, shutters, air through a window opening to a quiet courtyard).

It is the opinion of the author that the provision of adaptive opportunities - whether through building design, systems controls or personal variables - would be preferred by occupants to a potentially more energy intensive closely controlled environment. This is based not only on research interests but also significantly on personal experience. Although most environments are not designed to maximise adaptive opportunities, many of the most enjoyable environments provide environmental diversity, choice and stimulation. For example, sunbathing on the beach – which should according to current comfort theory be utterly uncomfortable – has a number of built-in adaptive opportunities making it, for some at least, the epitome of a pleasant environment. These include the choice to dive in to cool water, the provision of parasols for shade, ice-cream consumption to reduce the core body temperature and a low metabolic rate, not to mention the association of this environment with relaxation.

Another more prosaic example is an office in a 19th Century building with high ceilings, tall openable windows and exposed thermal mass. I am lucky enough to work in such a building in a room where I have views out to trees, can open windows for ventilation, open or close doors for acoustic privacy or cross ventilation, put on or take off a jumper, close or open blinds, switch lights and heating on or off, leave the room for a hot or cold drink in another space, leave the building to spend time outdoors to sit in a garden or go to a cafe, etc. These may sound like trivial factors, but cumulatively they make a significant contribution to my perception, as well as quantification, of comfort conditions and enable me to adapt my environment to cover a wide range of climatic conditions.

By contrast, my previous work environment was a 1970s air-conditioned office. It had views out to a sterile courtyard, no openable windows, no blinds, poor controls over the air conditioning, low suspended ceilings yet large areas of glazing, a basement café in the building reached via long corridors, and so on. Despite lighting controls and the opportunity to adapt personal variables, the environment offered very little diversity or adaptive opportunities. Thus any additional stresses that may result from climate change - such as increased temperatures, solar gain, glare - would be difficult to respond to in the short term except by increasing energy use for cooling and mechanical ventilation.

There may be examples of air-conditioned buildings that provide a perfectly adequate environment to counteract the above anecdotal descriptions. I am not aware of many that enable, let alone encourage, the occupant to interact with the building. There are also examples of low energy and environmentally responsible buildings which exploit BEMS to control conditions with limited occupant intervention. In the context of climate change, neither would arguably seem to offer adequate adaptation potential. As average temperatures rise, the former will use more energy for cooling and the latter is likely to increasingly drift outside comfort limits.

Conclusions

Although buildings are often not at the forefront of climate scientists' minds when assessing climate change, the fact that we spend a large proportion of our time in buildings, that they house our economic, social and cultural life, and that they are a primary contributor to climate change, suggests that they are a central issue.

It is clear that adaptation to climate change presents one of the most pressing building research challenges, although there are still numerous issues of mitigation that require much work. Current research and information dissemination tends to focus on mitigation and structural strategies. In this paper, adaptation has been taken to refer to the physical building in terms of its environmental response to climate change, but also includes an awareness of occupant behaviour. Ultimately, buildings are there to serve the occupants, so occupant perception, behaviour and interactions are an important part of the adaptation equation. The concept of the 'adaptive potential' of buildings and occupants in response to climate change is one that has been shown to warrant further exploration, particularly in terms of developing generic, demonstrable and measurable techniques.

Though not the focus of this paper, the structural effects of climate change on buildings are relatively well developed and arguably more predictable on the basis of the climate scenarios. The environmental performance characteristics – reliant on the dynamics of building, systems and occupant interactions - are less clear, but are a largely untapped opportunity to respond to climate change. This notion can be extended from individual building design to urban design, and the larger scale interactions with transport and the urban microclimate. This requires cross-disciplinary activities between climate, building and transport researchers, and is in fact the focus of one follow-on proposal in the 3rd Phase of Tyndall projects.

This paper has primarily highlighted the potential roles of design and the occupant with respect to environmental performance in the context of climate change, and has raised a number of questions. It is expected that it will – and to a certain extent already has – contribute to the development and undertaking of future research avenues.

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The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

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