School of Architecture, Construction and Planning

CLIMATE, BUILDINGS AND OCCUPANT EXPECTATIONS: A Comfort-Based Model for the Design and Operation of Office Buildings in Hot Humid Conditions

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Abstract

Office buildings in hot humid Singapore appear to be designed for stable and uniform indoor conditions. It is proposed in this thesis that this is unnecessary, as occupant comfort expectations do not warrant it and energy is wasted as a result. A comfort-based approach to design is advocated, as a means of balancing user needs with the objective of energy conservation.

This issue of how perception of comfort is linked with indoor stability emerged from the question, 'why do office buildings, despite Bioclimatic prescriptions for hot humid conditions, continue to be predominantly climate rejecting and active-run?' The literature was found to be polarised by arguments for architectural solutions that are climatically responsive and present lower energy costs, and those for engineered solutions that deliver greater, more consistent comfort, albeit through reliance on electro-mechanical systems.

It is argued that comprehending the gaps in the literature, and between theory and application, requires a better understanding of occupant comfort. This would be an *inside-out* view of comfort and climate, predicated on how the occupant is affected by the building and the cognitive nature of comfort itself.

Relying on a sample of office buildings, the thesis set out to establish the following:

- Prevalence of the climate-based approach, specifically Yeang's Bioclimatic Model
- Prevalence of uniformity and stability of the indoor environment
- Occupant perception of indoor comfort, both thermal and visual, particularly with regard to variability of ambient conditions
- Occupant perception of various operational modes: passive, mixed and active.

These goals were addressed through observations of form, envelope and layout, occupant surveys and the monitoring of buildings in passive and active modes.

It was found that the Bioclimatic approach is non-existent in the context of the Singapore office building. In the case of two Bioclimatic buildings in Malaysia, the Model is not consistently applied. This disparity appears partly due to conflicting priorities, in particular style, cost and client pressures, and partly due to assumptions about occupant comfort.

The Singapore office building was found to be predominantly active-run, operating within a narrow bandwidth of temperatures across most spaces. Occupant perception of variability outside the primary workplace, however, is one of acceptance, even preference. It was found through analysis of user feedback that the office building, on the basis of comfort expectations, could be divided into three activity zones: Work, Support and Transit.

This 3-tiered structure was subsequently tested through a large-scale, longitudinal survey carried out across three spaces, each representing an activity zone, within a single building. The survey was accompanied by adjustments to the building's temperature settings to test the limits of acceptance in each zone. Findings from this exercise support the notion of a three-zoned office building, in which thermal conditions for each zone could be varied without affecting comfort. Energy figures that were monitored before and after the resetting showed drops of 7.1% in chiller consumption and 2.9% in overall consumption.

These findings led to a comfort-based, tri-modal proposal for office buildings in hot humid conditions, defined as the **Psychoclimatic Model** for its basis in comfort expectations and the interaction between climate, building and the occupant.

The implications of the thesis outcome on regulatory control in Singapore and thermal comfort theory are discussed. Recommendations are made for future research into other building types and national context, plus a parametric study into the full energy-saving potential of the Psychoclimatic Model.

Acknowledgements

To any budding Ph.D. candidate who picks up a copy of this thesis in the hope that it might in some small way point the way forward, let me say that the first step is to surround yourself with people who know more than you, who care about the issues, and in equal measure, care about the outcome of your endeavour. I have been very fortunate in all three regards.

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List of Abbreviations

AC - Air conditioning
Air - Air movement
BCA - Building Construction Authority
CSC -Civil Service College
DL - Daylight
EL - Electrical light
EL+DL - Electrical plus daylight
EST - Envelope surface temperature
ET* - Effective Temperature
ETTV - Envelope thermal transmittance value
FA - Fan-assisted ventilation
IAT - Indoor air temperature
MES - Menara Mesiniaga
MDS - Multidimensional Scaling Analysis
MND - Ministry of National Development Building
MRT - Indoor mean radiant temperature
MSA - Multiple Scalogram Analysis
MSP - Multiple Sorting Procedure
NV - Natural ventilation
OTTV - Overall thermal transmittance value
Out DBT - Outdoor dry bulb temperature
OutMRT - Outdoor mean radiant temperature
PMV - Predicted Mean Vote
RevH - Revenue House
RH - Relative humidity
SET* - Standard Effective Temperature
T_N - Neutral Temperature
T_{Opt} - Optimal Temperature
TT_F - Thermal transmittance of fenestration
TT_W - Thermal transmittance of wall
UMNO - Menara UMNO
URA - URA Centre
WWR - Window-to-wall ratio

Chapter 1. Introduction

1.0. Overview of Thesis

This thesis seeks to identify design solutions for office buildings in hot humid conditions with a view towards balancing occupant comfort needs with energy considerations. It does this by examining the way in which a building's envelope and electro-mechanical devices interact within the context of the climate, thereby creating indoor conditions for comfort. Understanding comfort expectations is seen here as the key to developing prescriptions for future designs.

The central contention of the thesis is that a consistent, uniform indoor environment is costly in energy terms and not warranted in terms of occupant needs. In seeking out new prescriptions, this present thesis looks to past studies and theories that have advocated a low-energy, non-uniform building, typically by way of establishing a relationship with its contextual climate.

Of these, the Bioclimatic approach by Yeang (1996) is scrutinised as it embodies the dual objectives of delivering occupant comfort and lowering energy consumption. This has been translated into a set of design guidelines described as the Bioclimatic Model (Yeang, 1994), tailored specifically for tall buildings in hot humid conditions, similar to many of the office buildings found in Singapore.

In adopting an approach that juxtaposes a theoretical framework against actual buildings, the research question becomes one of asking why, in the light of all that is promised by theory, are climatic principles rarely seen in action. The thesis begins with a reflection on the gap that exists between that which is advocated as a climate-responsive ideal and what is actually built and operated.

It is suggested that ignorance on the cognitive nature of comfort limits how far a theoretical ideal can be advanced. A key objective of the present thesis is to address the building occupant, both directly through comfort surveys and indirectly through the design assumptions made about his/her comfort needs. A deeper understanding of comfort, specifically comfort expectations, can provide insights into how future buildings might be designed to operate at lower energy costs and yet stay within the parameters of acceptability.

The research question will be expanded upon in Section 1.1 with a discussion on the three key tenets of the Bioclimatic Model: climate, comfort and energy consumption. It is argued here that the gap between theory and practice is underpinned by gaps in how these terms are defined and prioritised, and by whom.

1.1. Delineating the Problem

The issues of climate, comfort and energy consumption are discussed here primarily in the context of Singapore, but often extend to publications and opinions expressed on the architecture of South-east Asia, which broadly falls within the same hot humid zone, with some seasonal variations (de Blij & Muller, 1993). It is argued in the present section that the deliberation of each of these issues represents a minor 'gap' of understanding in itself. The question of whether the Bioclimatic approach makes an impact on the design of buildings will therefore depend on how questions of climate, comfort and energy consumption are delineated by the different groups that make up the force of critical opinion. This exploration in Section 1.1.1 is followed by an examination of why the disparity of understanding is significant to theory and in practice (see Section 1.1.2).

1.1.1. Identifying the Gaps

Climate and its implicit role in the making of buildings constitute the first gap of understanding. Nicol and Humphreys (2001), in speaking of thermal comfort, suggest that climate is *"the overarching influence on culture and thermal attitudes of any group of people and the design of the buildings they inhabit"* (p. 47). To this suggestion it could be added that in whichever position adopted on climate, even its exclusion, a designer makes an implicit statement that reflects attitudes towards climate and its desirability as an influence on architectural design.

Within the camp that views climate favorably, there appear to be two schools of thought. Khosla[1] (1997) noted a sharp divergence of opinion on the perceived role of climate as discussed in recent books on architectural design for the hot humid tropics. At one end of the spectrum, climate is seen as form-giver and maker of identity and experience (Tan, 1996). At the other extreme, climate is a condition that shapes the performance of buildings in quantifiable, verifiable terms (Yeang, 1996). The debate seems polarised by concerns with style and performance (Kishnani, 1999), a 'gap' of definition, whereby climate in the hands of different theorists serves different ends.

It is significant that *Tropical Architecture*, as a style, is most commonly illustrated with low-rise, residential, resort and/or institutional buildings (Tan, 1994; Tan, 1996). Rarely does the 'stylist' present examples of high-rise homes and offices, such as is the day-to-day reality for a vast majority of people living in Singapore and other urban centres in Southeast Asia (Kishnani, 1999).

Advocates for performance, represented by Yeang and his projects in Malaysia, do better on this account with some examples of tall buildings. From the media's general enthusiasm for these buildings (Pearson, 1993; Powell, 1998), it remains unclear if they actually achieve what they set out to do vis-à-vis the climate. There are no post-occupancy studies that conclusively show them to function effectively in hot humid conditions.

The question of occupant comfort, the second tenet of Bioclimatic Model, is signified by the absence of *user* from the discourse of architecture. This is a gap of omission whereby the issue of building performance appears to preclude the parameter of occupant comfort needs from its deliberation. Typically, in media coverage of buildings in Singapore, the popular press celebrates energy efficiency, building intelligence and lifestyle (Cooke, 2000; Leong, 2000; Quek, 2000; Sim, 2001). In the architectural media, including books and design magazines, the concerns appear to revolve primarily around questions of style, history, innovativeness of form and appearance (Powell, 2000; Tan, 1997). Rarely, in either domain or discourse, is the occupant discussed in depth. In a recent debate on the role of architects and architecture in Singapore, it was suggested that a key problem facing the profession was that non-architects, who are also developers and

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[1] Jay Khosla is the nom de plume used by the thesis author since 1994, when writing about architecture and design for the Singapore press.

building users, did not understand what architects do through the activity of design (Choo, Koon, Sng, & Hoo, 2000). No one at this gathering argued that architects might also fail to understand the building's users and their needs.

Energy conservation constitutes the third and final 'gap'. On the surface there appears to be a broad consensus amongst various parties associated with building regulation, design and operation, each maintaining that lower consumption is desirable (IACEE, 2000; Koo, 2001). The raison d'être in popular and architectural media, however, shows a divergence on how this might be achieved, and more importantly, why lower consumption is a priority.

Designers typically make the case that energy conservation is an ethical issue, one of safeguarding the environment (Daniels, 1997; Yeang, 1999). Energy saving features, as with Yeang's office buildings, often require occupant involvement by way of regulating natural air or light flow and distribution (Jones & Yeang, 1999) on the assumption that the building's users share the designer's ethical concerns.

The media and authorities in Singapore discuss energy primarily in terms of improved national economic competitiveness and lesser vulnerability to oil price fluctuations (Koo, 2001; Nathan, 2000). Green issues, such as recycling and carbon dioxide emissions, are mentioned by both parties, with the qualification that it is not an ideology that necessarily guides everyday choices (Kaur, 2001b; Nathan, 2001). It has been explicitly stated by the Singapore authorities that energy conservation would not be at the expense of the country's economic competitiveness in the global market (IACEE, 2000).

This then is a 'gap' of approach, a divergence of means despite seemingly similar objectives. Coldicutt (1992) argued that this could imply a divergence of ends. The approach that each party takes on how on objective is to be reached can affect the probability of its outcome, particularly if there are competing priorities. Not surprisingly the broad approach to energy conservation in Singapore veers towards improving building intelligence systems and system efficiencies. Existing statutory controls primarily target envelope design and equipment efficacy (Koo, 2001), as opposed to encouraging occupant behaviour modification that are implicit in the design solutions put forward by architects.

In the final analysis, these gaps in climate, comfort and consumption are most evident in what is seen[2] of the Singapore skyline and its workplace, or rather what is not seen by way of climatic response. Most office buildings appear to be wholly air-conditioned and electrically lighted, even through daylight hours. It is perhaps a consequence of this reliance on electro-mechanical systems that occupants are observed to don jackets to keep themselves warm, whilst blinds are kept shut for most of the day. By and large, there are few examples of office buildings with external sunshades and setbacks for windows; the majority appear to be tightly sealed and impermeable to outdoor conditions.

1.1.2. Understanding the Significance of Disparity

A question that follows from the research question is, 'why do these disparities matter?' After all, energy conservation measures, however piecemeal, continue to be reviewed by the Singapore government (Koo, 2001; Tan, 2000). A Singapore building was even awarded the Association of South East Asian Nation's (ASEAN) 'Most Energy-Efficient Building' title in the Year 2000 (Cooke, 2000). If there is workplace discomfort, occupants seem to adapt to the condition or bear with it. More to the point, there is no known survey that suggests this is a significant issue in the Singapore workplace.

To address this question, the issues must be viewed at the theoretical and the pragmatic levels, in the context of Singapore and beyond. Coldicutt and Williamson (1992) addressed the disparity between theory and practice as follows:

> *A mismatch between research concepts and narrative concepts can distort and confuse problem definition and analysis... [this] confusion between narrative definition and theoretical definition exacerbates the problem.*
>
> Coldicutt and Williamson (1992, p. 831)

In speaking of the 'narrative', they refer to knowledge on the basis of which everyday actions take place, a pragmatic approach to problem solving. To paraphrase their concern, a failure to reconcile the theoretical and the pragmatic can ultimately worsen the situation.

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[2] It should be noted that these observations are largely anecdotal. The thesis will begin by gathering data that seeks to substantiate them.

Others argue that this non-reconciliation may be akin to surrender to the status quo, or, more to the point, a failure to exploit the full potential of a situation. Todesco (1996) showed that a failure to employ passive principles diminishes possible energy savings. Improved system efficiencies and operations achieve some savings, but the cumulative effect of an integrated design approach, of having passive design theory alongside more practical engineering-based measures, yields much better outcomes than either on its own.

Banham's (1984) grievance with the status quo was that architects, by ignoring the role of the building shell in the making of comfort and delegating it to the building's systems, abdicate their role in the crafting of human shelter. This diminishes the value and meaning of architecture as a whole.

At the pragmatic end of the argument, the equation is one of cost and impact. The office building is one of the largest consumers of energy in Singapore (Lee, 2001; Nathan, 1999) with the largest proportion of energy being used with the making of thermal comfort through air conditioning (Kaur, 2001a). If Singapore is in any way representative of the present and/or future aspirations of people living in hot humid regions, numbered at 75% of the world's population (Barry & Chorley, 1992), any measures of improving comfort and reducing consumption here is likely to have an impact on the global scale

1.2. Defining an Approach

In seeking out an approach addressing the research question, the present section briefly examines the design process, with regard to a building's response to climate, comfort and energy. Watson (1984) spoke of the three modes of analysis that designers employ at the design stage: Scientific, Aesthetic and Behavioural.

In the Scientific mode, the building is seen as a 'product' of technology and cost parameters. In the aesthetic mode, it is regarded as an 'art object', representing philosophy, history and theory. In the Behavioural mode, the building becomes a 'social tool' with the occupant as the focus. Given the manner in which buildings are discussed in Singapore, it could be argued that the first two are represented; the third is conspicuously absent.

Coldicutt (1992) referred to the absent user as the 'passive subject' for whom, and on whose behalf, decisions are made. This user tends to be neglected, sometimes without representation during the design process. It should be qualified, however, that this is not always possible in the participatory sense. A building's user may not be known at the design stage, especially for projects in which a designer deals with a developer as client. In this scenario, Coldicutt suggests, the developer, designers and authorities become 'active subjects' undertaking to represent the passive subjects through their knowledge and/or interests. This by-proxy representation is often guided by the frameworks and norms that 'instruct' decision-makers on what is a desirable outcome from the viewpoint of a building's occupants. These may be thermal comfort guidelines or theories regarding the interaction between climate and buildings in the making of comfort. Theory, in the guise of models or norms, can therefore be a representation of user interests.

As mentioned in Section 1.0, the present thesis addresses the absent user, first, through the models and assumptions that represent him/her, and then through direct surveys of occupants of the selected buildings.

The research approach is premised on the notion that the Behavioural Mode, the missing voice of occupants, is at the centre of the gap that represents the research question. This is not to say that the building's users are under-represented or entirely passive. Indeed, in the post-completion, operative stage of a building's life, they intervene on a daily basis in the way a building is managed and its attributes altered. The present study seeks out and notes these interventions on the basis that they reflect a weakness of theoretical and/or narrative knowledge.

In extrapolating this approach into a research method, data collection is guided by a simple framework: compare the theoretical ideal with actual buildings. Representing theory is the Bioclimatic Model. The buildings selected are representative of office buildings commonly seen on the Singapore skyline.

It is predicted that there will be no outright examples of the Bioclimatic or non-climatic building. Some prescriptions of the Bioclimatic Model, such as the use of natural light and external shading, are principles of passive design that are common knowledge to many designers, who may require no theoretical basis to act on them. Most buildings, therefore, are likely to address passive principles in some manner or to a degree. To address this complexity and level of nuance, the thesis will examine a group of buildings in both passive and active modes[3], for whatever features or systems they are fitted with, to which occupants are exposed.

The precise criteria for selecting case studies is elaborated in Chapter 3 in which this approach is translated from philosophy to plan-of-action. Before that, however, the Bioclimatic Model needs some clarification as the chosen framework. Figures 1.1 and 1.2 show its evolution, from inception by Olgyay (1963) to a prescriptive Model by Yeang (1994). Olgyay defined the primary role of building as that of providing human shelter, moderating and tapping climate for the purpose of creating occupant comfort.

Figure 1.1. Bioclimatic approach (Olgyay, 1963)

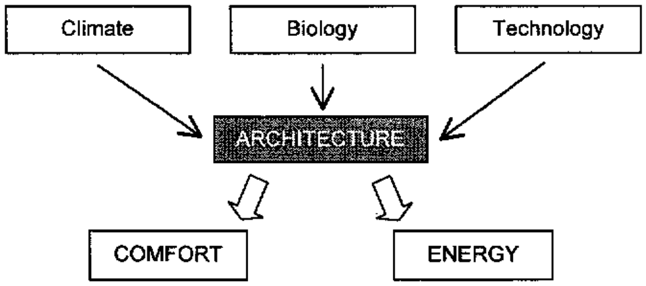

Figure 1.2. Bioclimatic approach (Yeang, 1994)

It is noteworthy that the Olgyay's approach is largely linear; the study of climate is followed by understanding human physiological needs, which is followed by understanding technology that goes into the making of architecture. The objective is primarily occupant comfort.

Yeang's approach, on the other hand, is simultaneous and integrative. He justifies this on the exigencies of running a design practice that have lead him to a process he calls *"rapid prototyping"* (Khosla, 2000). Here, ideas are tested quickly, sometimes partially, under pressure from client, time and budget (Yeang, personal

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[3] Passive and active modes, features and systems will be discussed in the Chapter 2.

communication, September 13, 2001). The reference to *Technology* includes the newly available software for the analysis of an environmental problem. Most notably, *Energy* is an added performance criterion, more specifically 'energy-efficiency'.

In fairness, Olgyay conceived his treatise on the Bioclimatic approach some years before the 1973 oil crisis altered the criteria by which buildings were assessed (Oseland & Humphreys, 1994). Yeang formulated his approach at a time when the use of fossil fuel was being viewed as a global threat. He nods to the complexity of the life in the 1990s and occupant expectations by suggesting that the issue is one of *how much* energy is used, not simply if a building can be energy-free altogether. The present day skyscraper, he suggests, is too complex an entity to be ruled by dogma (Yeang, 1996).

In adopting the Bioclimatic Model as its yardstick, the thesis approaches the question of performance on the basis of its desired outcomes of comfort and consumption. These considerations predispose this research to adopting a multidisciplinary framework, embracing ideas and adopting instruments from environmental psychology and building science. This framework is further explained in Chapter 3.

It should be noted that of the three modes delineated by Watson (1984), mentioned at the start of Section 1.2, the aesthetic is not directly addressed by the present study, largely because it is not a declared objective of the Bioclimatic approach. Even though Olgyay (1963) spoke of style and Regionalism, and Yeang's approach emerged from a Regionalist sentiment in Southeast Asia (Jahnkassim, 1998; Powell, 1989), neither explicitly suggests that Bioclimaticism involves aesthetics. For this reason also, the thesis steers clear of other advocates of climatic approach in Singapore, such as Tay Kheng Soon and Tan Hock Beng, whose ideas on Tropicality seem to be blurred by questions of style and identity (Powell, 1997; Tan, 1996).

1.3. Research Question and Hypothesis

To reiterate, the research question, as stated in Section 1.0, is 'why is there a gap between theory and application on the idea of climate-responsive design?' Evidence of this gap, relating to the specific questions of climate, comfort and energy consumption, has been identified. These tenets of the Bioclimatic Model (Yeang, 1994) will be further examined in the literature review and in the initial stages of data collection. The thesis will then examine, in depth, how occupied buildings perform.

The thesis hypothesis can be summed up as follows: the gap between theory and application is due, in part at least, to occupant expectations of comfort. A key assertion here is that this relates to the level of indoor variability. This is typically greater in a climate-responsive design and lesser in one that is not linked with climate. It is implied here that in accepting or rejecting one type of building over another, one set of conditions over another, occupants are in part responding to their own expectations of comfort and indoor variability.

Through this hypothesis, the thesis critically evaluates theory with the objective of contributing a set of prescriptions that are useful to designers and engineers engaged in the craft of comfort making. This outcome may also have a bearing on statutory codes that regulate building design and operations.

1.4. Outline of Thesis

The present study begins by being broadly inclusive, gathering information through a sweeping literature survey and data trawling, driven by the directions provided by the research question and hypothesis. The data from each stage is analysed immediately after it has been collected, thereby setting up the next stage, which then becomes that much more specific in what it is sought. In some respects, however, this description is a simplification of the process, which was more iterative and simultaneous. The synergy of these various components is most evident in the last two chapters, where the confining logic of each instrument gives way to cross-referencing of findings and hypothesis testing.

This thesis is made up of eight chapters. In the chapter that follows, a theoretical context is sought out and presented, looking at how the issues are discussed in the literature. It will examine current ideas on climate-responsive design, thermal and visual comfort, statutory guidelines and controls that collectively influence the approach to office buildings in Singapore. This chapter also breaks down the research question into sub-questions and sets up a framework for their exploration.

Chapter 3 begins with a theoretical consideration of the salient methodology issues before presenting an overall research framework. Each instrument and the analytical tools by which data is examined will be presented here.

Chapters 4, 5 and 6 present the three components of the fieldwork, each chapter complete with results, analysis and a list of preliminary findings. This is done to minimise potential confusion arising for the multi-pronged approach to data collection. These three chapters, in terms of the research question and sub-questions, are explained in greater detail in Section 3.5.

Chapter 7 reviews all findings from Chapters 4 to 6 in the context of current theory and past studies, discussing the meaning and significance of outcomes. In Chapter 8, these discussions are taken a step further into projecting their relevance and impact on the design of office buildings in hot humid conditions. The findings are synthesised into a comfort-based model and discussed in terms of statutory regulations and thermal comfort theory. This same chapter concludes with a set of recommendations for future research and a summing up of the thesis.

Chapter 2. Literature Review

2.0. Preamble

The research hypothesis presented in Section 1.3 suggests that occupant comfort is a factor that determines how well a building performs in terms of its climate response and energy consumption, that the perception of variability may be an underlying criterion affecting user acceptance of an indoor condition.

It is against this framework that the present chapter asks the questions of 'where, how and why'. The 'where' seeks to frame the *Context* of the study by delineating national, climatic and architectural parameters (see Section 2.1). The 'how' seeks to understand the constituents of *Design*, the components and precepts available to designers in the making of comfort (see Section 2.2). The 'why' is, in a sense, implicit in the hypothesis, i.e. that the perception of *Comfort* is, at least partly, responsible for a building's performance (see Section 2.3).

The question arising from these deliberations is 'where does this lead the present study?' In Section 2.4, at the end of this present chapter, the hypothesis will be re-examined in light of the literature reviewed and extrapolated into a research direction. This direction will then be elucidated in Chapter 3 where it will be translated into a strategy, supported by specific tools.

2.1. Context

Context focuses on Singapore (see Section 2.1.1), the hot humid condition (see Section 2.1.2) and the Office Building (see Section 2.1.3). In Section 2.4.1, the question of context will be reviewed by asking how these three parameters affect the question of comfort and energy consumption.

2.1.1. Singapore

Singapore is an island situated on latitude 1° N, between longitudes103° E and 104° E (Singapore Department of Statistics, 2000), a democratic city-state with a reputation for an authoritarian government and an orderly and highly regulated environment (Baker, 2000; George, 2000).

In the 35 years since its political independence and existence as a sovereign state, it has become one of the most important international business centres in Southeast Asia and one of Asia's leading financial centres (Lee, 1996a). A priority of its government, vis-à-vis the built environment, has been to maintain the country's infrastructure and competitive edge by ensuring that it remains an attractive place to do business in Asia (IACEE, 2000).

A key strategy for achieving this has been to reduce cost via reduced energy consumption of buildings, for which guidelines and controls are in place (PWD, 1983). At the time of this study, the statutory framework, first formulated in the late 1970s, was being revised and new measures introduced (Koo, 2001).

At the last census, Singapore's 3.9 million residents were spread out at an average of 5900 people/km^2, figures that, some 10 years earlier, were 2.9 million and 4,700 people/km^2 respectively (Singapore Department of Statistics, 2000). The Singapore cityscape, as such, is a growing, high-rise and high-density environment. One of the most visible buildings on the city skyline is the high-rise office tower.

The office building first made its appearance over a hundred years ago but it was not until the 1970s' building boom that the population of office buildings greatly expanded (Lee, 1996b). By the 1990s, a total of 5.8 million square metres of office space (Nathan, 1999) and an excess of 500 office buildings (Lee, 2001) were recorded.

Given the current trend in population growth and economic focus, the importance of the office building is underscored by two factors. Firstly, the sectors of commerce, transport and communications are major users of office space (Lee, 1996a), and are likely to sustain the demand for new office buildings in the future. Secondly, the office building is one of the biggest consumers of energy in Singapore (Lee, 2001;

Nathan, 1999). Cost savings here are likely to have a significant impact on the economy and competitiveness of the nation as a whole.

The question of energy is viewed with concern by the government primarily because Singapore has no indigenous energy sources (Wong, 1984) which makes it far more vulnerable to fluctuations in oil prices (IACEE, 2000). Despite this, national energy demand in the years between 1980 and 1995 grew by an average of 11.9%, outstripping Gross Domestic Product (GDP), which grew by 7.6%. The energy bill for the nation in 1999 was reportedly S$3.2 billion (Kaur, 2001a). By Year 2000, Singapore ranked 25th out of 45 nations for the amount of energy used per dollar of GDP. It is predicted that at current rates of increase, consumption levels by the year 2007 will have jumped 60% over existing figures (Nathan, 2000a).

This disproportionate growth is partly attributed to changing lifestyle expectations. In 1988, for instance, only 19.4% of all households had an air-conditioner at home. By 1997, the figure had jumped to 53.1% (IACEE, 2000). Partly the upswing is attributed to the advent of telecommunications and information technology, which introduced many new appliances to the Singaporean. Within the context of overall national consumption, buildings consume 34% of the energy, of which commercial[1]/industrial buildings consume 57% (see Figure 2.1).

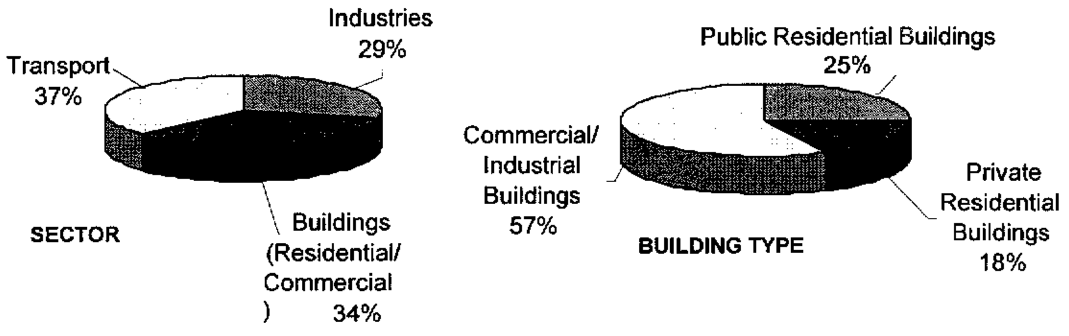

Figure 2.1. Breakdown of energy consumption in Singapore
(IACEE, 2000, pp. 3-4)

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[1] Office Buildings are classified under the Commercial heading by the Singapore government's Inter-Agency Committee on Energy Efficiency (IACEE).

The average consumption level of an office building currently stands at 224 kWh/m^2/year, with the least efficient building consuming some six times more than the figure for the most efficient (Nathan, 1999). Air conditioning is a key consumer, amounting to 24% of total national energy consumption and over 60% of the energy consumed by a typical office building (Kaur, 2001a;IACEE, 2000). This trend has led to new government initiatives on energy conservation through building design, which focus specifically on air conditioning systems (Leong, 2000).

This current figure of 60% for air conditioning is a significant increase over that from the 1980s when it was shown that air conditioning consumed some 50% of a building's total (Goh, 1986). The figure for electrical lighting, on the other hand, has dropped from 25% in the 1970s (Tay, 1976) to 5% in the 1990s (Lee, 1999). This may explain the general shift on the question of energy over the last few decades, away from the question of electrical lighting[2] to one emphasising air conditioning.

Another significant shift concerns the global question of ecological responsibility and environmental sustainability, which entered public awareness in the 1990s after a recurrent haze problem due to forest fires in Indonesia (Kaur, 2001b). While the Singapore government appears committed to an environmental agenda (Ministry of Environment, 2001), it is not clear exactly how committed the typical Singaporean is to these issues. Surveys have shown that despite awareness of ecological issues like global warming and the 1998 Kyoto Protocol[3] (Kaur, 2001c) there is a reluctance to tradeoff on lifestyle issues (Kaur, 2001b).

It has been argued that the solution, therefore, lies with regulatory control (Nathan, 2000b). Under existing energy conservation laws, architects and engineers are required to submit detailed drawings and envelope transmittance calculations to the Building and Construction Authority (BCA) which oversees all new developments.

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[2] A key strategy advocated in the 1970s and 1980s was the introduction of daylight as a means of reducing reliance/use of artificial lighting (Turiel, Curtis, & Levine, 1984; Wong, 1976).

[3] The United Nations Framework Convention on Climate Change (UNFCC) international agreement has the objective of stabilising atmospheric concentrations of greenhouse gases at safe levels. The Convention was opened for signature at the UN Conference on Environment and Development in Rio de Janeiro, Brazil in June 1992. Singapore signed the Convention and subsequently ratified it through its parliament in 1997. The subsequent Kyoto Protocol aimed at committing Annex I parties (essentially the world's developed countries) to individual legally binding targets to limit or reduce their emissions of several greenhouse gases, adding up to a total cut of at least 5% from 1990 levels in the 'commitment period' 2008-2012. The text of this Protocol was adopted at the 3rd session of the UNFCCC in Kyoto, Japan in December 1997. As of December 2001, Singapore was not a signatory to the Kyoto Protocol (United Nations Framework Convention on Climate Change, 2001).

The statutory codes for these requirements were put in place in the 1970s after the oil crisis of 1973 (Chou, Wong, Chang, & Yap, 1994). In the PWD Handbook on Energy Conservation (1983) two direct constraints[4] were placed on consumption:

- Inefficacy of indoor electrical lighting[5] cannot exceed 20W/m^2
- Heat load entering the building through its envelope cannot exceed 45W/m^2

The lighting constraint is a straightforward calculation of load carried out by the building's engineer. The heat load constraint is an envelope transmittance standard that requires the architect to submit detailed façade information and calculations relating to window to wall proportion and thermal performance of envelope as a system.

The premise of the building envelope standard, the Overall Thermal Transmittance Value (OTTV)[6], is that a building with a higher OTTV will admit more heat through its skin which will then have to be removed by its air conditioning system (Goh, 2001). In other words, the *"smaller the OTTV, the less the energy [needed] for cooling"* (Lam, Chan and Li, 2000, p. 194).

The Singapore climate is incorporated into the OTTV formula by way of several constants, derived from measurements carried out in the late 1970s (Goh, 2001). These constants, specific to solar heat load according to orientation, are applied to the calculation of façade thermal transmittance value. The 45W/m^2 limit is a cap that applies to the transmittance value of the whole building, averaged across its total surface area. This concept and formula of the OTTV was adapted for Singapore from ASHRAE Standard 90:1975, later modified to the ASHRAE Standard 90A: 1980 (Chou et al., 1994).

Prior to the introduction of the OTTV in 1979, office buildings in Singapore let in an average of 70W/m^2 (Wong, 1984). It was estimated then that the envelope standard would result in 6% savings in new buildings; the upper limit on lighting inefficacy would achieve some 5.5% to 13% energy savings (Turiel et al., 1984).

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[4] There are other requirements pertaining to access and control, flexibility of mechanical and electrical systems and the ability of the building systems to be logged for energy audits.

[5] This is specific to office spaces. The figure varies for other space types.

[6] OTTV is largely indicative of the heat load entering the building and is used as a device to compare thermal performance of buildings.

In 2001 new energy guidelines and standards were announced in the follow-up to a review of energy consumption trends in Singapore (IACEE, 2000). These are expected to reduce energy consumption in new buildings by 24% (Koo, 2001). These revisions consist of a more stringent OTTV limit, down from 45 W/m^2 to 35W/m^2, along with new energy efficiency standards[7] that apply to a building's mechanical and electrical equipment[8]. The OTTV formula has also been revised for its climate constants[9]. The new envelope standard is referred to as the Envelope Thermal Transmittance Value (ETTV).

While the regulatory framework is tweaked, the focus in building design in the last ten years seems to have been towards creating more intelligent and efficient buildings. Building automation and intelligence systems are now part and parcel of design of new buildings in Singapore where they facilitate smart control environmental systems that minimise the need for day to day management of a building's indoor conditions and resources (Harrison, Loe, & Read, 1998).

Meanwhile, the rhetoric in the architectural media, as suggested by recent publications, revolves around lifestyle issues and questions of architectural style and identity (Powell, 2000; Tan, 1996). In the context of office buildings, some are openly critical of the prevailing ethos of curtain-walled, International Style designs borrowed from the West.

> *Architects working in the region have forgotten how to design bearing in mind the climate and landscape. They are now caught in the homogenising forces of mass-media and repeating the built mediocrities of International fashion.*
>
> Tan (1994, pp. 14-15)

Others suggest that a new ecological awareness is entering the design debate. Powell (2000) cites the award of the new Singapore National Library to Malaysian architect Yeang, known for his ecological agenda, as evidence of this. When

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[7] A new index for consumption is proposed (Quek, 2000), along with a strategy for energy pricing and demand-side management (Nathan, 2000a). The recommendations also cover a review of facade materials for lower solar load retention (Tee, 2000).

[8] This includes air conditioning equipment, water heaters, electrical motors and artificial lighting (Goh, 2001).

[9] The earlier formula had assumed a lower solar load than is the case with the Singapore climate(Goh, 2001).

completed, the new Library will be the first 'green' building constructed in Singapore (Khosla, 2000a).

Noteworthy, perhaps, is that neither of the two authors was able to demonstrate broad-based applicability of the climatic or ecological ideal. Tan's books are a catalogue of tropical resorts and residences, not office buildings or public housing (Kishnani, 1999). Powell's book on Singapore architecture covers some ninety projects, of which the National Library Board Building, for its ecological stance, appears to be the exception rather than the rule.

2.1.2. Hot humid climate

Huntington (1915) suggested that climate is one of the three[10] great factors determining the condition of civilisation. Olgyay (1963) argued further that buildings, in their role as human shelter, should derive their form and operational logic by linking the attributes of climate with the needs of human comfort. This coupling of architecture, climate and comfort generated a design approach, labeled Bioclimatic, in which the design process begins with an understanding of climate, of when it should be treated as a resource and when as a constraint.

In Southeast Asia, the notion of *Tropical Architecture*, in which architectural form is derived and inspired by climate, was evident through the 1980s and 1990s in the work and writings of Yeang (1984), Tan (1994), Tay (1997) and Lim (1999). Each architect in his own way argued that climate should be seen as a catalyst for design. Precedents from history would tell designers how this can be meaningfully and effectively achieved without undue reliance on electro-mechanical devices (Powell, 1997).

Singapore is typified by seasonal thermal uniformity, a modest diurnal range, high humidity levels and low wind speeds (Nieuwolt, 1977). Situated at the southern tip of the Malaysian peninsula, the island falls within a subcategory of the Tropical zone[11], one that is persistently warm and moist (de Blij & Muller, 1993). There are

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[10] The others being racial inheritance and cultural development (Huntington, 1915).

[11] The Koppen climate classification describes Singapore conditions as being 'Tropical, with no dry seasons.'

no distinct wet or dry seasons, although it is wettest between the months of October and December. The average annual rainfall is 2169 mm; its mean annual temperature is 27.4°C with daily diurnal range averaging 8.3K. Relative humidity averages at 83.6%, although it can reach 90% in the early hours of the morning (Singapore Department of Statistics, 2000; Singapore Meteorological Service, 1994).

Givoni (1969) prescribed a simple two-prong strategy for human comfort in this climate: stay in the shade and counter the humidity with high air velocities, so as to increase efficiency of sweat evaporation. On the basis of this, and other climatic arguments (Fry & Drew, 1956), architect Tay Kheng Soon (1997) devised a set of principles[12] guiding form and structure of buildings in the tropics. The solution seemed to centre around the creation of shade, the exclusion of solar radiation, and reliance on air movement as a means of diminishing the effects of the heat and humidity on human comfort.

Wind speeds in Singapore, however, are low, rarely rising above 5 m/s and conditions are calm 20% of the year (OveArup, 1998), making indoor comfort via natural ventilation somewhat unreliable. The average solar radiation at noon is between 900-1000 W/m^2 (Ding, Pederson, McCulley, & Rao, 1984; Turiel et al., 1984). Significant cloud cover and moisture in the atmosphere means that the diffuse component of the solar radiation, against which sunshades have limited success, averages between 50-60%, no lower than 18% even on clear days.

Szokolay (2000) pointed out that the hot humid climate is the most difficult to design for because the common strategies for extending the comfort zone in cooler or dryer climates, such as evaporative cooling, thermal mass and trombe wall, are simply not applicable here. The humidity is too high for evaporative cooling, the night sky too cloudy to be used as an effective infra-red radiation sink, and high night temperatures are not low enough for diurnal convection cooling (Santosa, 1999).

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[12] Tay's (1997) principles for tropical design:

a. Roof is the dominant feature with deep overhangs
b. Adaptable envelope consists of walls that are permeable and moveable for dealing with diurnal shifts,
c. Transitional spaces (such as verandahs and terraces) act as buffers between indoor and outdoor spaces
d. Large openings (doors and windows) facilitate air movement, with external shades that keep out sun and rain
e. Light-weight structure (preferably raised on stilts) minimise heat retention by structure

In comparing the Singapore conditions with those in a temperate setting, the climatic hurdle of the hot humid tropics becomes evident. Figure 2.2 shows monthly temperature and humidity averages for Singapore and Perth (Western Australia), the latter situated in a Temperate Zone[13] with mild conditions for most of the year.

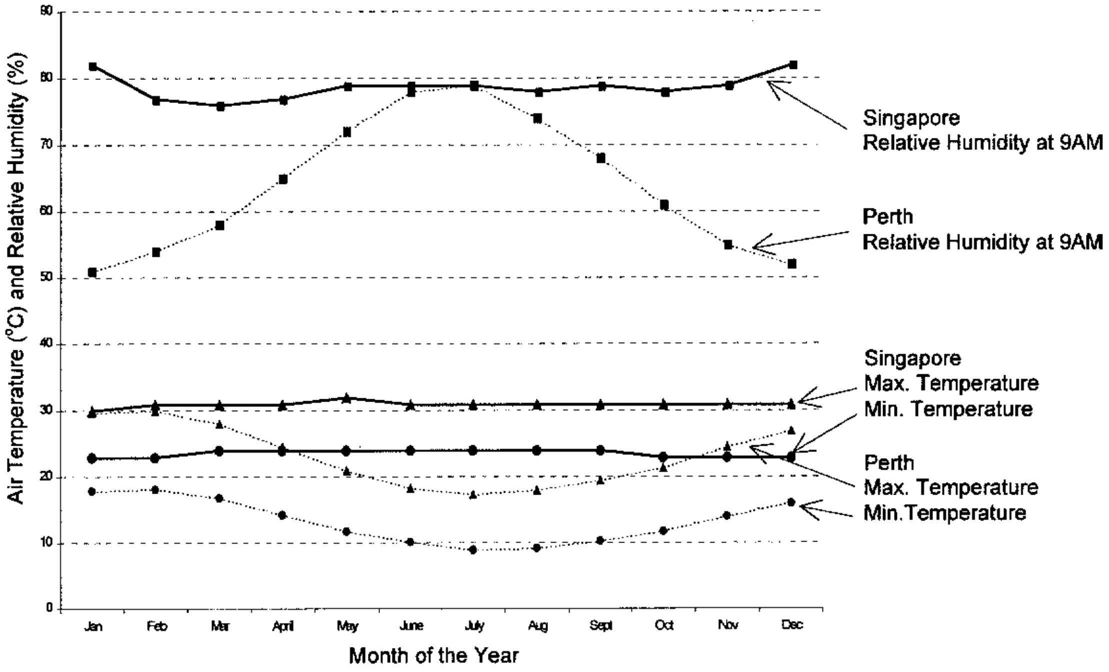

Figure 2.2. Monthly averages of outdoor air temperature and relative humidity for Singapore and Perth

It is evident from the graph that Perth can be as hot as Singapore in summer. These temperatures, however, are partly offset by dryer conditions with relative humidity levels dipping as low as 40%. Winter nighttime temperatures can dip below 10°C for about two months of the year but even in this period, daytime average is a comfortable 17-20°C (Australia Bureau of Meteorology, 2001). The question of thermal comfort here can be seen to be a seasonal issue with outdoor discomfort experienced for short periods every year.

Singapore, on the other hand, has temperature and humidity highs of about 32°C and 90% respectively, all year round. There is little diurnal or seasonal variation (Hawlader, Bong, & Mahmood, 1987; OveArup, 1998). The weather ellipses described in Figure 2.3 suggests that in Perth, some of the design strategies

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[13] Classified under the Koppen system as 'Mesothermal with dry summer' (de Blij & Muller, 1993).

mentioned by Szokolay (2000) and Santosa (1999) can potentially be used to extend the comfort zone. It helps that outdoor conditions are, in themselves, within the comfort zone for a significant part of the year. The Singapore ellipse suggests that comfort can only be achieved, as Givoni (1969) suggested, with increased air speeds. Inside an office building, this may be problematic, as air movement over 3-4 m/s may cause papers to fly about, thereby creating a distraction (Lim, Rao, & Rao, 1979).

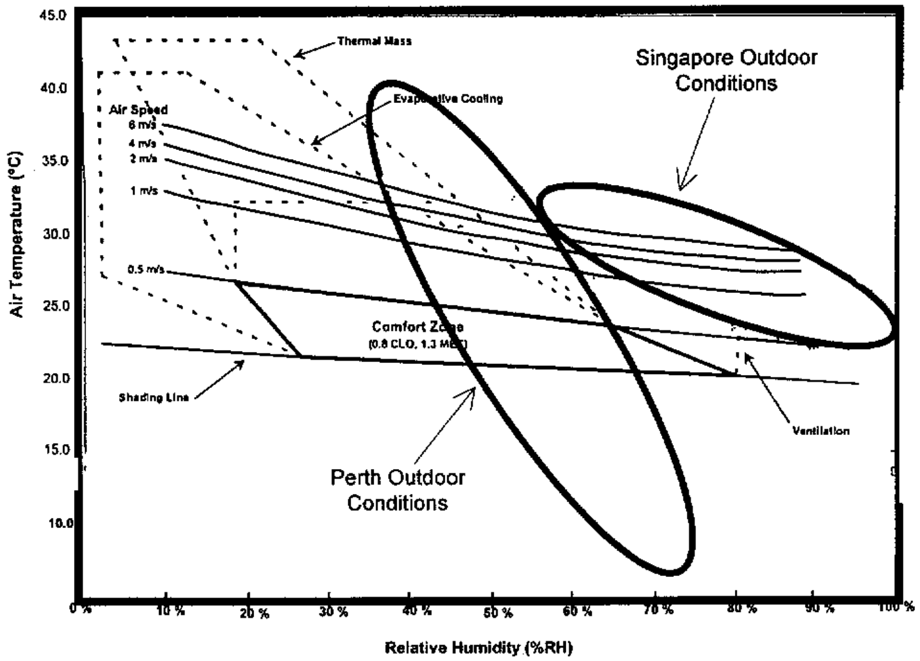

Figure 2.3. Annual Singapore and Perth outdoor conditions as indicated on Olgyay's Bioclimatic chart[14]

This intrinsic disposition of the hot humid climate is compounded by problems of urban noise and air pollution. A recent study of residential structures in Indonesia challenged the hot humid ideal of lightweight structures and permeable walls (Soebarto, 1999). It was suggested that the indoor condition of many buildings is exacerbated by urban context. This problem is likely to be all the more critical for office buildings which, unlike private homes and resort hotels, are often situated in high density city centres.

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[14] Singapore data is from OveArup (1998). Perth data is from the website of the Australia Bureau of Meteorology (2001).

2.1.3. The Office Building

At the start of the last century, when the Office Building was relatively new, it was designed to be primarily climate-reliant (Arnold, 1999). Mechanical ventilation, electrical lighting and air conditioning were available by the 1930s but their use did not become widespread until after World War Two. Early office buildings, such as the Wainwright Building (1891, St. Louis, US), were typically designed with a U-shaped plan (Cook, 2000) in which a central court and narrow plan-depth made possible daylight penetration and natural ventilation.

The Larkin Building (1906, Buffalo, US) by Frank Lloyd Wright, is considered to be one of the first *"hermetically-sealed, air-conditioned buildings"* (Frank Lloyd Wright, cited in Cook, 2000, p. 18) for which cooled air was pumped in via specially designed air-ducts. The idea of the controlled indoor environment received an impetus, however, after the Second World War with the advent of the International Style and a post-war economic boom in the US (Arnold, 1999; Laing, 1997).

The International Style was an offshoot of the Modern Movement (Darton, 1990), its buildings typically without external ornamentation, strong geometric forms, a horizontal emphasis with large windows and a 'curtain wall' system (Arnold, 1999; Cook, 2000). The curtain wall constitutes the building's envelope, consisting of a 'skin' often made from steel and glass, designed to hang off the steel-reinforced frame of the building.

The United Nations Secretariat (1950, New York, US) by Le Corbusier is one of the best known examples of the International Style which, despite its problems with solar heat gain and leaks, became influential worldwide as the prototypical slab tower and icon of the office building (Cook, 2000).

This combination of preferred style and available technology is blamed for the 'dissociation' of the building's indoor environment from its climate (Laing, 1997), a trend propelled by the inexpensive and plentiful supply of energy through the 1950s and 1960s. In a sense, though, the most compelling argument for the 'glass-box' formula was economic. An office building that is not constrained by daylight, in terms of fenestration design, ceiling height and plan depth, could have a deeper plan, lower floor to ceiling height and greater floor-to-envelope area ratio, all of which made it economically more viable (Arnold, 1999). Each floor would consist of a large, undifferentiated space that could be partitioned by a building's tenants. This made sense in the context of office buildings that were to be leased out to tenants, most of who were not known during the design stage.

The de-coupling of building from climate paralleled developments in workplace design and organisational theory (Laing, 1997). The latter, in the way it affected workplace design, has been covered by Duffy (1993, 1997) and van Meel (2000) and will not be examined here. Noteworthy, however, in the evolution of the workplace was the advent of the *open plan concept* and *system furniture* in the 1960s.

The open plan office was typified by the absence of full-height partitions, where spaces could be differentiated according to activity, often signified by furniture placement. System furniture was based on the idea that office furniture should be a kit of parts responding to task. It brought modularity to the way an office could be designed and assembled.

These ideas and systems were driven by the perceived need for greater organisation flexibility and communication, activity and privacy. They also reinforced the dissociation of the building shell from its internal layout (Laing, 1997) in that the shell and layout became two separate design processes. This was helped along by the fact that air conditioning and electrical lighting offered zoning flexibility across deep plans. Office buildings today continue to rely on this principle of separating building skin from internal layout in the interest of providing open flexible spaces that facilitate flexibility and change.

The next significant development in office design took place in the 1980s and 1990s with the widespread use of computers at the workplace (Duffy, 1988). This was paralleled by the advent of Building Intelligence, beginning in the 1980s, which refers to building automation systems that manage its processes and operations (Harrison et al., 1998).

The availability of the personal computer spurred the Information Technology (IT) revolution, which prompted a rethink of the way work is carried out and, consequently, how offices are designed. The key question asked is if the traditional workstation, now home to an increasingly mobile workforce with nomadic work patterns, would be meaningful in the computer age (Laing, 1997; Sims, Joroff, & Becker, 1996).

In delineating the old and new economies, traditional and progressive workplace, Duffy (1997) described the office environment as being typified by a balance between worker autonomy and workplace interaction. Within this framework, he cites four types of workplaces: Hive, Cell, Den and Club (see Figure 2.4).

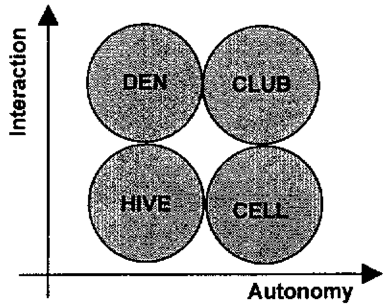

Figure 2.4. Taxonomy of the Workplace (Duffy, 1997, p. 61)

The Hive is a workplace with low autonomy and low interaction levels, typically routine processing work. At the other end of the spectrum, the Club is a place with higher worker autonomy and activities that require interaction. A worker in this environment is likely to be mobile, and work is often done on a group basis or from remote locations. In finding a fit between work type and workplace layout, the work process is potentially enhanced, yielding greater productivity.

The link of workplace design and productivity was suggested by Wineman (1986) who argued that the primary role of the office setting was providing support for the task. This 'support' included environmental factors such as ambient conditions of light and temperature, space standards and furniture, none of which should contravene the occupants needs for privacy, status and autonomy.

This argument linking the physical workplace setting with productivity was taken a step further by Loftness et al. (1999) who suggested that occupant well being also relates to the way the building functions as a whole. This would include links to the outside world, i.e. access to daylight, air and view. The term *"fresh air architecture"* (Hartkopf et al., 1993, p. 11; Shepard et al., 1995, p. 6) was used to describe a new generation of office buildings. The Commerzbank Building (1997) in Frankfurt and

Tower RWE (1996) in Essen, both in Germany, are two examples that rely on sophisticated building envelope systems that selectively admit air and light, allowing the buildings (and their occupants) to 'breathe' more naturally (de Olivera, 2000). The Frankfurt building also provides a series of vertically distributed transitional spaces, gardens in the sky, where occupants can experience the outdoors without actually leaving the building.

In Singapore there are no known examples of this conscious attempt to link climate with the workplace, with the explicit purpose of creating a better environment or improving productivity. Some buildings rely on natural ventilation in non-critical spaces such as entrance foyers and corridors[15] but connectivity with the outdoors, particularly in the thermal sense, appears to be rare (except for fresh air supply to air conditioning systems). Elsewhere in Southeast Asia, the exception to this rule would be the Malaysian Bioclimatic skyscrapers by Yeang. These will be discussed further in Section 2.2.1.

It should be noted, however, that the assumption equating comfort with productivity is challenged by past studies. In a literature review of indoor environment and productivity, Shensarma, Woods and Goodwin (1998) suggested that optimal comfort and optimal performance might not necessarily occur for the same set of conditions. Wyon (1973b) made the same argument when he suggested there are tasks for which a certain margin of discomfort may result in arousal and hence, improved performance.

Returning to the question of IT and the workplace, there is no evidence to suggest that the 'new office', as suggested by Duffy (1997), exists in Singapore. Certainly, computers have become far more prevalent in the past ten years, in keeping with Singapore's reputation as an advanced centre for IT (Harrison et al., 1998). A more fundamental shift in work patterns, however, is not visible. After one publicised example of 'telecommuting' (Gwee, 1997) and initial media enthusiasm for the 'virtual office' (Sitathan, 1997), the ideas of the mobile/shared workplace do not seem actively discussed in the media nor actively promoted by the government.

The two issues that do get coverage in the media are energy efficiency and building intelligence. Two of the most celebrated buildings in this regard have been the URA

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[15] Two such buildings in Singapore, both built in the late 1980s, are Parkway Builder's Centre and Cecil Court (Powell, 1997, pp. 60 and 66).

Centre (1999) and IRAS Building[16] (1996). The former was described as having state-of-art smart systems, making it one of the most intelligent building in Singapore (Gwee, 1999). The latter was awarded the title of most energy efficient building in ASEAN in the year 2000 (Cooke, 2000). Both are owner-occupied buildings housing government departments, suggesting a government-led initiative to improve office building design. A report on the future of energy efficiency in Singapore suggests that this will continue to be the case (IACEE, 2000).

2.2. Design

This present section looks at the design process in general (see Section 2.2.1), and then specifically in terms of the passive (see Section 2.2.2) and active options (see Section 2.2.3). These refer to the various modes and systems that are available to designers and engineers in the making of comfort. This is followed by a review of mixed- and multi-mode options (see Section 2.2.4). Section 2.2 ends with the suggestion that passive and active approaches have become polarised by opposing paradigms, associated with energy consumption and comfort respectively (see Section 2.2.5). These paradigms are revisited in Section 2.4.2 where variability versus control is suggested as an alternative means of viewing mode options.

2.2.1. The Design Process

The design process, since it first came under scrutiny in the 1940s, has moved from being viewed as a linear sequence of inputs and outputs in search of the 'correct' answer, to one that is more iterative and less absolute in what constitutes an 'acceptable' outcome (Zeisel, 1981). In a striking departure from earlier definitions, it has been suggested lately that emotions play a significant role in the judgements and tradeoffs made during the design process (Papamichael & Protzen, 1993).

As an 'irrational' activity, design can be premised on a set of values that influence its outcome (Papamichael & Selkowitz, 1990). With his/her value system, a designer begins by projecting a vague idea of the whole, i.e. of how the building will

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[16] The IRAS Building is also known as Revenue House.

come together and what issues and ideas will be pertinent to its making (Zeisel, 1981). This projection is then challenged, during the design process, by everyday realities, for instance cost and client needs.

The act of designing, therefore, becomes one in which a desirable 'end' is imagined, tested, refined and re-tested against criteria that are deemed to matter. This shrinking circle of test-and-refine ceases when an acceptable solution is found or, as is sometimes the case, when the designer runs out of time. Watson (1984) described this activity as the *"Habits of Imagination and Truth"* (p. 6), the habit of imagination projecting an outcome and that of truth testing its validity against real-world circumstance. He further suggested that designers, in conceptualising or communicating an idea, rely on models, paradigms and metaphors:

> *Models and metaphors tell us how to design. Ethical paradigms tell us how to live... those nagging questions of economics, energy and human resources are profoundly ethical and not resolved by arguments of pragmatics or aesthetics alone.*
>
> Watson (1984, p. 9)

The value system affecting design, particularly in the context of comfort and energy consumption, will be discussed in Section 2.2.5. Prior to that, the design process will be reviewed briefly in terms of its sequences and the constituents that come together in the making of indoor comfort.

The activity of design is typically viewed as a process that begins with the general, and works its way towards the specific. Rivard et al. (1995) delineated the design process as one consisting of three distinct stages:

- *Conceptual,* in which decisions are made regarding building form, orientation and layout
- *Preliminary,* involving decisions on envelope, windows, walls, openings, etc
- *Detailed,* when construction details, dimensions are finalised

Hyde and Pedrini (2001) suggest that the conceptual stage is the most critical in terms of climate response. They argue that this stage represents the best opportunity for improving a building's energy performance, and that any effort made later will represent additional cost.

In both the Rivard et al. (1995) and Hyde and Pedrini (2001) studies, the building envelope is identified as a key component. This is partly for its impact on a building's performance, and partly for the fact that it is one of the earliest decisions made about a building. The envelope is also a building's most visible component and, therefore, makes a key *aesthetic* contribution. Yeang adds to these the role of envelope as environmental filter (Powell, 1989). This becomes all the more critical in climates that do not offer optimal conditions for human comfort:

> *[The envelope is] a system enclosing and protecting the indoor environment from disturbing outdoor conditions... the greater the differences between inside and outside, the greater is the stress or duty imposed on the envelope.*
>
> Rivard et al. (pp. 391-392)

It has been argued that an envelope's ability, or indeed inability, to cope with stress imposed by climate has a significant knock-on effect on a building's electro-mechanical systems in terms of the loads they must eventually deal with (Hyde, 2000). It stands to reason that a poorly designed envelope is likely to affect occupant comfort and/or a building's electro-mechanical systems.

Implicit here is the notion is that a building is part external shell, part interior-regulating system. The question arises of how these constituents are designed in relation to each other. It has been suggested that the shell is often designed early in the design process by the architect (Keneally, 1995; Shaviv & Capeluto, 1992); a building's systems are resolved downstream by its engineers (Parlour, 1994). Banham (1984) and Lovins (1992) have argued that this delineation of sequence and expertise is artificial and counterproductive, leading to a mindset of competing disciplines, conflicting priorities and agendas.

There are calls for an 'integrated design approach', one that consciously unites the disciplines with a view to achieving energy savings (Prasad, 1995a; Todesco, 1996). An integrated approach begins with a simultaneous consideration of shell and systems, a synergy that results in greater outcomes than a consideration of either on its own.

Before reviewing impediments to such an integrated approach (see Section 2.2.5), the following sections will review, in greater depth, the various modes, features and systems that are available to architects and engineers, specifically in connection with climate, comfort and energy consumption.

2.2.2. Passive Design

> *[Passive design is] essentially low-energy design achieved not by electro-mechanical means but by the building's particular morphological organisation. [Passive systems are] cooling and/or heating techniques to enable the indoor temperature of the building to be modified through natural and ambient sources in the natural environment."*
>
> Yeang (1999, p. 202)

In effect, Yeang (1999) suggests that a passive building responds through form, orientation, detail or system to its climate in a manner that either counters its negative climatic attributes or utilises its positive ones, without consuming energy in the process.

Passive *design* involves a consideration of the building's shape, form and relationship with the climate, decisions typically made early in the design process. A passive *system* may be little more than envelope insulation or external shading, introduced at any point during the design process, sometimes even after the building has been completed. A passive *mode* refers to a building's operational reliance on passive systems, such as natural ventilation and daylighting (Yeang, 1999). A building that utilises these is sometimes described as 'free-running' (Hyde, 2000).

The literature on passive design for hot humid conditions lists the following principles, features and systems:

- Built-form configuration and site layout planning in relation to sun-path and wind rose for the location (Keneally, 1995; Prasad, 1995a; Todesco, 1998; Yeang, 1999)
- Orientation of main facades and openings according to solar load times of day and year (Keneally, 1995; Prasad, 1995a; Yeang, 1999)
- Provision of openings for natural ventilation (Loftness et al., 1999; Yeang, 1999)
- Plan depth and layout to optimise daylight (Prasad, 1995a; Todesco, 1998) and natural air-movement (Loftness et al., 1999; Yeang, 1999)

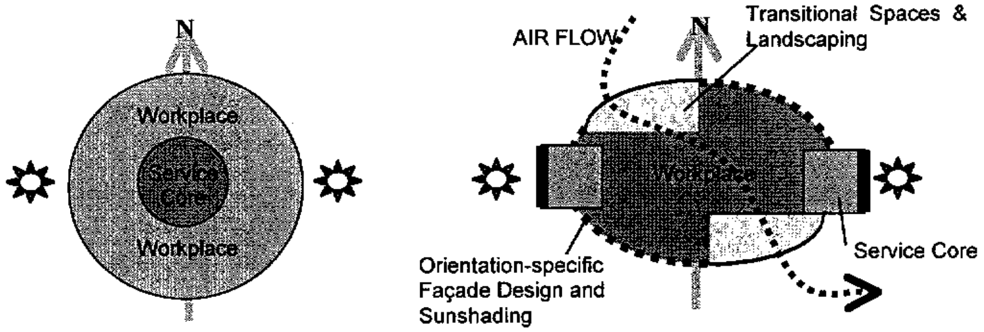
- Façade design for minimising thermal load via wall-to-window ratio, location of fenestration (in relation to orientation), details and choice of materials (Keneally, 1995; Prasad, 1995a; Todesco, 1998) (Loftness et al., 1999; Yeang, 1999)
- Vertical landscaping to cool the building's exterior (Yeang, 1999)
- Transitional spaces acting as thermal buffers between outdoor and indoor spaces, for instance, verandahs, balconies and courtyards (Yeang, 1999)
- Admittance of daylight via light shelves and skylights (Loftness et al., 1999; Prasad, 1995a; Todesco, 1998; Yeang, 1999)
- Solar load control via external shades for facades and windows (Keneally, 1995; Prasad, 1995a; Todesco, 1998; Yeang, 1999)
- Service core placement to minimise the impact of solar load on hot facades (Keneally, 1995; Yeang, 1999)
- Colour of envelope exterior (Keneally, 1995)

At the heart of the passive-run interior is its link with the outdoors. This implies a variability of indoor condition (temperature, humidity, light and air movement), one that fluctuates with time of day and season. Temperatures, for instance, may float over time and light levels may change with shifting cloud cover (Arens, Huizenga, & Zhang, 2001). Whilst a well-designed passive building is likely to dampen the amplitude of these fluctuations (Prasad, 1995) the variability of its indoor environment will depend on the permeability of its envelope. A passive-run building runs the risk of discomfort, especially when outdoor conditions stray well outside the comfort zone (Hyde, 2000).

The most common reason cited for the deployment of passive principles and systems is lower energy consumption (Choi, Johnson, & Selkowitz, 1984; Keneally, 1995; McHugh, Burns, & Hittle, 1998; Todesco, 1998). The justifications of health and comfort are also used in some cases. Jones and Yeang (1999), for instance, cite concerns with sick building syndrome as a key reason for introducing natural ventilation as an alternative to air conditioning in a Bioclimatic office building in Malaysia. Natural ventilation is meant to provide 'comfort cooling' here, as opposed to just meeting fresh air requirements.

In the context of passive design, a Bioclimatic building is one that maximises its reliance on passive modes, systems and principles, utilising configuration and building form to minimise the impact of solar loads, admit natural light and prevailing winds. It is not, as a rule, an exclusively passive-run building. The deployment of air conditioning and electrical light, where used, is minimised and their loads kept down.

The difference between a Bioclimatic building and one that is reliant on electro-mechanical systems is illustrated in Figure 2.5[17]. Kishnani and D'Cruz (2000) referred to the latter as 'Conventional' as it appears to be the most commonly observed in office buildings in Singapore.



CONVENTIONAL BUILDING **BIOCLIMATIC BUILDING**

Figure 2.5. Conventional vs. Bioclimatic Building
for hot humid conditions (Kishnani & D'Cruz, 2000).

In essence, the Conventional building is likely to have a hermetically sealed envelope with less exposed surface area to minimise fabric heat load (Prasad, 1995). The Bioclimatic building is likely to incorporate a more permeable skin that admits light and air. Whilst the Conventional building has greater plan depth and a central service core, the Bioclimatic building is typified by shallow plan depth (an aspect ratio of 1:3 is deemed ideal for hot humid conditions) and a side-placed core. The Conventional building may not differentiate façade design according to orientation, i.e. all façades are likely to be similar. The Bioclimatic building acknowledges orientation in terms of where its service core and transitional space are placed, and how its façade are treated. The objective of the latter is to minimise solar load, particularly with regard to the hotter E and W orientations.

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[17] The diagram is a graphical representation of climatic *principles*, as such contains no reference to context. It is not intended to be viewed as a layout of either a Conventional or Bioclimatic building.

The Bioclimatic office building in a hot humid context is exemplified by two buildings in Malaysia, Menara Mesiniaga and Menara UMNO; both designed by Yeang (Morris, 1990; Pearson, 1993; Powell, 1998; Richards, 1993; van Schaik, 1998).

Mesiniaga (1992) is situated in Kuala Lumpur and has the following features (Yeang, 1992):

- Circular plan form with service core facing the morning sun
- External sunshades positioned according to sun-path
- Transitional spaces with landscaping (called *Skycourts*) on every floor, acting as thermal buffers
- Toilets and fire escape stairs situated on the plan periphery; able to function with natural ventilation
- Admission of daylight via a high window-to-wall ratio

It is noteworthy that all of Mesiniaga's office spaces were designed to be air-conditioned.

UMNO was completed six years later (1998) in Penang. It has all of the Bioclimatic attributes of Mesiniaga, in addition to the following (Yeang, 1998a):

- Rectilinear plan form with service core facing morning sun
- Specially designed external walls *('wind wing-walls')* and operable windows which act together to draw air through each floor for the purpose of *'comfort cooling'* (Jones & Yeang, 1999)

UMNO is equipped with air conditioning as well, and therefore offers its occupants a choice of operational modes at their workspace (Khosla, 2000b).

2.2.3. Active Design

A space or building operating in the active mode relies on artificial lighting and/or cooling[18] systems to create and sustain indoor comfort (Yeang, 1999). The design of these systems generally begins when a schematic layout of the building has been provided by the architect to the mechanical or electrical engineers, along with

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[18] This is specific to hot conditions and may include mechanically induced ventilation systems. In cool conditions, an active thermal mode will imply a heating system.

a schedule of activities and occupancy (Lim, 1992; Parlour, 1994). Before reviewing how an active system is designed, it is worth briefly reviewing the evolution of active systems.

Air conditioning had its origins in the 19th Century in factory environments (Cook, 2000) but came into extensive use after the Second World War, by which point it had, as a system been invented by Willis Carrier (Shepard et al., 1995). By the 1950s, the air conditioning industry greatly expanded because of advances in chiller and refrigeration technology[19] (Lewis, 1995). By the 1960s and 1970s, the air-conditioner had moved from being perceived as a luxury to one deemed a necessity. Electrical light was introduced into buildings earlier than air conditioning, but it went through the same sharp ascent in use after the War. This had much to do with invention of the tubular fluorescent lamp in the late 1930s, which had an efficacy some three to four times higher than the incandescent lamps that preceded it (Boer, 1982).

A rethink of reliance on these systems came in 1973 when, as a result of the oil crisis, energy costs spiraled upwards. Energy codes soon became mandatory in some countries and the focus in design and research moved in the direction of improving efficiencies of these systems, and minimising waste (Oseland & Humphreys, 1994). Part of this re-evaluation involved a closer look at the loads that are imposed on a building's systems.

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[19] Refrigerant cycles, on which air conditioning systems are based, is not covered here but can be found in the literature (ASHRAE, 1993). The chronology of 20th Century lighting is covered by Boer (1982), whilst that of air conditioning is covered by Arnold (1999). The 'how-to' of active systems is covered by Ruck (1989), McLean (1995) and Parlour (1994).

The design of an active system begins with the analysis of a building's loads. Rao (1976) outlined four thermal loads in the design of air conditioning for hot humid conditions (see Figure 2.6):

- *Fabric*: heat gains through envelope due to temperature differences between indoor and outdoor and solar heat penetration through windows and walls
- *Lighting*: heat generated by electrical light fittings
- *Ventilation*: fresh air drawn into the system introduces both sensible and latent heat gains
- *Occupancy*: people and equipment operating within a space give off sensible and latent heat

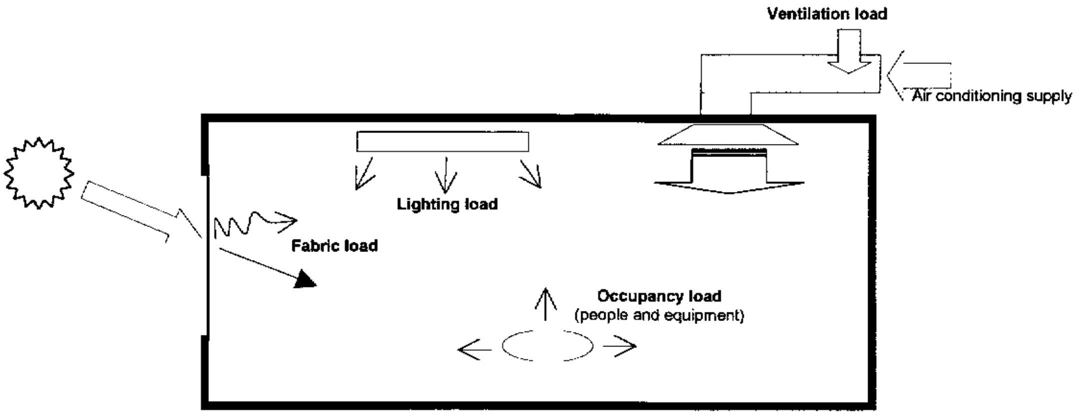

Figure 2.6. Air conditioning loads

It is noteworthy that Singapore's statutory codes on energy conservation, which were introduced in the 1980s (see Section 2.1.1), targeted fabric and lighting loads (PWD, 1983). A parametric study of office buildings in Singapore showed that fabric load continues to be the highest component amounting to 43.5% of the total heat load. Lighting contributes 19.8%, ventilation 18.1% and occupants 14.6% (Chou & Chang, 1993).

In the design of air conditioning systems, the consideration of fabric load involves a strategy of thermal zoning, i.e. a subdivision of the spaces, typically in relation to the envelope (Parlour, 1990). Zoning is an implicit acknowledgement of the impact of climate on a building's interior and the role of the building envelope as filter. Figure 2.7 shows the delineation of perimeter zones for a square office floor plan. The perimeter zone can be between 4 and 8 m deep, depending on orientation and window-to-wall ratio (Parlour, 1990). The question of orientation is deemed important in the case of thermal loads, as solar radiation can vary significantly across a building's various facades (see Figure 2.8). In the design of the system, the perimeter areas, warmed by contact with the envelope, may receive a greater share of cool air than the central zone (Lim, 1992).

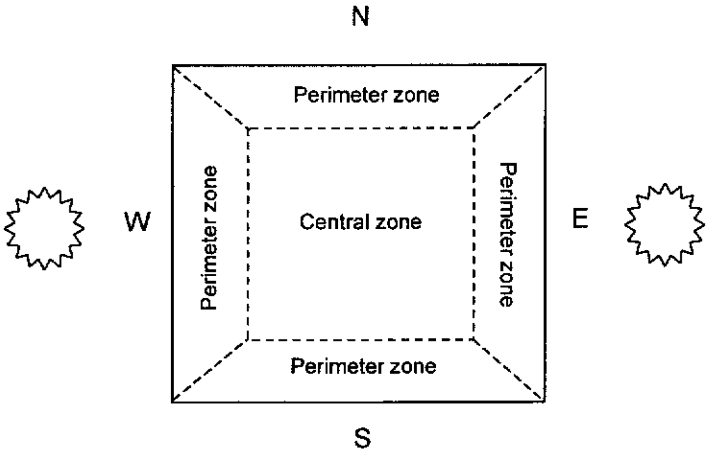

Figure 2.7. Thermal and visual zones

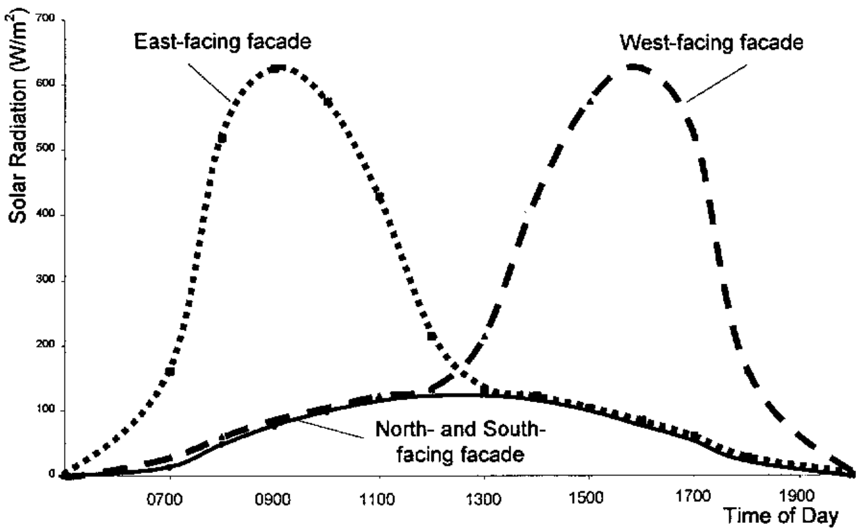

Figure 2.8. Diurnal variations in solar radiation according to orientation based on climate of Singapore (solar load data from PWD[20] Handbook on Energy Conservation in Buildings and Building Services, 1983).

Zoning for electrical lighting relies on the same principle, i.e. the perimeter zone receives more natural light hence merits a specific design response. A visual

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[20] PWD is the abbreviation for the Public Works Department.

perimeter zone can be 4 to 6 m deep for a typical office floor, depending on window-to-wall ratio and floor-to-ceiling height (Ruck, 1995). When equipped with dimmers and controls, this zone could, in theory, be designed to be less dependent on electrical lighting, thereby reducing overall energy consumption load (Choi et al., 1984).

2.2.4. Mixed- and Multi-Mode Design

In the literature there is reference to modes and buildings that are neither exclusively passive nor active. A thermal mode, for instance, that relies on ingress of outside air through its envelope (akin to natural ventilation) may be supported by warmed or cooled air from its systems. Yeang (1999) refers to these hybrid systems as *mixed-mode*. He suggests that the term may also be used in the context of a building that alternates between modes in the course of a day or year. For the purpose of clarity, however, such buildings will be referred to here as *multi-mode*. A mixed-mode system, therefore, is one that relies *simultaneously* on a combination of modes within a given space. A multi-mode operation is one in which a given space *alternates* between modes over time.

A third term of reference is proposed here: *bimodal*, which refers to a building in which two modes are in use simultaneously in different spaces, for instance, air conditioning in offices and natural ventilation in toilets.

The key issue in the consideration and evaluation of these modes is comfort and consumption (Yeang, 1999). A mixed-mode represents an intermediate level between passive and active options. Figure 2.9 illustrates this relationship in the context of comfort.

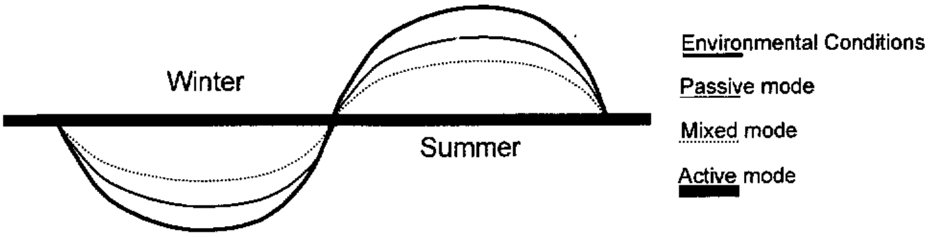

Figure 2.9. Comfort ranges of different modes (Yeang, 1999, p. 201)

Implicit in Figure 2.9 is the impact of the seasons, i.e. a building's active systems are most needed at the height of winter and summer. It is noteworthy that many of the examples cited for mixed- and multi-mode operations are situated in temperate climates where they become a means of extending the milder mid-seasons, i.e. reducing the need for heating and cooling (de Olivera, 2000). There are fewer examples cited, however, for application in hot humid climates (Khosla, 2000b). In the context of Singapore, an innovative variation of the mixed-mode system was proposed by Lim, Rao and Rao (1979), who suggested combining two *active* systems: ceiling fans and air-conditioners. The electrical fans provide the air movement necessary to offset the higher temperature settings, thereby achieving lower consumption levels than reliance on air conditioning alone. The sole example of a multi-mode office building found in the hot humid conditions is Yeang's Menara UMNO, where office spaces were designed to function with either air conditioning or natural ventilation (van Schaik, 1998).

More commonly seen in hot climates is the simultaneous application of two modes to different spaces within a building. These bimodal buildings typically deploy air conditioning in the primary workspaces and mechanical ventilation in certain non-critical areas such as toilets and fire escapes. The use of natural ventilation in frontline spaces, such as entrance foyers, takes place in some office buildings in Singapore (Powell, 1997, pp. 60-63, 66-69).

A noteworthy variation on the bimodal concept for hot humid conditions was proposed by Hyde (2000, p. 162) who suggested that the perimeter zone of a floor plan might be used in the passive mode. The inner zone, which has less access to natural light and ventilation, could be operated in the active mode. A building during conceptual design stage could, in theory, be configured to minimise its reliance on electro-mechanical systems by optimising, through plan shape and layout, the passive/perimeter zones. Hyde cites no actual examples of office buildings designed as such in hot humid conditions. He also acknowledges that the idea owes much to a similar proposal for temperate conditions in southern Europe (Baker & Steemers, 1996), which has more temperate conditions.

In a rare example of a tri-modal project, Olgyay and Boonyatikaran (2000) proposed a combination of passive, active and semi-passive[21] modes for a university campus in hot humid Bangkok. The basis for the three-way split is unclear but a reference is made to occupant tolerance for discomfort in certain non-critical activity areas. The campus was not completed at the time of the present study and no data was available regarding its impact on comfort or energy consumption (Boonyatikarn, personal communication, September 3, 2001).

There are no known examples of a tri-modal office building in Singapore or Southeast Asia.

2.2.5. The Making of Paradigms

It is argued in this section that the design process is affected by mindsets about passive and active modes, the former seen to offer better outcomes in terms of reduced energy consumption, the latter in terms of occupant comfort. These mindsets are labeled here as paradigms.

A paradigm is defined as a 'pattern or model' (Hanks & Long, 1979) which, in the design process, can be little more than a habit affecting choices (Watson, 1984). The danger with a paradigm is that it can preclude, by virtue of its emphases and assumptions, a critical exploration of issues and a meaningful search for solutions.

The passive paradigm, represented by the Bioclimatic Model, suggests that application will result in lower energy consumption, along with comfort conditions acceptable to a building's occupants. The two buildings that illustrate this, namely Mesiniaga and UMNO, were declared significant examples of the passive approach without any evidence of performance. The former was described as a *"model for environmentally responsible tropical Modernism"* (Pearson, 1993, p. 30). UMNO was declared an *"important breakthrough in passive low-energy building design [which provided a] concept for developing energy-efficient, naturally ventilated 'green' skyscrapers "* (Powell, 1998, p. 68).

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[21] It is not clear if *semi-passive* cited here is the same as mixed-mode. Their paper proposed *radiant cooling* from chilled water piping along circulation spaces. It was not clear how water condensation from these pipes would be handled, or how much energy might be expended by such a system.

In a recent post-occupancy evaluation of the two buildings, Jahnkassim and Ip (2000) suggested that these buildings succeed in delivering comfort to their occupants and reducing energy consumption[22]. Their study, however, offers no explanation why neither building was able to deliver on the level of energy predicted during the design stage (Yeang, 1992; Yeang, 1998). The observed lack of use of the natural ventilation option in Menara UMNO is attributed to user expectations, without an explanation on what these might be or how they differed from what was assumed by Yeang. There appears to be here, and in the endorsements by Pearson (1993) and Powell (1998), a willingness to embrace the passive paradigm, as represented by the Bioclimatic Model, without challenging its assumptions.

The passive paradigm has its roots in the 1970s' oil crisis. Reliance on passive principles became a key argument in a bid to reduce reliance on fossil fuels that were fast becoming a depleting resource. Designers, guided by research and standards, looked to passive principles such as daylighting (Levine, Turiel, & Curtis, 1984), envelope attributes (Turiel et al., 1984) and shading (Lim et al., 1979) as means of tempering the energy needs of a building.

The second passive catalyst, in the context of Singapore and Malaysia, came about in the 1980s and the search for identity through architectural design. Climate became a rallying cry for designers looking for neutral denominator (Abel, 1994) in countries where ethnicity and culture were politically sensitive issues. In this climate-based approach, labeled Regionalist[23], passive features such as sunshades, deep overhangs and verandahs, are symbolic of identity and rejection of the West:

> *The challenge to the development of the new tropical aesthetics is therefore predicated on both an understanding and appreciation of the inherent characteristics of the tropics as the aesthetics of shade and shadow as well as a parallel process of deconstructing modern-western hegemonic aesthetics and culture.*
>
> Tay (1997, p. 45).

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[22] The argument of Jahnkassim and Ip (2000) was made on the basis that Mesiniaga's consumption of 248 kWh/m^2/year is less than a typical Singapore office building at 260 kWh/m^2/year. A recent survey of Singapore office building consumption, however, suggests the Singapore average figure is 224 kWh/m^2/year (Nathan, 1999), against which Mesiniaga is marginally worse.

[23] Regionalism was an 1980s debate in which it was argued that architectural design should be specific to the forces of context, such as climate, culture and lifestyle (Powell, 2000).

This line of argument, of countering Western influence with climate, was not unique to Singapore. Ken Yeang and Jimmy Lim in Malaysia were simultaneously pursuing a Regionalist cause of climate-driven identity (Murray, 1984). By the 1990s, books on this subject covered examples from Indonesia and Thailand (Tan, 1994; Tan, 1996) making the notion of Regionalism truly regional and seemingly consensual.

The third catalyst emerged in the 1990s under the umbrella of 'ecological design'. By then, the issue had expanded to a global scale (Daniels, 1997). The Green debate brought a holistic view of design, beyond mere energy use and occupant comfort.

> *'Green buildings'... are designed, constructed, renovated and demolished in an environmentally sensitive and responsible manner. [They] exhibit a high level of environmental, economic and engineering performance in areas of importance, including energy conservation and efficiency, indoor air quality and resource and materials efficiency. Green building concepts are applicable throughout the entire lifecycle of a structure, including design, sitework, construction, operation and demolition.*
>
> Fedrizzi (1995, p. 36)

In the design strategy for Green buildings, it has been argued that passive systems are no less important (Daniels, 1997; Yeang, 1999). They reduce reliance on electro-mechanical devices, consume less energy from fossil fuels and therefore release less ozone-depleting gases linked with global warming.

The passive approach can be seen as a subset of the Bioclimatic, itself a low-energy approach. The Bioclimatic, in turn, falls under the broader umbrella of Ecological (Green) design, which embraces issues affecting the environment at large.

Figure 2.10 suggests that the shift from Passive to Ecological results in an increasing complexity of the design process. Whilst the former focuses on specific passive features and systems, the latter looks at how they come together, often in combination with active systems, to generate desirable outcomes. It also represents a shift from local concerns, in terms of what happens in and around the building, to global impact, referring to how it affects the environment beyond its immediate confines.

With Ecological design, the passive paradigm acquired a deeper resonance and global significance.

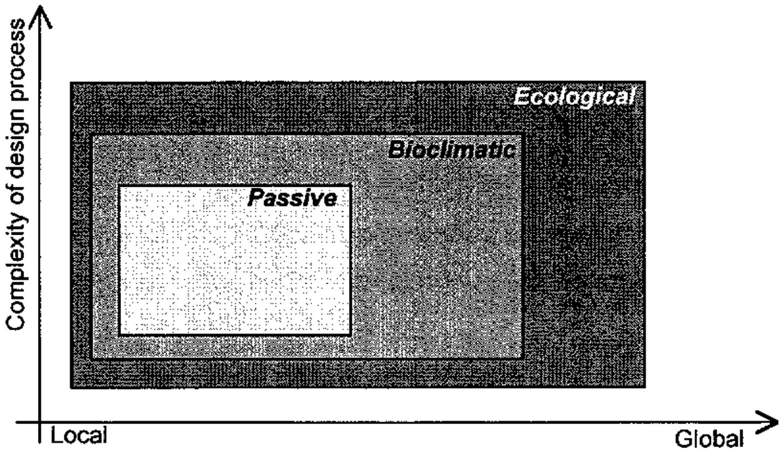

Figure 2.10. Relationship of Passive, Bioclimatic and Ecological approaches[24]

The inverse of the *passive paradigm* is the *active paradigm*. Whereas the former argued from a platform of lower reliance on energy, the latter gets its imperative from the need for human comfort.

Cannon (1939) suggested that the development of the thermally near-stable environment inside buildings should be regarded as one of the most valuable advances in building technology. Markham (1944) took it a step further by suggesting that a nation that gives its population the ideal indoor climate develops an edge in terms of health, energy, trade and culture.

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[24] The term Bioclimatic was first coined by Victor and Aldar Olgyay and was aimed at informing a designer the conditions under which thermal comfort would be possible (Olgyay and Olgyay, 1954; 1963). It preceded the other terms by about 20 years.

Recent comments by Lee Kuan Yew[25], Singapore's influential Senior Minister, suggest that the air-conditioner continues to be seen in a pivotal role, at least in the hot humid climate:

> *The humble air-conditioner has changed the lives of people in the tropical regions. Before air-con, mental concentration and with it the quality of work deteriorated as the day got hotter and more humid. Now, lifestyles have become comparable to those in the temperate zones and civilisation in the tropical zones need no longer lag behind.*
>
> Lee (quoted in Straits Times, 1999)

His comment suggests that beneath the argument for human comfort is the premise of individual and national productivity. Echoing the sentiment, a recent government report on energy use in Singapore argued that *"energy efficiency measures should not be pursued to the detriment of our ability to compete on the global market"* (IACEE, 2000, p. 11). It is noteworthy that this report did not advocate reduced reliance on air conditioning, even though this was identified as a key national consumer of energy. Much of what was argued in this report concerned improvements to the technology by which comfort is delivered. In a sense, this is not different from arguments made by some advocates of passive design, who seem to suggest that science is the key to improved building performance. The explanation, for instance, of the natural ventilation system in Menara UMNO is frequently cited as an analysis of wind velocities and indoor temperatures (Powell, 1998; Jones and Yeang, 1999).

The question that follows is how a paradigm or environmental framework, such as the Bioclimatic Model, can be critically evaluated. Coldicutt (1995) warned against a tendency, in environmental problem solving, to oversimplify the problem and its solution on the basis of science alone:

> *[There should be] caution attempting to generalise about environmental theory and the role of sciences: the problem is properly left complex... rather than seeking to generalise about science, it is more fruitful to generalise about the various types of ignorance, types of problems, types of theory...*
>
> Coldicutt (1995, p. 106)

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[25] Lee Kuan Yew is the former Prime Minister of Singapore, now elder statesman. He is widely regarded as the father of modern Singapore (George, 2000).

She adopted a Taxonomy of Ignorance[26]; a series of litmus tests that gauge the usefulness of a theory. The Taxonomy consists of four questions about the assumptions made by a theory or model:

- *Absence* – What should be present in or absent from the problem?
- *Confusion* – How should the key concepts be defined?
- *Uncertainty* – What degree of certainty is relevant?
- *Inaccuracy* – How accurate does it need to be?

It could be asked, in the context of Menara UMNO, what degree of accuracy is required, or indeed possible, in the design of natural ventilation? Coldicutt's Taxonomy will be revisited in Chapter 8, against findings from the present study that can shed light on the Singapore office building and the Bioclimatic Model.

2.3. Comfort

Comfort is discussed in terms of thermal comfort (see Section 2.3.1) and visual comfort (see Section 2.3.2). These are reviewed for the theory on how comfort takes place and the premise behind comfort standards. Section 2.3 ends with a deliberation on the nature of comfort (see Section 2.3.3) in which the question becomes one of how perception of thermal and visual conditions overlap. Section 2.4.3 re-examines these issues by suggesting that the study of comfort expectations might be an avenue for bridging the gap between thermal and visual comfort.

2.3.1. Thermal Comfort

As air conditioning gained widespread acceptance from the 1930s to the 1960s, research in thermal comfort increasingly focussed on establishing universally applicable standards that pertained to the design of these systems (Kwok, 2000). This posed the question of what it means to be thermally comfortable and what

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[26] The Taxonomy of Ignorance was first proposed by Smithson (1988) and followed upon by Coldicutt and Williamson (1991) and Coldicutt (1992).

parameters, affecting human comfort, need to be addressed in the making of indoor environments (Rohles, 1980).

The definition of thermal comfort, along with other responses to the thermal condition, are stipulated in ANSI-ASHRAE Standard 55, Thermal Environment Conditions for Human Occupancy (1992):

- *Thermal comfort*: the condition of mind that expresses satisfaction with the thermal environment
- *Thermal sensation*: a conscious feeling commonly graded into categories of cold to neutral to hot
- *Acceptable thermal environment*: an environment that at least 80% of the occupants would find thermally acceptable.

Thermal comfort research, and the design guidelines it generated, often relied on climate chamber[27] studies carried out in Europe and the USA prior to the 1980s (Oseland & Humphreys, 1994). From these explorations, six key variables were identified as affecting the perception of thermal comfort (ASHRAE, 1993; Auliciems & Szokolay, 1997):

- *Environmental*: air temperature, radiation, relative humidity and air movement
- *Occupant-related*: clothing and metabolic rate

The *'heat-balance model'* (de Dear, 1993) emerging from the studies of Fanger (1972) and McIntyre (1980) was based on the notion that the human body, so as to maintain its core temperature, strives for stability via a series of exchanges with its environment (Griffiths, Huber, & Baillie, 1988). These exchanges involve thermo-regulatory mechanisms of the body, primarily adjustments to blood flow near the skin and sweating, plus behaviour relating to clothing insulation and activity levels.

The model has been dubbed the "*constancy hypothesis*" by Auliciems (1989, p. 16) because it alludes to the need to maintain a steady-state condition of equilibrium.

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[27] A climate chamber is a controlled environment within which subjects are surveyed for their thermal state, while conditions are monitored and/or altered.

In this context, the aim of the mechanical cooling/heating system becomes one of creating and maintaining the thermal environment such that the human regulatory systems, in themselves, need only play a small role (Griffiths et al., 1988). Environment and physiology are believed to interact, resulting in sensation to which an individual reacts in an objective manner (see Figure 2.11).

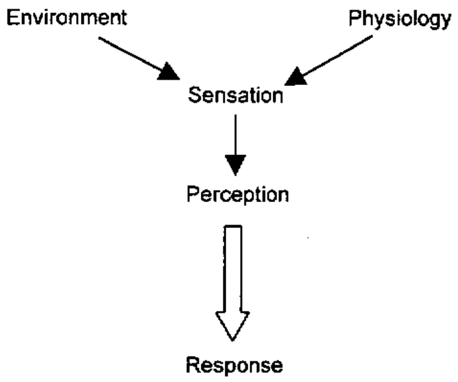

Figure 2.11. Objective assessment of comfort based on the heat-balance model (adapted from Raw and Oseland, 1993, p.5)

In order to facilitate design decision-making, the model had to yield prescriptive guidelines that could be applied to the making of comfort. The research supporting these guidelines had to demonstrate a relationship between environmental condition/s and human response, with a view to developing a predictive framework and/or a range of optimum conditions.

In this type of research, occupant response was, and continues to be, solicited by way of surveys and rating scales. The three most frequently used scales are the ASHRAE (Thermal Sensation), Bedford (Thermal Comfort) and McIntyre (Thermal Preference). A condition was deemed to be judged 'acceptable' if occupant votes fall within specific responses on a scale (Brager & de Dear, 2001).

Table 2.1 shows each of these scales along with the acceptability responses, highlighted in bold italic.

ASHRAE **Thermal Sensation** (7 point scale)	**Bedford** **Thermal Comfort** (7 point scale)	**McIntyre** **Thermal Preference** (3 point scale)
Hot +3	Much Too Warm +3	Cooler
Warm +2	Too Warm +2	
Slightly Warm +1	***Comfortably Warm +1***	
Neutral 0	***Comfortable 0***	***No Change***
Slightly Cool –1	***Comfortably Cool –1***	Warmer
Cool –2	Too Cool -2	
Cold –3	Much Too Cool –3	

Table 2.1. Summary of ratings scales commonly used in thermal research

In addition to needing tools with which to solicit response, the question of comfort needed to be understood in terms of how the six variables interact and affect the individual. This meant being able to predict if, for instance, an increase in temperature when accompanied by higher air speeds would result in the same thermal sensation.

A unified descriptor of the variables that *"corresponds with human response"* (Oseland and Humphreys, 1994, p. 14) is known as a Comfort Index. Indices are either rational, i.e. derived from detailed and mathematical knowledge of heat exchange between the person and the environment, or based on empirical observations of occupant response. Predicted Mean Vote (PMV) and Effective Temperature (ET*) are the most commonly used indices, both rational, the former written into ISO Standard 7730 (1994) standards, the latter into ASHRAE Standard 55-92 (1992).

PMV predicts the percentage of a population likely to be dissatisfied on the ASHRAE/Thermal Sensation scale for a set of conditions. It is based on Fanger's (1972) mathematical formulation for heat-balance in the human body, which is premised on the idea that thermal sensation in humans is predictable and the mechanism by which it occurs, universal.

ET* is defined at *"the temperature of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question"* (Auliciems and Szokolay, 1997, p. 36). It combines the environmental variables into *equal comfort lines* on a psychometric chart; any combination of variables along the same comfort line should, in theory, produce the same sensation on occupants. It was the most widely used index for 50 years since its inception in 1923. In 1977, ET* was revised to include clothing and metabolic rate, giving rise to the Standard Effective Temperature (SET*).

With these indices, the range of conditions representing a comfortable thermal environment could be plotted. This is referred to as the *Comfort Zone*. The idea of the comfort zone was first mooted by Olgyay (1963), who combined three environmental variables, dry-bulb temperature, wet-bulb temperature and air movement, into a Bioclimatic Chart. This chart was later revised by Givoni (1969) to describe conditions within a building, thereby becoming useful to the design process.

Indices and comfort charts are the foundations of comfort design. Both PMV and ET*, however, came from a small number of climate chamber experiments, all based on test conditions. The standards they support, however, were subsequently applied in a generic, universal way to all manner of interior environments (Arens et al., 2001).

One of Fanger's key discoveries, which was taken to justify the universal use of his thermal comfort equation, was that the preferred temperature is invariant, i.e. not significantly dependent on age, sex, etc. (Oseland & Humphreys, 1994). This precept was instrumental in the development of international standards of which the two internationally most accepted are the ANSI-ASHRAE 55-92 (1992) and ISO 7730 (1994).

It has been shown, however, that PMV, in non-air-conditioned buildings in warm climates, predicts a warmer thermal sensation than occupants actually feel (Fanger & Toftum, 2001). Neither PMV nor ET* allow for acclimatisation (Oseland & Humphreys, 1994), a phenomena in which people appear to respond partly on the basis of conditions that they are familiar with. Some studies also found that simple measures, such as air temperature and globe temperature, sometimes correlate better with human response than the more elaborate indices (Busch, 1990).

The growing consensus in the literature is that the heat-balance model is not sufficiently representative of real-world settings in terms of the range of conditions people deem acceptable (Nicol & Humphreys, 2001). Brager and de Dear (2001) argue that it is very difficult to meet the standards' narrow definition of thermal comfort without mechanical assistance, even in relatively mild climatic zones. This therefore precludes reliance on passive systems and predisposes the deployment of mechanical cooling/heating.

With the advent of comfort zones and indices, the making of human comfort became an engineering problem, premised on prescribing optimal conditions. In this framework, it was difficult to account for cognitive factors in the interpretation of bodily sensation or the value placed upon a particular sensation (Griffiths et al., 1988). The heat-balance model has been criticised as little more than a *"mechanistic stimulus-response tradition, where comfort is seen in quantifiable condition, arising directly from thermal sensation through physiological stimuli of a thermal nature"* (Pacuik, 1989, p. 1).

Despite the limitation of the model, engineers and researchers continue to rely on the heat-balance model and the standards[28] it supports (Oseland & Humphreys, 1994). This results in a considerable amount of energy being consumed through reliance on electro-mechanical systems. The oil crisis of 1973 started a trend in research that began to address the question of comfort with help from the fields of social and environmental psychology (Griffiths et al., 1988). It was subsequently shown that occupant response to thermal comfort surveys could be influenced by 'non-thermal' factors, such as the colour and materials in a room (Rohles, Bennett, & Milliken, 1981), what they were told about the thermal environment and the season of the year (Rohles, 1980).

These studies suggest that a building's occupant is not a passive recipient of conditions; that s/he brings a set of expectations to everyday situations. This recognition of the occupant as an active participant in the making of his/her comfort, is the basis for the *adaptive model* of thermal comfort (de Dear, 1993).

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[28] The Singapore standards for thermal comfort are found in the PWD Handbook for Energy Conservation (1983), which specifies indoor conditions for air-conditioned buildings in terms of temperature (23°C – 27°C), relative humidity (<75%) and air movement (<1.25 m/s).

Studies in hot humid climates were instrumental in highlighting the limitations of the heat-balance model. Nicol (2000) showed that the ISO standard does not apply to buildings in the Tropics, particularly naturally ventilated ones:

> *The condition which [subjects] find comfortable (or neutral on the ASHRAE scale) differ from predictions of ISO 7730, particularly in hot climates when buildings are not mechanically cooled. ISO 7730 overestimates the occupant response on the ASHRAE scale at high temperatures. It predicts discomfort at temperatures which subjects in field surveys find comfortable.*
>
> Nicol (2000, pp. 1-2)

Two earlier studies carried out in Singapore and Bangkok support this argument. It was shown that occupant response in naturally ventilated homes (de Dear, Leow, & Foo, 1991c) and offices (Busch, 1990; de Dear et al., 1991c) deviated significantly from that in air-conditioned buildings and climate chambers (de Dear, Leow, & Ameen, 1991a; de Dear, Leow, & Ameen, 1991b).

In research carried out in other hot humid cities in Southeast Asia, this deviation was confirmed. Karyono (1995b) found that neutrality for office workers in Jakarta[29], Indonesia, occurred at 26.4°C, with a comfort range between 23.3°C and 29.5°C. This was 1.2°C higher than predicted by PMV. In a similar study in Bangkok[30], Thailand, Jitkharjornwanich et al. (1998) found that neutrality was higher, at 27.1°C.

Arguments on thermal comfort continue to move in the direction of *psychological* variables affecting the perception of comfort (Oseland & Humphreys, 1994). Brager and de Dear (2001) suggest that this *"psychological dimension to adaptation"* must incorporate *"expectations and thermal preferences"* (p. 61).

De Dear (1993) further suggests that the question of comfort expectation is critical to the field as it opens up the *"cognitive realm"* (p. 130) in the question of thermal comfort. By this he refers to the perceptual framework that influences the exchange between individual and the environment. There are also calls to look at the social, cultural and economic considerations of how people judge the thermal quality of their environment (Griffiths et al., 1988).

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[29] A survey of 596 subjects in air-conditioned and naturally ventilated buildings.

[30] A survey of 593 subjects in indoor and outdoor, air-conditioned and naturally ventilated spaces.

It is noteworthy that Fanger, the 'father of PMV', recently argued for the role of expectations. Fanger and Toftum (2001) suggest that an 'expectancy factor' should be applied to correct PMV predictions according to geographical and/or national location. This involves ascribing a number to the notion of expectation, according to population group, without actually delving into its nature or cause.

Elsewhere it has been suggested that any empirical, rational approach is in itself insufficient. Olweny, Williamson and Sufianto (1999) argued that socio-cultural factors make a difference to the way thermal preferences are perceived. In comparing responses from subjects in Uganda and Indonesia, they showed that attitudes differed with regard to housing, climate and adaptive response, and that these differences were tied to real-world factors. Meanwhile, Oseland (1995) found that a group of subjects, when tested in three environmental contexts, i.e. climate chamber, workplace and home, progressively became more tolerant with thermal conditions, accepting temperatures 3K lower at home than in the climate chamber. Griffiths, Huber and Baillie (1988) suggested that shifts in the acceptability of comfort across different types of environments might be connected with attitudes towards energy conservation. This, in turn, affects their tolerance for discomfort.

Raw and Oseland (1993) argued that thermal comfort must be rethought in terms of a subjective assessment of the environment, in which context and culture affect both perception and response (see Figure 2.12):

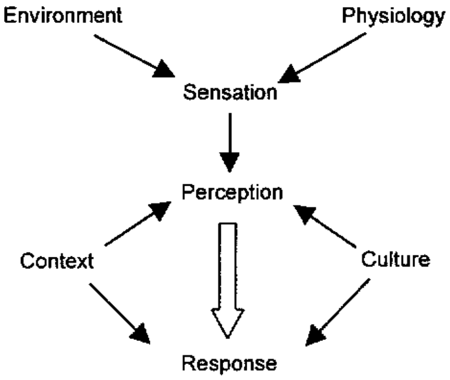

Figure 2.12. Subjective assessment of comfort
based on the adaptive model (Raw and Oseland, 1993, p. 5).

Thermal comfort research, having explored the physiological dimension, appears to be moving on to an elaboration of the psychological, looking for new instruments of investigation and new ways of defining the value of comfort to an individual and group (Auliciems, 1981; Holmer & Nicol, 2001).

2.3.2. Visual Comfort

Unlike the question of thermal comfort, the literature on visual comfort embraces the qualitative dimension of human perception more readily, supporting psychological as well as physiological premise. Studies on the impact of light on mood, for instance, are deemed relevant to the question of lighting (McCloughan, Aspinall, & Webb, 1999) as are ones that evaluate the impact of illumination levels on task (Ruck, 1989).

At its most basic level of impact, light has been shown to affect biorhythms of the human body and its production of hormones and vitamins (Veitch and Arkkelin, 1995). Natural light, in particular, is connected with a sense of well being that is part psychological, part physiological.

The visual condition, unlike the thermal, is also seen to have an aesthetic dimension in the perception of architecture and space (Phillips, 1975), a sensual quality that goes beyond its quantitative descriptors. This effect of light cannot be easily dissected into stimuli and response, cause and effect.

Designing with light begins with two options, natural and/or artificial light, to which there can be an infinite degree of combinations and variations. The literature on the visual environment reflects on this duality, broadly delineating lighting design into a consideration of *"comfort and pleasure"* (Lim, 1999, p.12).

Comfort

Typically, light is discussed quantitatively in the context of task. Unlike thermal comfort, in which research is directed at finding a set of universally applicable conditions, lighting needs are often seen to be specific to space types, such as is the case in the Singapore Standard, CP38; Code of Practice for Artificial Lighting in Buildings[31] (1987). Illuminance design is also about minimising distraction or

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[31] In the Singapore codes that govern lighting of office building, workplace illuminance range is stipulated at 300-750 Lux (500 recommended) with an upper consumption limit of 20W/m^2 (Singapore Standard, CP24, 1982; Singapore Standard, CP38, 1987). Circulation areas are prescribed between 50-100 Lux, at 10 W/m^2; lecture theatres are 200-500 Lux and 25 W/m^2, etc.

discomfort in the visual field (Daniels, 1997). This is unlike thermal comfort again, which seems to have focused on finding an optimality of comfort conditions.

As with air conditioning, the energy crisis of 1973 resulted in a flurry of international interest in consumption via lighting. In 1974, ASHRAE and Illuminating Engineering Society (IES) formed a task committee on energy budgeting procedure, which led to the publication of Chapter 9 of ASHRAE 90-75 (1975), later adopted by the American National Standards Institute (Lim, 1999).

The parameters that lighting designers most frequently concern themselves with are as follows (McLean, 1995; Ruck, 1989):

- *Light intensity and distribution:* appropriate task-related illuminance levels
- *Glare:* contrast between sources of light, which can cause discomfort and/or disability
- *Colour:* choice between warm and cool light
- *Interior design:* primarily the reflectance of surfaces

There is considerable literature on the impact of lighting on performance, a factor deemed to be critical in the workplace (Bullet and Fairbanks, 1980; Ne'eman, Hopkinson and Vine, 1984; Ruck, 1989; Wells, 1965). Past studies on workplace lighting in Singapore however have mostly focussed on energy consumption and conservation measures. Daylight use, through the 1980s and 1990s, was considered primarily for its impact on air conditioning load and potential energy savings through reduced reliance on electrical fittings (Lee, 1993; Tay, 1994; Woods, 1987; Woods & Pickup, 1985; Ullah, 1996).

The premise and approach of these studies was largely engineering-based. They began with the analysis of how much natural light is available, which was then assessed in terms of its impact on perimeter zones of a building where it could be used to reduce reliance on electrical light. The intent was that the overall illuminance level, as a combination of these two illumination types, might be managed through environmental controls, such as blinds, dimmers and switches (Levine et al., 1984).

Pleasure

The qualitative questions of visual comfort are often, though not exclusively, discussed in the context of natural light. It is generally accepted in the literature that natural light is preferred over electrical light for reasons of improved quality of the environment (Ruck, 1995).

In the context of the workplace, Markus (1967) found in a study set in the UK that 95% of people preferred to work with natural light as compared with electrical light. Heerwagen and Heerwagen (1984) likewise noted that office workers in Seattle overwhelmingly favoured daylight at their workplace. Parpairi (1999) found that daylight was preferred in a Cambridge library even where it caused disability and discomfort glare.

It is noteworthy that these studies were carried out in cold climates where natural light may also be appreciated as a source of warmth. With regard to the impact of climate on preference for natural light, Ruck (1989) sounds a cautionary note:

> *While there is a strong desire for daylight and sunlight in temperate climates, these conclusions are unlikely to be applicable in tropical climates.*
>
> Ruck (1989, p. 112)

Prescriptions for architecture in the hot humid climate often recommend *shade* as a key objective, i.e. the exclusion of large amounts of natural light (Fry & Drew, 1956; Givoni, 1969).

Natural light is often also attributed curative and therapeutic properties. These have been known since antiquity, reflected in Greek and Roman writings (Swarbrick, 1953; Phillips, 1975) and seen to make a difference to recovery from poor health (Baker, 2001). In a study set in the UK, Keep, James and Inman (1980) reported that a comparison of groups of patients with and without access to daylight showed that those who had access were less likely to be disorientated or delusional. Ulrich (1984) found similar effects on recovery but he argued that such outcomes might be due to the presence of windows and a preference for views to the outdoors. Others have echoed this sentiment, suggesting that preference for natural light falls within a larger preference for connectivity with the outdoors (Collins, 1976; Leather, Pygras, Beale, & Lawrence, 1998; Phillips, 1975).

2.3.3. The Nature of Comfort

It would seem that thermal and visual comfort research occupies separate domains. Visual comfort standards, for instance, suggest that user acceptance is contingent on task; it is not clear if the same criterion might apply for thermal comfort. Thermal comfort, meanwhile, appears to be influenced by acclimatisation. It is unclear if this affects the perception of light as well. In the last twenty years there has been a convergence of the two domains as thermal comfort research begins to look at psychological parameters affecting perception, a factor that has long been accepted in visual comfort studies. A cognitive framework for comfort expectation, as yet under explored in both domains, could well apply to both types of comfort.

Related to this question of how research views comfort is how designers view it in the making of buildings. Whilst research appears to overly differentiate the comfort types, advocates of climate-responsive approach do not seem to make a distinction at all.

Yeang's Bioclimatic approach, for instance, is broadly optimistic on both counts of the thermal and visual environment. Menara UMNO is geared for simultaneous reliance on both natural ventilation and daylight (Yeang, 1998a). Hyde (2000) meanwhile, speaks of passive zones without differentiating between thermal and visual conditions. There is an implicit assumption that as passive-reliance is a desirable end in itself, daylight and natural ventilation are likely to be equally desirable.

Coutier, Kammerud and Place (1985) sound a warning that passive buildings all too often neglect the question of comfort. They refer to the *"thermal non-uniformities"* (p. 62) within these buildings, the *"large amounts of solar radiation ... hitting either the surfaces or the human body [causing] warm discomfort during many hours of the year"* (p. 68).

Elder and Tibott (1981), in their post-occupancy evaluation of an energy-efficient building with passive features, make the point that thermal comfort is most often compromised by internal asymmetry of ambient conditions, particularly in areas nearest the envelope.

The underlying implication in these studies is that indoor variability is a key cause of discomfort and that this results, at least partly, from a failure to account for the interaction between thermal and visual conditions. Coutier et al. (1985) go on to say that in failing to understand these dynamics, and overly focusing on energy issues, these passive buildings ultimately risk failure on both counts of comfort and consumption.

2.4. Outlining Research Directions

In light of the complexities of theory and practice, evident in the literature reviewed so far, the present research narrows the focus of study to specific aspects of the climate-building equation. These have been identified in the research hypothesis as the questions of *indoor variability* and *comfort expectations.*

Against these specific issues, the literature is viewed as a canvas; one that outlines gaps in what is known and suggests how broadly the data-gathering net should be cast. Stemming from necessity, the scope is narrowed. For instance, emphasis on thermal comfort is greater than visual comfort, largely because the former is known to have a bigger impact on energy consumption. Urban parameters affecting building performance in terms of air conditioning and waste heat are not discussed. The analysis is confined to intra-building assessments on the assumption that as all buildings selected are situated in high-density urban settings, the 'urban factor' should apply equally.

Later in the thesis, the literature provides a framework for discussions and implications (see Chapters 7 and 8). In the present section, the questions of Context (see Section 2.4.1), Variability (see Section 2.4.2) and Comfort Expectations (see Section 2.4.3) are recapitulated with a view towards developing a research strategy and framework in Chapter 3.

2.4.1. The Forces of Context

In the context of Singapore, it has emerged that the questions of thermal comfort and statutory control are critical. The making of thermal comfort, via air conditioning, has been identified as the biggest consumer of energy in the context of the office building (IACEE, 2000). The literature is unclear, however, on whether the operation of electro-mechanical systems takes advantage of the wide bandwidths of light and temperature permitted under the Singapore statutory codes (PWD, 1983), with a view to conserving energy.

The literature on Singapore also suggests that statutory controls have long been the instrument for influencing building design, particularly with regard to energy use and conservation (Nathan, 2000b). The role and impact of OTTV, the building envelope standard formulated in the early 1980s, has recently been reviewed. The new standard, ETTV incorporates adjustments to the way in which envelope transmittance is calculated and the threshold that is prescribed (Goh, 2001). The stated objective with these revisions is that they will yield greater energy savings (Koo, 2001). It is noteworthy, however, that the computation of OTTV, as an average of the thermal transmittance of all façades of a building, is essentially unchanged. It remains unclear if OTTV in the past has been used in a manner that addresses solar load meaningfully, or if the final figure for the building conceals widely differing fabric loads across its facades.

Whilst designers and engineers in Singapore are required by law to comply with the codes, it is unclear if they comply with the spirit of the regulation by giving due consideration of solar load and minimisation of active-mode reliance. The present study will look at general compliance with these codes to better understand if statutory controls and design practice, with regard to envelope design and indoor conditions, strive for the same outcomes.

With regard to the question of the hot humid climate, the literature on architectural response can be broadly grouped into pre and post 1980s. The prescriptions of Fry and Drew (1956) and Givoni (1969), examples of pre-1980s text, seem difficult to apply in the high-rise, high-density context of much of Southeast Asia today. The urban reality of the cities along with population affluence and expectations challenge the passive ideals of deep roof overhangs, light weight structures and free air flow (Soebarto, 1999).

Much of the post-1980s literature concerns itself with questions of identity and style (Abel, 1994; Murray, 1984). Of the many advocates for climate-response, the present thesis has opted for Yeang and his Bioclimatic Model (Yeang, 1994; Yeang, 1996). The question with regard to Yeang's Model is if it delivers on its promises of occupant comfort and lower energy consumption. It was suggested in Section 2.2.5 that the *passive paradigm*, which embraces the Bioclimatic ideal, has hampered a critical assessment.

The final parameter of context, the Office Building, appears to be often discussed in terms of how IT has changed the nature of work and organisational culture (Duffy, 1997). Whilst IT is evident in the Singapore workplace, there is a need to view this trend with caution. In a study of office design across Europe, van Meel (2000) noted that workplace culture and national values, more than technological advances alone, play a significant part in the physical design of the office. The literature is unclear on how IT has affected the workplace in Southeast Asia. However, whilst it is acknowledged here that the nature of work and workplace culture are important to the question of design, these will be addressed in the present thesis only where they overlap with the question of climate response.

The notion of *Fresh Air Architecture* (Hartkopf et al., 1993), for instance, attempts this by linking indoor conditions and climate with workplace productivity and satisfaction. This represents an important perspective that is, as yet, under explored in the context of the hot humid climate. The present thesis will review how outdoor conditions are perceived in the making of indoor comfort in the Singapore workplace, with a view to establishing if the *fresh-air* idea has potential for application.

In general, on the broader question of context, it could be argued that the current shortage of post-occupancy data on Singapore office buildings in itself represents a handicap in the critical assessment of theory, statutory controls and future approaches. The present study will begin by generating a database that looks at Singapore office building in terms of what it does, by way of envelope design and deployment of modes, before asking how well it performs.

2.4.2. The Question of Variability

Hyde (2000) suggested that a key difference between a space operating in the passive mode and one that is active-reliant is the degree of indoor variability. A passive-reliant space tends to be far more variable due to its link with the outdoor conditions. It has been argued this link with the climate might be better exploited but that the standards for indoor thermal comfort predispose buildings towards active solutions (Brager & de Dear, 2001). This is because they seek optimal conditions for all spaces, which presupposes conditions of stability and uniformity (Arens et al., 2001).

There are many critics of these standards, some advocate new 'adaptive standards' (Oseland, 1993; Brager and de Dear, 2001), while others argue the merits of the 'variable' building. Zmeureanu and Doramajian (1992), for instance, suggest that temperature drifts[32] in summer conditions can reduce energy consumed by air conditioning systems by 11%. Kwok (2000) argues against the 'thermal boredom' that results from unchanging environments, suggesting that there is pleasure to be had from a variable, non-uniform setting.

Arens et al. (2001) suggest that there are three types of variability:

- *Non-uniformity within a space* due to links with outdoors
- *Asymmetry within a space* due to proximity with envelope or position of electro-mechanical systems
- *Variability across spaces* due to occupant movement, for instance from workplace to transit space

Of these, there is a need for particular caution with regard to the first two. The failure of the passive approach, it has been suggested, is due to designers neglecting non-uniformity and asymmetry due to outdoor links and proximity with envelope, and the impact that these have on occupant comfort (Coutier, Kammerud, & Place, 1985, Elder & Tibbott, 1981).

The arguments in favour of active-reliant stability typically centre on the desirability of control, with many studies focussing on environmental controls provided by

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[32] A temperature drift occurs when a cooling system allows a building's indoor condition to rise or fall marginally, in sync with outdoor conditions.

active systems, such as light switches and thermostats. It has been argued that controls that allow people to decide on their preferred environmental condition are popular with occupants (Arens et al., 2001) and enhance satisfaction with the thermal environment (Pacuik, 1989), even where the opportunity to use these controls was not taken (Guedes, 2000).

Nicol and McCartney (1999) sounded a cautionary note on the design of environmental controls: the existence of controls did not mean that they were used. Merely adding up the number of controls, they suggest, did not give a good measure of the success of a building or its adaptive opportunity. The role of environmental controls in Singapore, their existence and use in office buildings, is not evident in the literature. The present study will review the presence and usage of these controls, both in passive and active systems.

On a broader note, it is worth asking in the present study if the design of passive and active systems can be meaningful from the standpoint of energy consumption versus occupant comfort alone. It is proposed here that *variability* versus *control* might be a better alternative. In Figure 2.13, two ways of viewing mode options are illustrated. The bottom tier suggests that the deliberation of passive and active design tends to be polarised, when confined to questions of consumption and comfort. The graph below suggests that with variability and control, the passive versus active question has shades of meaning into which the mixed-mode option might be slotted. The design process here becomes one of deciding on the degree of variability and control.

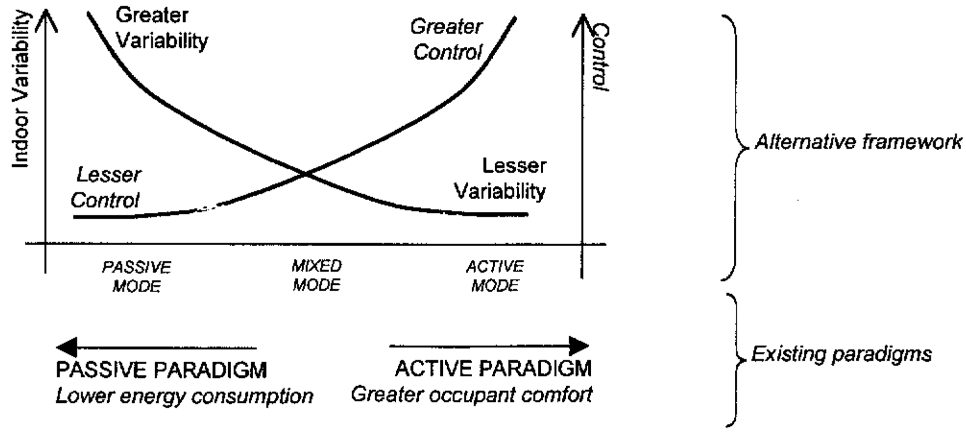

Figure 2.13. Variability versus Control

The present study will address these issues by asking, firstly, if variability in itself is a factor affecting comfort. It will also examine how much variability exists as a result of active and passive modes and features. Finally, it will look at the adaptive opportunities available to occupants to determine if they are used and affect the perception of comfort.

2.4.3. The Importance of Comfort Expectations

The debate on thermal comfort is caught between two seemingly contradictory models: heat balance and adaptive (Holmer & Nicol, 2001). The heat-balance model predicts human response fairly accurately within a narrow bandwidth of conditions, whilst the adaptive model suggests that beyond these bandwidths, people adapt to the environment through behaviour and perception (Nicol, 2000). Occupant response, in the latter, goes beyond mere physiological comfort, requiring a consideration of the human condition in the broadest sense, embracing socio-psychological parameters (Griffiths et al., 1988; Olweny et al., 1999).

In theory, the problem is partly one of reconciling the two perspectives. Both models are viewed as intrinsically correct, albeit applicable to different conditions. This hampers a unified theory of comfort, one that applies to people in varying contexts.

On the cause of this disparity, it has been suggested that not enough is understood about comfort expectations which are, at least partly, responsible for the way people judge what is acceptable (Brager & de Dear, 2001). Advocates for the adaptive model argue that expectations can be affected by a wide range of factors from climate to building type (Nicol & Humphreys, 2001). Understanding comfort expectations has the potential of bridging the gap between the two models and to allow for the emergence of design standards that do not predispose designers towards active, energy-reliant solutions (Holmer & Nicol, 2001).

The 'expectation' question is partly methodological: how does one solicit response for comfort expectations? Much of the current research relies on semantic rating scales (see Section 3.4.3.1) which are deemed inadequate in dealing with underlying factors, such as preference and attitudes, which affect human response (Canter, Brown, & Groat, 1985; Williamson, Coldicutt, & Riordan, 1995).

It is noteworthy also that in much of the research, comfort is seen typically to be a question of 'degree.' Semantic rating scales are often used to solicit response in terms of degree of sensation or comfort, which limits the equation of comfort to one of stimuli and response.

It is suggested in the present study that comfort might also be a question of 'type' which, in turn, might be modes of operation with which occupants are familiar. This examination of type would open up the question of how acceptance occurs, i.e. on what criteria does one decide if a given set of conditions is acceptable? This delineation of 'degree and type' opens up new avenues in the exploration of comfort expectations, which will be discussed in greater depth in Chapter 3.

Finally, on the question of visual comfort, there appears to be a general optimism in both research and design with regard to natural light (Heerwagen and Heerwagen, 1984; Parpiari, 1999). Advocates of climate-response do not appear to differentiate between thermal and visual conditions in recommending passive modes (Hyde, 2000). Critics warn that this may be something of a simplification in hot climates, where natural light may be seen as a source of warmth (Ruck, 1989), and in passive buildings, where occupant discomfort often results from the interaction between thermal and visual conditions (Coutier et al., 1985). The present study will assess the impact of light on the perception of thermal comfort. It will also ask what comfort expectations apply to visual comfort.

Chapter 3. Research Method

3.0. Preamble

Beyond the literature reviewed so far, there still needs to be considered a theoretical framework for how to proceed with the research. This chapter begins with a philosophical overview of this question (see Section 3.1). It then proceeds to elucidate research strategy (see Section 3.2), decisions about context and case studies (see Section 3.3), instrument and analyses (see Section 3.4).

Where a theoretical framework affects a choice of instrument or analysis, this is stated as such and the arguments are presented. This is then followed by a description of the procedure. Where the thesis relies on a pragmatic, atheoretical slant on what is to be gathered, observed and collated, it proceeds to explain the procedure without attempting to force onto it any precedent or precept.

3.1. Research Philosophy

A research philosophy effectively guides the way in which data is gathered, analysed and how conclusions are drawn. Van Meel (2000) delineates two philosophical stances in research: positivist, relying on *"precise definition, objective data collection, systematic procedures and replicable findings"*, and interpretivist, relying on *"subjective interpretations and understanding of the phenomena observed"* (p. 16).

In selecting the interpretivist approach for his study into office design and national context, he argued that the positivism is handicapped by the need to show causal and deterministic relationships. He concedes, however, that the interpretivist approach is less objective, therefore offers fewer possibilities for generalisation.

These are important distinctions, but the question of which approach to adopt hinges on the end goal of the research as a whole. In the present thesis, this has been stated as 'seeking solutions for office buildings in hot humid conditions' (see

Section 1.0). In seeking solutions, the thesis outcome must be both applicable and replicable as design is, by nature, prescriptive (Sime, 1985). Therefore, unlike the van Meel study, which was largely descriptive and atheoretical, this thesis adopts a positivist approach. A theoretical model is judged here by its own objectives, as a set of specific quantifiable outcomes. A critical evaluation of these, in turn, becomes a means of theory building. Any new model arising from this loop has the potential to contribute to future design activity.

There needs, however, to be a qualification on the notion of the 'quantitative'. Even the seemingly most objective aspect of the study is an implicit value-judgement, a subjective statement of how a building should perform.

To establish a framework for performance, the thesis has turned to the Bioclimatic Model. The evaluation of performance, vis-a-vis questions of comfort and consumption, has to be multifaceted, straddling the disciplines of building science and environmental psychology. These are called upon to extract and evaluate data.

3.2. Research Strategy

A research strategy is the roadmap that gives the thesis its structure and progression. It must be noted, however, that the linear approach outlined in the present section is something of a simplification. It should be viewed as a signpost, rather than a step-by-step progression. The actual sequence was iterative and moved laterally; some parts carried out concurrently with others.

The data from each building, after preliminary analysis, sometimes affected the approach to the next case study. Adjustments to an instrument or new concerns often meant returning to an earlier building for further monitoring. Revenue House, for instance, was accessed on three separate occasions over a period of 13 months, each time with a different emphasis and greater depth of scrutiny.

Broadly speaking, the research can be broken down into three parts (see Figure 3.1). The first sought to support the research question, vis-a-vis the gap between theory and application. The second sought to relate observations of indoor conditions with occupant perception and behaviour, and vice versa. This involved a scrutiny of the building-occupant dynamic, looking specifically for comfort expectations that guide occupant response.

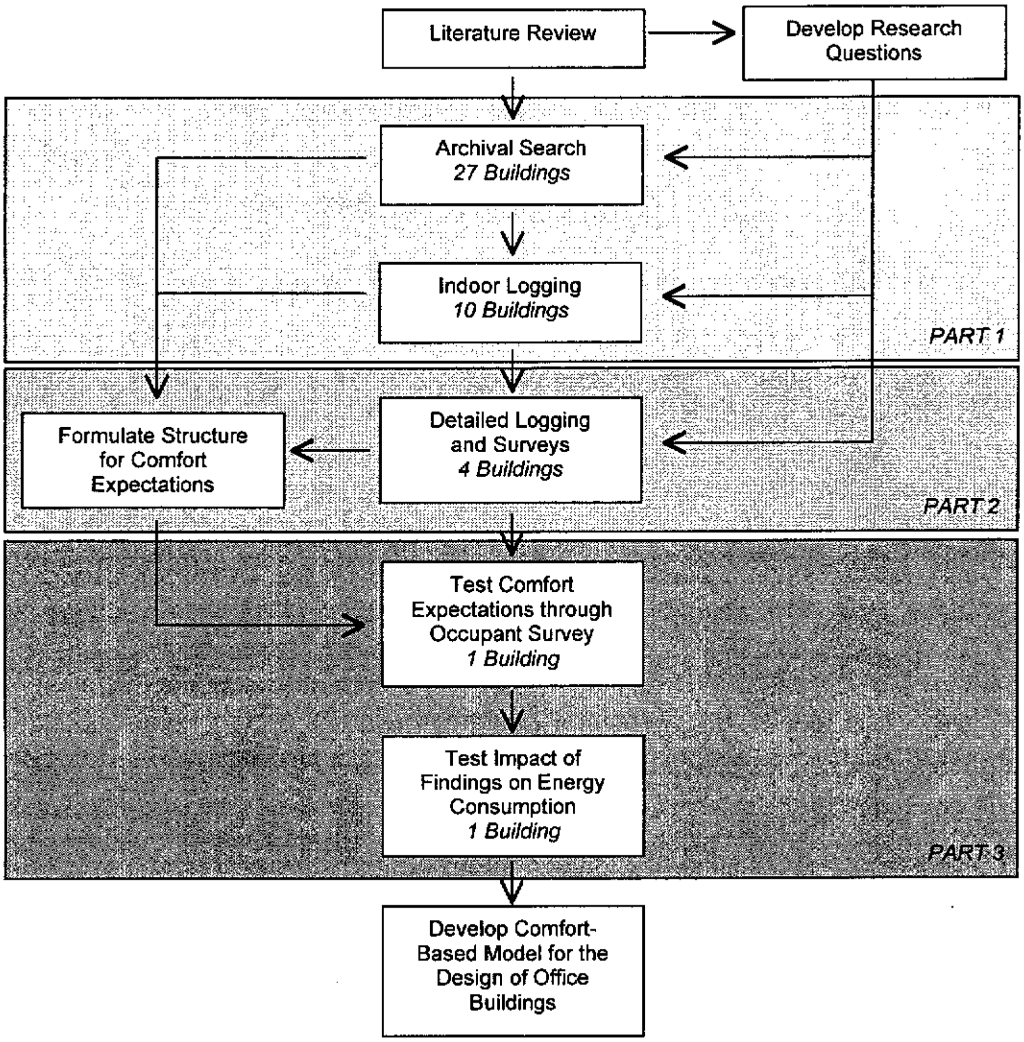

Figure 3.1. Research strategy

The third part would test these outcomes, particularly the criteria behind comfort expectations, in terms of their potential usefulness in generating a model that improves on the twin goals of comfort and energy consumption.

The thesis progressed towards increasing focus and depth. Data collection began with an archival search involving information about the envelopes of 27 buildings, progressed to 10 buildings for a survey of their indoor conditions, and then to 4 buildings in which occupants were surveyed and workspaces monitored in the passive and active modes. The next and final phase was a large-scale comfort survey involving just one building.

The emphasis throughout has been on fieldwork with data from actual buildings and feedback from occupants in operational workplaces. This was deemed necessary within the context of the thesis objective of focussing on the gap between theory and application. A conscious decision was made to not proceed via computer simulations or a laboratory-based approach as it was felt that this could not sufficiently reflect real-world complexity.

3.3. Context and Case Studies

The focus of the study was narrowed to the context of Singapore and the office building as it was felt this would allow for a greater depth of understanding without necessarily oversimplifying inherent complexity of the research question. The Singapore constraint was relaxed only when no climatically designed office building was found in the government database of new office buildings. None of the 27 buildings selected appeared to rely on passive modes or climate-responsive envelope strategies.

At this point two Bioclimatic buildings from Malaysia were introduced to the data to represent a climate-responsive, theory-based perspective. Even though the two countries are in the same climatic zone, socio-cultural differences exist and are noted, where pertinent, in the analysis.

The 27 buildings were selected from the database of OTTV submissions. The only criterion applied to this list was that they should be relatively new so as to ensure a certain consistency in terms of the technology available to their designers. Older office buildings from the 1970s and 1980s would have relied on less sophisticated glass products and envelope systems. Also, the building intelligence systems that regulate a building's operations and energy use came into widespread use only in the 1990s (Harrison, Loe, & Read, 1998). All the Singapore buildings selected, as such, were completed from the mid- to late-1990s.

A shortlist of 10 buildings was subsequently selected from this list for onsite logging of indoor conditions. The buildings on this list were meant to represent a range of building types and locations: government vs. commercial buildings, high-rise vs. low-rise, city centre vs. city outskirts.

For the second part of the study, two buildings were picked for detailed logging and surveys: Revenue House (RevH) and URA Centre (URA)[1]. These were selected because they represented good building practice in Singapore. RevH had won the title of Most Energy-Efficient Building in ASEAN for the Year 2000 (Cooke, 2000). URA, which is home to the Singapore urban planning authority, is touted as an example of tropical excellence, with state-of-the-art building intelligence features (Gwee, 1999).

The two Bioclimatic buildings from Malaysia were Menara Mesiniaga (MES) and Menara UMNO (UMNO). The decision to survey these well-known buildings designed by architect Yeang was strategic in as much as he is also the author of the Bioclimatic Model (Yeang, 1994; Yeang, 1996).

It should be highlighted here that occupants from two additional buildings[2], Ministry of National Development Building (MND) and the Civil Service College (CSC), were added to the occupant survey database in a bid to increase the sample size in Part 2 of the study. The former is a high-rise office building situated in the city and home to a government department that is also sponsor of the thesis author's research. The latter is an out-of-city, medium-rise, training institute, with a substantial office component. The CSC building was designed by the thesis author and its tenant organisation was supportive of the present study.

Subjects were selected by each building's manager so as to facilitate access[3]. No criteria for subject selection was given, other than that it should be an even mix of age, gender, ethnicity and job types. In most cases, however, this was not the case and the sample reflected the demographic bias of the population of each building. Prior to being approached, subjects were informed of the exercise by email but not given any specific details.

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[1] To facilitate the discussion of data and results in subsequent chapters, abbreviations described in this chapter will be used for building names (see above), envelope variables (see p. 68), indoor variables (see p. 71), mode options (see p. 83) and types of analyses (see p. 84).

[2] These two buildings were only used to generate data on *occupant feedback at the workplace*. They were not part of the database for the building's shell and systems, passive and active logging, as they did not meet the twin criteria of being1990s-completed, purpose-designed office buildings.

[3] The sole exception was MES, in which the researcher was offered access to all occupants on pre-selected floors.

In the final phase of the study, RevH was selected for the large-scale occupant survey and temperature re-settings. The primary reason for picking RevH was that the owner-operators of this building offered to support the research by opening up their building to a survey on this scale and granting carte blanche access to the building's electro-mechanical systems. It represented an interesting choice in that this particular building was already deemed most energy-efficient in Singapore. The question, in part, became one of how much further its efficiency could be improved.

3.4. Instruments and Analyses

Triangulation is described as a process of comparing and checking results from different sources, via different instruments, thereby improving the reliability of results (Jick, 1979). The research question is approached here from a variety of angles with data from different sources that can be compared and contrasted, so as to develop a robust picture.

The present study employs three modes of data collection relying on a variety of instruments and analyses:

- Archival Search (see Section 3.4.1)
- Indoor Conditions and Energy Consumption (see Section 3.4.2)
- Occupant Response (see Section 3.4.3)

3.4.1. Archival Search

This part of the research sought to construct an overview of the way in which office buildings are designed vis-à-vis the climate, primarily in terms of building shape, orientation and envelope attributes. The importance of these parameters has been stated by Watson (1984), Prasad (1995a), Todesco (1998) and Hyde (2000), who suggested that shape and orientation, in particular, are a building's first line-of-defense in an energy-efficiency approach.

The research looked to OTTV records kept by Singapore's Building and Construction Authority (BCA) typically in the form of hardcopy files and microfilm.

OTTV[4] as a regulatory control was discussed in Section 2.1.1. Its usefulness as an archive comes from the requirement that the architect or engineer of each new building, with a substantive air-conditioned component, makes a detailed submission of the building attributes. Of interest to the present study are the following:

- Site plan/location
- Shape, form and layout
- Summary of gross floor area
- Number and orientation of facades
- OTTV for the building (OTTV)
- OTTV of each façade ($OTTV_{Facade}$)
- Overall window-to-wall ratio (WWR)
- Window-to-wall ratio of each façade (WWR_{Facade})
- Thermal transmittance of the fenestration of each façade (TT_F)
- Thermal transmittance of the wall of each façade (TT_W)

With data from 27 buildings, consisting of 125 facades, an assessment could be made of the climatic approach, as represented by the principles of the Bioclimatic Model (see Section 2.2.2). This involves two protocols. First, the drawings of each building are reviewed against specific features and strategies recommended by the Model:

- Presence of optimal shape and orientation; a rectangular plan, aspect ratio of 1:3 with wider elevations facing N and S
- Service cores situated against E and W facades, acting as thermal buffers
- Presence of transitional spaces, i.e. vertically-distributed balconies
- Presence of external sunshades

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[4] The OTTV submission is based on the following formula (PWD, 983, pp.15-16):

$$OTTV = \frac{(A_w \times TT_W \times TD_{eq}) + (A_f \times TT_F \times T_{dif}) + (A_f \times SC \times SF)}{A_o}$$

$OTTV$: Overall Thermal Transmittance Value (W/m^2)
A_w : Opaque Wall Area (m^2)
TT_W : Thermal Transmittance of Opaque Wall (W/m$^{2\circ}$K)
TD_{eq} : Equivalent Temperature Difference ($^\circ$K)
A_f : Fenestration Area (m^2)
TT_F : Thermal Transmittance of Fenestration (W/m$^{2\circ}$K)
T_{dif} : Temperature Difference between Exterior and Interior Design Conditions (5°K)
SF : Solar Factor (W/m^2)
SC : Shading Coefficient
A_o : Gross Area of Exterior Wall (m^2) = $A_w + A_f$

The second protocol was a quantitative review of facade attributes extracted from the files, specifically, $OTTV_{Facade}$, WWR_{Facade}, TT_W and TT_F, which collectively and individually represent envelope permeability. These were averaged for each orientation; the mean value then compared with solar load from the weather files for Singapore. A key prescription of the Bioclimatic Model is that solar load should be the primary consideration for the design of each façade, a bigger load implying lower envelope permeability.

The solar load[5] shown in Figure 3.1 applies to various orientations in the Singapore climate (PWD, 1983). These values are plotted in Figure 3.2.

	N	NE	E	SE	S	SW	W	NW
Solar Load on an upright surface (W/m^2)	93.6	130.0	162.5	132.6	96.2	132.6	162.5	130.0

Table 3.1. Solar loads for Singapore

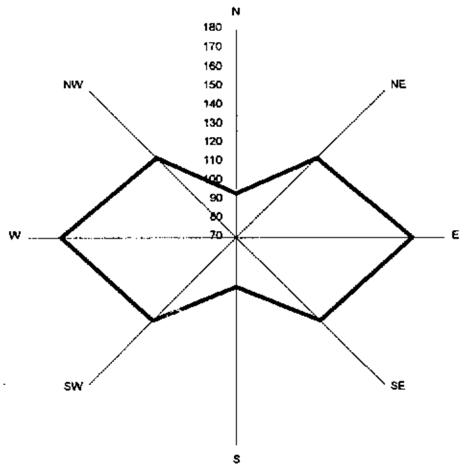

Figure 3.2. Solar Load (W/m^2)

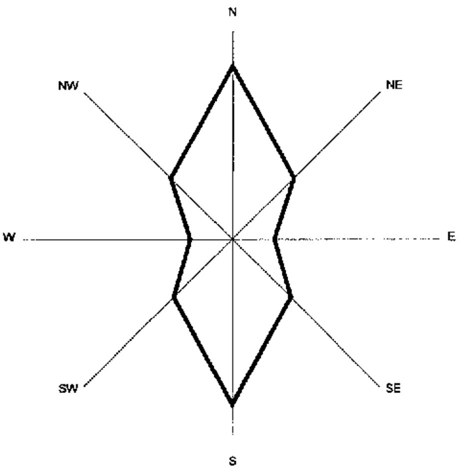

Figure 3.3. Solar Response

From the Solar Load plot, a Solar Response spindle is extrapolated (see Figure 3.3). This is the mathematical inverse of the load; a graphical representation of a Bioclimatic response in which a higher solar load implies lower façade permeability.

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[5] In the PWD Handbook on Energy Conservation in Buildings and Building Services (1983), a summary of correction factors (CF) is presented for each orientation (p. 17). The solar load for that orientation is computed to be 130xCF (p.16)

The Solar Response spindle serves as a template for the evaluation of façade design in Chapter 4. From the database of 125 facades, each attribute (WWR_{Facade}, TT_F, TT_W and $OTTV_{Facade}$) is mathematically averaged for each of the eight orientations and plotted in the same manner. Its shape is then compared with the spindle to ascertain fit. A better fit suggests that solar load was a likely design consideration for that particular attribute.

3.4.2. Indoor Conditions and Energy Consumption

Having addressed how building envelopes are designed vis-à-vis the climate, we now look at how buildings perform in terms of indoor conditions and energy consumption.

Indoor Conditions

The survey of indoor conditions was conducted in two parts: first, a broad survey of 10 buildings logged for short periods across a range of spaces typically found in a Singapore office building. This was followed by a second, more detailed, logging of four buildings, primarily at workplace areas, over a period of up to 2 weeks each.

The objective of the first part was to establish representative values for indoor air temperature, relative humidity and illuminance. This will be compared with statutory codes for the same, to ascertain compliance.

In each building, five spaces were surveyed:

- Atrium/Entrance Foyer
- Lift Lobby
- Cafeteria
- Offices
- Toilet

In each space, readings were taken of Indoor Air Temperature (°C), Relative Humidity (%) and Illuminance (Lux) at desktop level. Logging was carried with due care to avoid proximity to heat-generating equipment, windows, light fittings and air conditioning outlets. In each space, several readings were taken so as to get a representative value for the space as a whole. The number of readings generally depended on the size of the space and the variability observed in terms of layout, occupant and equipment density. Also noted during these visits were the positions of full height partitions and furniture layouts, in as much as they affected distribution of light and air. The buildings' exterior was also observed for signs of climate response, namely the presence of sunshades, placement of service cores and uniformity of façade treatment.

The second part of this study involved a detailed logging of key environmental variables affecting indoor visual and thermal comfort conditions. Whereas the preceding section involved a cursory exploration of representative values, this is an in-depth review of how indoor conditions vary over time and location, accounting for the role of passive features and the envelope.

Each building was monitored for periods of between one and two weeks. The exact duration depended on the level of access granted. In UMNO, for instance, which had both unoccupied and occupied floors, it was possible to simultaneously log passive and active modes. In the other buildings, passive readings had to be taken on weekends[6] and the study lasted longer.

Each building was logged[7] for six variables:

- Envelope Surface Temperature (EST)
- Indoor Air Temperature (IAT)
- Mean Radiant Temperature (MRT)
- Relative Humidity (RH)
- Air Movement (Air)
- Illuminance (Light)

These were repeated for passive and active modes of operation. In the passive mode, all windows and doors (to transitional spaces, where present) were kept open; air conditioners and electrical lights switched off. In the active mode, the building was logged with these same systems switched on and blinds left to occupant discretion.

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[6] The sole exception to this was the URA in which weekend access was denied for security reasons. The only passive readings available for this building are those that could be logged without supervision, i.e. automated temperature loggers for IAT, MRT and EST.

[7] See Appendix A1 (Instruments and Instrumentation) for a summary of equipment used in the logging of indoor conditions.

Temperatures and light readings were taken with reference to the building envelope (see Figure 3.3). The first reading was taken 1m from the envelope with all subsequent readings at 3m intervals. Due to a shortage of loggers, MRT readings were taken at 6m intervals beginning at the 4m mark.

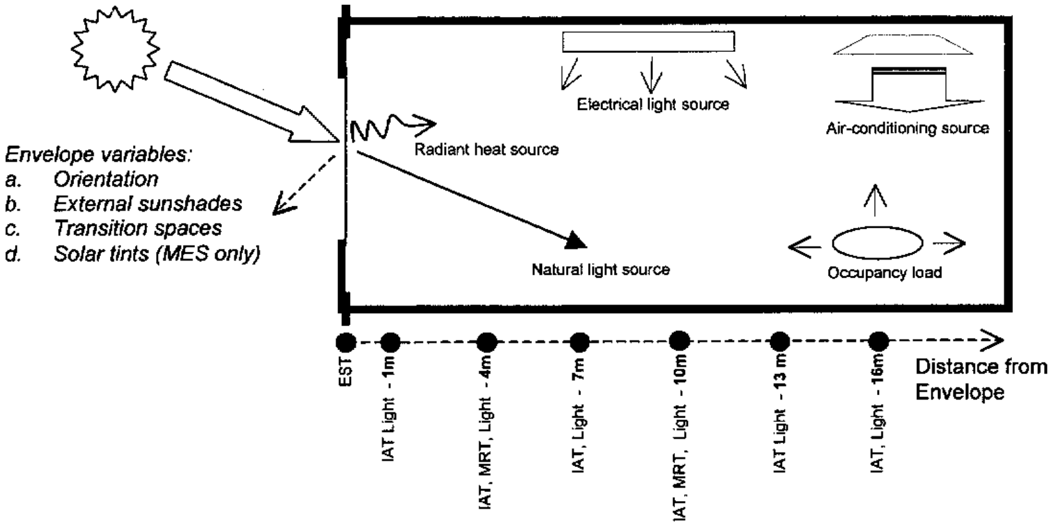

Figure 3.4. Logging of indoor conditions

Imaginary lines were drawn on the plan, as if emanating from each façade, along which temperature loggers were situated (see Figure 3.4). RH and Air were taken manually at locations that were evenly distributed across the plan.

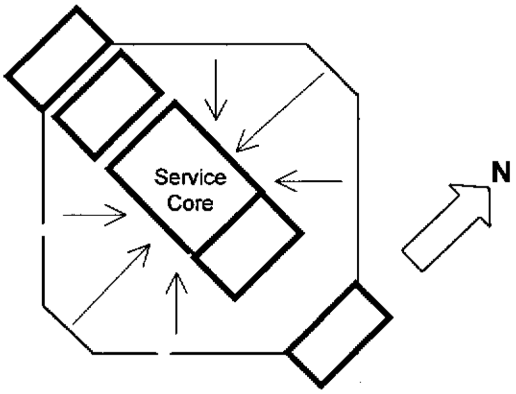

Figure 3.5. Strategy for monitoring as per RevH plan

Each building was also reviewed for the impact of envelope features and attributes such as external sunshades, orientation, transitional spaces and glass tints. Simultaneous readings were taken to ascertain the impact of each. In MES, for instance, where envelope design varied from one level to the next, it was possible to determine, via a series of paired readings, the impact of specific features.

In addition to the logging of indoor conditions, records were kept of outdoor conditions by way of summary observations of rainfall, sunshine and cloud cover. Four temperature loggers were situated outdoors at any one time, measuring outdoor dry bulb temperature (OutDBT) and mean radiant temperature (OutMRT) levels. Data from Meteorological offices in Singapore and Malaysia were also collated for each period of monitoring (see Appendix A5: Summary of Weather for Period of Logging).

A noteworthy inclusion in this exercise was the measurement of envelope surface temperature (EST). According to Olgyay (1963) and Givoni (1969), EST can be a useful index of envelope performance, an indicator of the impact of passive solar features/strategies. Recent studies have also suggested that EST results in temperature gradients across the floor plan with distance from the envelope (Chen, Kamimura, & Watanabe, 1999; Lyons, Arasteh, & Huizenga, 2000). By logging EST in these four buildings, this present study is able to review these arguments and concerns.

Energy Consumption

The four buildings selected for passive and active logging were reviewed for the consumption levels for the Year 1999. This was done through collation of monthly utility bills requested from each building's owner.

The timeframe of one calendar year was selected so as to average out variations in occupancy, workload peaks, public holidays and seasonal differences. The energy consumption of each building was then collapsed into an index (kWh/m^2/year) for which only AC floor areas were used. The final index was corrected for a standard workweek of 55 hours, as is the norm for energy benchmarking in Singapore (Ganesh, personal communication, January 28, 1999).

The buildings are compared with each other and with the Singapore average for office buildings: 224 kWh/m^2/year (Nathan, 1999). No equivalent consumption index was found for Malaysia.

3.4.3. Occupant Response

Four types of surveys have been deployed to investigate the question of occupant response. The choice of each is an implicit acknowledgment of the weakness of the others, and a further attempt to triangulate data. These strengths and weaknesses are summarised in the sections that follow.

- Cross Sectional and Longitudinal Surveys (see Section 3.4.3.1)
- Multiple Sorting Procedure (see Section 3.4.3.2)
- Behavioral Observations (see Section 3.4.3.3)

3.4.3.1. Cross Sectional and Longitudinal Surveys

Theoretical Basis

A cross sectional survey solicits response at a given moment to a particular set of conditions, typically through semantic rating scales that ask a subject for his/her perception of particular conditions, for instance, IAT and RH. This survey technique is akin to taking a 'snapshot' of a population's perception at a given time.

A longitudinal survey, conversely, is the equivalent of a 'film', a series of snapshots over time, typically through repeat surveys of the same group. It may involve deliberate manipulation of ambient conditions, for instance, air temperature, with a view to gauging response over a range of conditions.

Humphreys (1976) describes the difference between these two survey techniques as one of investigating variation of response across a sample (cross sectional) versus consistency within (longitudinal). In the present study, which set out to study occupant comfort and indoor variability, both survey types were used. The cross-sectional survey was used to gauge sensitivity and response at the workspace to specific environmental conditions, specifically IAT, RH and Light, and to establish between-building differences in occupant response. The longitudinal survey was used to test the upper limit of thermal comfort in different spaces in the same building. This was achieved by daily adjustments to temperature settings for each of the spaces in which occupants were surveyed. Air temperatures were slowly raised over a period of three weeks, in margins small enough such that users perceived steady-state conditions. The objective here was to show that comfort could exist inside a non-uniform building, one with temperature differences across spaces.

A corollary to the choice of survey technique was the selection of rating scales used to solicit response. The most common rating scales used in thermal comfort studies have been described in Section 2.3.1. Rohles, Bennett and Milliken (1981) suggested that in any study on comfort, it is desirable that more than one rating scale be used, as *"sensation and thermal comfort... whilst comparable, are not identical"* (p. 517).

Tables 3.2 and 3.3 summarise the scales used in the context of the present study.

ASHRAE **Thermal Sensation** *(7 point ordinal scale)*	**Thermal Comfort** *(6 point ordinal scale)*	**McIntyre** **Thermal Preference** *(3 point nominal scale)*	**Acceptability** *(2 point nominal scale)*
Hot +3	Very Comfortable +3	Cooler 1	Acceptable 2
Warm +2	Moderately Comfortable +2	No Change 2	Unacceptable 1
Slightly Warm +1	Slightly Comfortably +1	Warmer 3	
Neutral 0	Slightly Uncomfortable –1		
Slightly Cool –1	Moderately Uncomfortable -2		
Cool –2	Very Uncomfortable -3		
Cold –3			

Table 3.2. Thermal rating scales

Perception of Light *(7 point ordinal scale)*	**Perception of Natural Light** *(6 point ordinal scale)*	**Preference for Natural Light** *(3 point nominal scale)*	**Overall Satisfaction with Light** *(6 point ordinal scale)*
Very Bright +3	*Variable (6)*	Increase it 3	Very Satisfied +6
Bright +2	Very Bright and Direct +5	No Change 2	Moderately Satisfied +5
Slightly Bright +1	Strong and Direct +4	Decrease it 1	Slightly Satisfied +4
Just Right 0	Soft and Diffused +3		Slightly Dissatisfied +3
Slightly Dim –1	Very Dim/Negligible +2		Moderately Dissatisfied +2
Dim –2	None At All +1		Very Dissatisfied +1
Very Dim –3			

Table 3.3 Visual rating scales

In addition to these, several other scales were used pertaining to perception of RH, Air and satisfaction with environmental controls (see Table 3.4).

In the present study, the ASHRAE and McIntyre scales were used to gauge sensation and preference respectively, along with a scale each for thermal comfort and acceptability. For thermal comfort, a 6-point scale for thermal comfort was used (see Table 3.2) in place of the Bedford scale. The latter has been criticised for blurring the semantic boundary between sensation and comfort by asking if a subject is comfortably warm or cool (Humphreys, 1976).

The 6-point thermal comfort scale used in the present study asks only if the subject is comfortable, without intimating that this may have something to do with his/her perception of warmth or coolness. S/he was told at the start of the survey, however, that this question pertained specifically to the perception of thermal comfort. The same scale was deployed by Schiller in her 1990 survey of office buildings in San Francisco where she cross-referenced data from this scale with that from the ASHRAE scale, so as to comment on the relationship of sensation and comfort.

In general, rating scales for visual comfort appear not be discussed in the literature as readily as those applied to thermal comfort studies. The visual scales adopted here have been adaptations of thermal scales in that they seek to establish occupant sensitivity to the parameter measured, namely illuminance, and its effect in terms of response to the visual environment. Unlike the thermal condition, for which IAT and RH were logged at each workstation at the end of the survey, it was not possible to measure the two types of light, natural and electrical, separately. Occupants were nevertheless asked for their perception of both. Illuminance levels at desktops were then noted.

With data from the various scales, analysis consisted primarily of regressions in which occupant response was plotted against the salient indoor condition, for instance, the perception of thermal sensation against IAT. Response to each scale was also tested against response to another, using appropriate statistical tests[8], such as the Chi-Square, Kruskal-Wallis and Mann-Whitney tests. This was to establish if, for instance, perception of visual condition relates with perception of the thermal condition or is affected by background variables such as gender and age.

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[8] The analysis was carried out using SPSS Version 9.0 for Windows (Kinnear & Gray, 1999).

The Cross Sectional Survey Procedure (Survey 1)

Subjects were asked to respond to the conditions they experienced through a detailed questionnaire (see Appendix B1: Survey 1 Questionnaire). Ordinal and nominal rating scales were used to determine perception of temperature, air movement, light and humidity levels (see Table 3.4).

This was followed by a series of questions on background variables covering individual differences such as ethnicity and gender. Each survey ended with observations of outdoor weather conditions and subject's proximity to the envelope, followed by readings of IAT, RH and Light at his/her workspace. The intention here was to create a broad database consisting of occupant response and ambient condition at the time of survey.

Subjects were also asked about their adaptive responses to discomfort, such as the use of jackets. These would later form the basis for behavioral observations (see Section 3.4.3.3). Finally, they were asked which outdoor conditions affected their perception of comfort indoors.

Following the first survey in RevH, additional questions were introduced to the Survey 1 questionnaire. These questions, and their rationale, are as follows:

- Subjects were asked to respond to the ASHRAE and Thermal Comfort scales in terms of their perception '*in general*' in addition to '*at the time of interview*'. This allowed a comparison across buildings beyond the conditions recorded at the moment of interview, which may have been atypical.
- Overall Satisfaction with Light on a 6-point ordinal scale was introduced to give an indication of the acceptability of the visual condition. Data from this was subsequently tested against illuminance levels and overall perception of light and daylight levels.
- Questions pertaining to Availability, Frequency of Use and Satisfaction with Environmental Controls were introduced so as to allow the issue of control to be addressed directly.

Ratings Scales	Objectives	Sample Size
Thermal Condition • ASHRAE/Thermal Sensation Scale – 7 point ordinal • Thermal Comfort Scale – 6 point ordinal • Perception of Relative Humidity – 7 point ordinal • Perception of Air Movement – 7 point ordinal **Visual Condition** • Perception of Overall Light Level – 7 point ordinal • Perception of Daylight Level – 5 point ordinal • Preference for Daylight – 3 point nominal • Overall Satisfaction with Light – 7 point ordinal • Relationship of Daylight with Thermal Comfort – 2 point nominal **Environmental Control** • Access to Controls – 2 point nominal • Satisfaction with Control – 7 point ordinal	Establish... • If there an optimal condition for thermal and visual comfort • If the subject's location in terms of building and his/her physical proximity to the envelope affects perception of comfort • If there a link between thermal comfort and presence of natural light • If environmental controls are used and what is their impact on the perception of comfort	RevH, n = 24 URA, n = 21 MND, n = 20 CSC, n = 20 MES, n = 24 Total N = 109

Table 3.4. Summary of Survey 1 rating scales

The Longitudinal Survey Procedure (Survey 4)

The Survey 4 questionnaire (see Appendix C1: Survey 4 Questionnaire) introduced two additional thermal scales: McIntyre (Thermal Preference) and Acceptability, which allowed further avenues for analysis. These had not been used in Survey 1 due to the already extensive coverage of issues and responses. The focus in Survey 4 was narrowed to the question of thermal comfort and perception *'at the time of interview'*. The questionnaire was streamlined, partly due to its repeated use on some subjects.

Other variables thought to affect thermal comfort were solicited, for example, activity level, clothing ensemble, food and drink consumption. Subjects were also asked for background variables such as ethnicity and age. At the end of the interview, IAT and RH readings were taken at each subject's location.

Due to a shortage of equipment, representative readings were taken for the following variables:

- MRT[9]
- Air[10]
- Vertical stratification of temperatures[11]

Weather data was recorded thrice daily via onsite outdoor observations of cloud cover, rainfall, brightness, plus manual readings of RH. This was in addition to the continuous logging of OutDBT and OutMRT relying on several automated loggers.

During the re-setting of temperatures, adjustments were kept to no more than 0.5 degrees per day[12] at the workplace. This was intended to minimise the impact of temperature change on occupants who were surveyed repeatedly. In the Cafeteria and Atrium, where no subject was surveyed twice, temperature adjustments were kept to 1 degree per day. All adjustments were carried out in the evening, when the building was largely unoccupied. No change was made during the workday so as to minimise the likelihood that the memory of a past setting interfered with response.

To prepare for analysis, clothing insulation values (Clo) and metabolic rates (MET) were calculated for each subject (see Appendix C2: Clo and Met Calculations for Survey 4). These values, along with IAT, MRT, Air and RH, were used to derive ET* and SET* indices[13].

A fourth thermal index was created to test the hypothesis that perception of indoor conditions was linked with outdoor conditions. In/Out Temperature refers to the numeric difference between indoor and outdoor air temperature at the time of survey.

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[9] MRT loggers were paired with IAT loggers and situated within each zone. On each workplace floor, a pair of loggers was positioned near the envelope and another, deeper in the plan. In the cafeteria and atrium, paired loggers were situated near locations where surveys were conducted.
MRT was assumed = IAT measured + typical margin of difference (MRT-IAT) for subject's location.

[10] Air movement readings were taken at each workplace subject's location for a period of one week. Spot readings were taken in the atrium and cafeteria.

[11] The difference between IAT readings at 0.1m and 1.1m above floor level was noted at each subject's location on a randomly selected day during the three weeks.

[12] Literature suggests that a step-change in temperature of more the 0.6 degrees an hour can generate a response to the perception of that change (i.e. the transitional effect) rather than to the temperature itself (Rohles, Milliken, Skipton, & Krystic, 1980).

[13] These indices were calculated online using the Human Heat Balance (de Dear, 2001).

The procedure described in the present section are confined to the scales used and variables measured; a more detailed explanation of how and where it was conducted will be presented in Chapter 6. The reason for this deferment is that the strategy for Survey 4 is partly based on findings from Surveys 1 and 2 and is best understood after these have been presented at the end of Chapter 5.

3.4.3.2. Multiple Sorting Procedure

Theoretical Basis

The key objective of this survey instrument was to identify and extract a set of criteria that an individual applied in deciding on a mode of operation. This is inferred to reflect his/her comfort expectations. The study implicitly presupposed that comfort was more than a question of ambient conditions, and that the rating scales used in Surveys 1 and 4 could not relied upon for the task of understanding expectations.

Williamson, Coldicutt and Riordan (1995) argued the same suggesting that rating scales, and the comfort indices they support, are insufficient to developing an understanding of comfort preferences, which are influenced by an individual or group's attitudes and beliefs. Canter, Brown and Groat (1985) also expressed reservations on the rating scale as a tool for understanding differences between individuals:

> *The semantic differential with its 7-point scales, standard set of items and factor analysis of results has been shown to be insensitive to differences between cultures... it does not suggest itself as a technique that will reveal important differences between individuals.*
>
> Canter et al. (1985, p. 82)

Canter et al. turned to Kelly's Personal Construct Theory from psychology to seek out the theoretical foundation for an alternative tool:

> *The ability to function in the world relates closely to the ability to form categories and to construct systems of classification...[There is recognition in psychology] that the worldview is built around the categorisation schemes people employ in their daily lives.*
>
> Canter et al. (1985, pp. 79 and 81)

Coldicutt (1995) elaborates on Kelly's theory:

> *Kelly's Personal Construct Theory [is] a social science method which elicits from participants (building occupants) descriptions in their own words of the main constructs which they use to make sense of and evaluate built environments"*
>
> Coldicutt (1995, p. 103)

With the multiple sorting procedure (MSP), a subject is allowed to elaborate on a set of constructs that s/he volunteers. The simplest way of triggering these 'hidden' constructs is to ask them what they prefer or like. In an MSP-based study, Kraemer (1995) showed that preference has a direct relationship with evaluation; if one asks a subject for their preference for a set of options, it brings into play the criteria by which they evaluate those options.

In an earlier survey by Wilson and Canter (1990), the same procedure had been used for extracting the criteria by which architectural students categorise buildings. They asked students to sort photographs of well-known buildings according to what they liked.

The MSP procedure asks subjects to assign elements to categories. This can either be by way of a 'free-sort', where the categories are of the interviewees' making, or a 'structured sort', where the researcher provides categories. In the Kraemer, Wilson and Canter studies, subjects were asked to sort a set of labels[14] according to categories describing degrees of preference.

This 'structured sort' approach has been modified to the question of comfort by asking occupants to sort labels of room names, according to passive, active and mixed mode options (see next section on MSP Procedure). By asking them to sort according to 'preference', it is suggested, comfort expectations enter the equation.

The key difference between the MSP and cross-sectional and longitudinal surveys is that the latter seeks out occupant response to a given set of ambient conditions,

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[14] Kraemer's 32 'labels' were building types, for instance house, cinema, shopping centre, etc. each written on a card. She found that the notion of 'place' was categorised according to three constructs: *Function* of places, *Specificity* of function and *Privacy*.

Wilson and Canter's used photographs of 26 well-known 'contemporary' buildings presented to students in a school of architecture. It emerged that these images were sorted on the basis of *Style*.

whilst the former focuses on the perception of comfort at the workplace in general. In other words, MSP addresses comfort *expectation*, as opposed to comfort *experience*.

Data from MSP sorts was part qualitative and part quantitative. Subject verbalisation, through which they explained mode-groupings, made up the qualitative component. The quantitative element came from the groupings themselves, which were used to create a matrix which had each subject (in rows) tabulated against each space (in columns). The entry in each cell is a number signifying subject's choice of mode.

Wilson (1995) explains the analysis that follows: the first step " *in dealing with the qualitative data is to set up some type of classification scheme [through] content analysis*" (p. 259). In content analysis, the researcher groups words or phrases under headings that represent shared meaning. This preliminary list of 'constructs' would be tested in the second part of the analysis, which deals with the quantitative data matrix. For this, Wilson suggests using Multidimensional Scaling (MDS) and Multidimensional Scalogram Analysis (MSA), two analytical tools that look for a structure within the data.

Wilson explains that in the MDS and MSA plots, each label or subject is presented *"as a point in geometric space... the more qualities two items have in common, the closer they are in the plot"* (p. 265). Stalans (1995) suggests that the interpretation of a plot *"consists of identifying relevant dimensions. These discovered dimensions represent continuous directional features in the pattern of items"* (p. 140).

To illustrate how dimensions are tested, consider the question of how fruit might be perceived. If the dimension hypothesised were weight, for instance, the MDS plot would be expected to show heavier fruits at one end and lighter ones at the other. If the dimension hypothesised is categorical, for instance colour, the plot might be divided according to commonality of colour, for instance, red fruits in one cluster, green ones in another. The act of dividing a plot according to gradients or categories is described as partitioning.

In the MSA plot, subjects emerge as points on the plot, in which partitioning is used to test the role of background variables, such as ethnicity and gender. If an MSA emerges with clusters of male and female subjects, gender would be said to be a factor affecting perception.

By this process of testing plots, it becomes possible in the present study to review outcomes vis-à-vis comfort criteria postulated.

The MSP Procedure (Survey 2)

In the present study, subjects were given a context of 'comfort' in which to express their preference. In the absence of this lead-in, the sorting may have veered towards other constructs, such as were found by past studies (Wilson and Canter, 1990; Kraemer, 1995).

Subjects in the present study were asked to sort a list of spaces[15] typically found in office buildings, organising them into three categories (see Table 3.5). These categories were presented to the subject as the three modes of building operations: Passive, Mixed and Active, explained to them in a frame of reference that they would be familiar with, such as air conditioning, fan-assisted ventilation and natural ventilation.

	Categories	**1st Sort**	**2nd Sort**	**Sample Size**
Thermal Comfort	*Passive* – Natural Ventilation only (NV) *Mixed* – Fan-assisted Ventilation (FA) *Active* – Air-conditioning only (AC)	Subjects instructed to place as many cards into each category as they wished.	Subjects asked to place EXACTLY 5 cards into each category.	Total N= 42 RevH, n = 12 MND, n = 10 CSC, n = 10 MES, n = 10
Visual Comfort	*Passive* – Daylight only (DL) *Mixed* – Electrical Light and Daylight (EL+DL) *Active* – Electrical Light only (EL)			Total N=41 RevH, n = 12 MND, n = 10 CSC, n = 10 MES, n = 9

Table 3.5. Overview of Survey 2

Each subject was asked to sort twice. In the first sort, they were told that they could place as many cards as they wanted into each category, that it was entirely a question of their *preference*. In the second, they were told that each mode could

---

[15] This list was collated from an earlier pilot that asked subjects for what they considered to be spaces typically found in the modern Singapore office building. See Appendix B4 for details of that study. The 15 labels/spaces are as follows: Workspace, Meeting Room, Staff Lounge, Cafeteria, Auditorium, Atrium, Lift Lobby, Fire Escape Stairs, Toilet, Store Room, Staff Pantry, Photocopy Room, Gymnasium, Library, Day Care Centre.

have only 5 cards, indirectly bringing in the question of *tolerance*. At the end of each sort, they were asked to articulate their reasons for the groupings and explain why certain spaces were moved from one mode to another in the second sort.

Each subject's verbalisation at the end of both sorts was transcribed. The groupings from the first and second sorts were also noted and tabulated. In dealing with this data, three types of analyses were carried out. These are summarised in Table 3.6.

Analysis	**Data**	**Method**
Content Analysis	Data consisted of each subject's verbalisation at the end of 1st and 2nd sorts.	Sifting through all raw comments and extracting categories *(criteria of comfort)* based on common use of words and meaning (Krippendorf, 1980). Categories were ranked according to the frequency with which they were cited.
Multidimensional Scaling (MDS) Analysis	Each sort was organised into matrix consisting of rows for each subject (about 20) and columns for each space label (15). Each data entry indicates subject's choice of modes – Passive, Active or Mixed – annotated by the numbers 1,2 and 3.	The output shows a 2 or 3-dimensional plot that positions each *label* as a point in space. Proximity (or distance) between two points was seen to be indicative of the way the two spaces are viewed by the group as a whole. Criteria from content analysis were used to partition the plots. A successful partition suggested that a particular criterion had affected choice of mode.
Multiple Scalogram Analysis (MSA)	A data matrix was created with all subjects (n=83) as rows and 15 labels as columns.	The MSA output showed each *subject* as a point within a two-dimensional plot. The plots were tested by partitioning, based on background variables like gender, age, ethnicity, job and building. A successful partition suggested that particular variable affected the groups' response.

Table 3.6. Summary of Survey 2 analyses

Methodological Concerns:

With MSP, there were two concerns with regard to subject response:

- Carry-over impact between sorts

  It was noted in the second sort, a minority of subjects moved labels quickly from one mode grouping to another, appearing not to rethink the three groupings as a whole. It would have been preferable if the procedure had required them to re-sort the labels, i.e. rethink groupings entirely in the context of tolerance. The exercise would then have taken considerably longer, something that was not tenable in buildings where the manager had capped the time spent with a subject.

- Subject's ability to articulate

  A minority of subjects had difficulty expressing reasons for their choices in the English language, particularly on the question of whether the various modes were different in terms of the Type or Degree of comfort. Results from the analysis are therefore likely to reflect the opinions and preferences of those who were better able to articulate their thoughts.

3.4.3.3. Behavioural Observations

Theoretical Basis

On behaviour, Brager, Fountain, Benton, Arens and Bauman (1993) argue that observing and asking after behaviour in real environments is a critical piece of the comfort puzzle:

> *One of the things we have begun to do in field studies is to ask people about the ways in which they modify their behaviour or their environment. We note if they have windows, which they can open, blinds that can be drawn, or fans that can be operated... what controls are available to them... and whether they use such controls.*
>
> Brager et al. (1993, p. 38)

Their comments suggest that on the question of the environment, subjects should be asked what they do, what choices are available to them and then observed to see if they actually do what they say they do.

Griffiths, Huber and Baillie (1988) emphasised the importance of behavioral observations on grounds that they can support, or indeed challenge, assumptions of the surveys. The problem with simply asking people what they think or do is that there is a possibility that they might not be candid, or may have misunderstood the question. Conclusions on the basis of what a subject says, in itself, may be insufficient. A second reason for including behaviour is that the adaptive approach in thermal comfort is premised on the subject's ability to *act* on discomfort. Nicol and Humphreys (2001) define this as the adaptive principle:

> *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.*
>
> Nicol and Humphreys (2001, p. 46)

Even if an individual says s/he is comfortable for a given set of conditions, the fact that a jacket is worn at the time of interview, or a fan switched on, says something about the means by which comfort has been achieved.

The Observation Procedure (Survey 3)

The primary purpose of behavioral observations is to elaborate on findings from earlier surveys. In Survey 1, occupants were asked what they do when they experience discomfort and how often they interact with environmental controls that were available to them. In Survey 2, they were asked for their comfort expectations. Behavioural observations sought to support this list of actions, interventions and expectations.

This approach of ask-and-observe had the following objectives:

- Confirm the criteria affecting comfort expectations
- Determine if environmental controls, such as electrical lights, blinds and thermostats, were used where available
- Note occupant use of transitional spaces
- Observe adaptive behaviour, such as adjustments to clothing

Other aspects of building-occupant interaction were also noted. Those related to actions resulting in changes to ambient conditions, such as doors left open or windows permanently sealed. The full list of observations will be presented in Section 5.3.1 in the follow up to findings from Surveys 1 and 2.

3.5. Structure and Progression

Having outlined the various intents and instruments of this present study, it remains to be said that the next three chapters are organised in a manner that facilitates comprehension. This is done with due consideration to the fact that data came from a range of buildings by a variety of means. Instead of the chronological structure suggested by the research structure described in Section 3.2, the breakdown of results and analysis is organised according to type of data (see Table 3.7).

Chapter/ Tools	Context/Sample Size	Questions	Objectives
Chapter 4 **Shell & Systems** • Envelope Attributes and Appearance • Office Layouts • Indoor Conditions • Passive and Active Logging	*Envelope*: 27 buildings *Indoor Conditions*: 10 buildings *Passive and Active Logging*: 4 buildings	What is the prevalence and performance of active/passive strategies and systems found in office buildings in Singapore? How much indoor variability exists?	Ascertain what constitutes typical envelope design and indoor conditions for office buildings in Singapore Ascertain impact of passive features/strategies and the role of the envelope, specifically with regard to indoor variability.
Chapter 5 **Perception & Behaviour** • Survey1: Cross-sectional survey • Survey 2: Multiple Sorting Task Procedure • Survey 3: Behavioral Observations	Surveys of 109 subjects in 5 buildings Behavioral observations of occupants of 6 buildings	How do occupants perceive and behave towards conditions to which they are exposed?	Construct an overview of occupant comfort experience and expectations with regard to the thermal and visual indoor environment.
Chapter 6 **Delineating Thermal Comfort** • Survey 4: Longitudinal Survey ***Impact on Energy*** • *Thermostat Resetting and Energy Monitoring*	1000+ occupant surveyed in one building *One building*	Is it possible to create a non-uniform indoor environment without compromising on occupant comfort? *What is the impact of this non-uniform environment on energy consumption?*	Identify upper limits of comfort based on occupant expectations. *Gauge the energy impact of the variable thermal environment.*

Table 3.7. Overview of Chapters 4, 5 and 6

Chapter 4 presents all results and analyses pertaining to the building shell and systems, including the archival search. This summarises the building science component of the thesis. Chapter 5 addresses all questions regarding occupant perception and behaviour, summarising data from Surveys 1 to 3. This covers all tools and analyses from environmental psychology. Chapter 6 summarises Survey 4, a synthesis of building science and environmental psychology. It is then incumbent on the Chapters 7 and 8 to synthesise all findings in a manner that brings together the various themes and questions identified in the thesis.

Chapter 4. Shell and Systems

4.0. Preamble

This chapter presents data in terms of shell and systems, the former referring to the building envelope, the latter to electro-mechanical systems that regulate a building's indoor environment. The first two sections deal specifically with each in turn; the third infers their interaction through detailed observations of the indoor environment.

On the subject of office buildings and a climate-responsive approach, the literature review concluded by suggesting, in part, that not enough is known of how office buildings are designed in Singapore. This refers specifically to how frequently passive and active options are deployed. It had been earlier suggested that the level of indoor variability resulting from the presence and interaction of these systems might affect the success of any climatic model or approach adopted.

The question, therefore, of how much variability exists and the role that passive and active features and systems play, will be reviewed here. It will form the foundation for discussions in Chapter 7 on the role of indoor variability in the making of comfort.

Of the three components of the present chapter, the first consists of a review of the envelopes of 27 recently completed office buildings. The second looks at indoor conditions found within 10 buildings, short-listed from the sample of 27, and the third consists of detailed logging of 4 buildings in passive and active modes.

Table 4.1 summarises these three segments of research, along with their specific objectives.

Stage	Approach	No. of Buildings	Objective
Review of Building Envelope	Archival Search	27	Establish the prevalence of Bioclimatic strategies
Review of Indoor Conditions	Onsite Logging	10	Establish workplace indoor conditions in terms of IAT, Light, RH, presence of daylight
Detailed Passive & Active Logging		4	Establish... • impact of passive features • impact of envelope • patterns of variability

Table 4.1. Overview of Chapter 4

The overall objective of the analysis is, firstly, to generate a 'snapshot' view of office buildings in Singapore. Secondly, it seeks to understand the dynamics of indoor variability and the role that passive features, in particular, play in its presence and amplitude.

4.1. Review of the Building Envelope

4.1.1. Overview

As mentioned earlier, architects and engineers in Singapore are obliged to submit design proposals of every new air-conditioned building to the Building and Construction Authority (BCA) with calculations of envelope transmittance, the OTTV (see Section 2.1.1).

In order to generate a 'snapshot' of the building shell, the OTTV records of twenty-seven office buildings were collated and analysed. The analysis consists of a review of these buildings and their 125 constituent facades against Bioclimatic design principles. This entails a review of form, orientation and placement of service cores, followed by the more detailed assessment of façade permeability. Four façade variables found in OTTV records are used to assess envelope permeability: $OTTV_{Facade}$, WWR_{Facade}, TT_F and TT_W. These will be tested against solar load for their respective orientation. If magnitude of load relates with degree of permeability, it is inferred that climate may have been a design consideration.

4.1.2. Results

Tables 4.2 and 4.3 summarise the range of data collated for each variable and each orientation.

	Envelope Attribute	Mean	Std. Dev.	Min.	Max.
Building	OTTV (W/m^2)	38.6	6.1	19.7	44.7
N=27	WWR (%)	45.0	13.7	13.7	79.7
Façade	$\text{OTTV}_{\text{Facade}}$ (W/m^2)	38.6	8.7	16.6	69.5
	$\text{WWR}_{\text{Facade}}$ (%)	45.7	17.8	0.0	96.7
	TT_F ($\text{W/m}^2\,{}^\circ\text{K}$)	68.2	19.3	0.0	112.3
N=125	TT_W ($\text{W/m}^2\,{}^\circ\text{K}$)	13.9	6.7	4.8	32.7

Table 4.2. Building and Façade Attributes

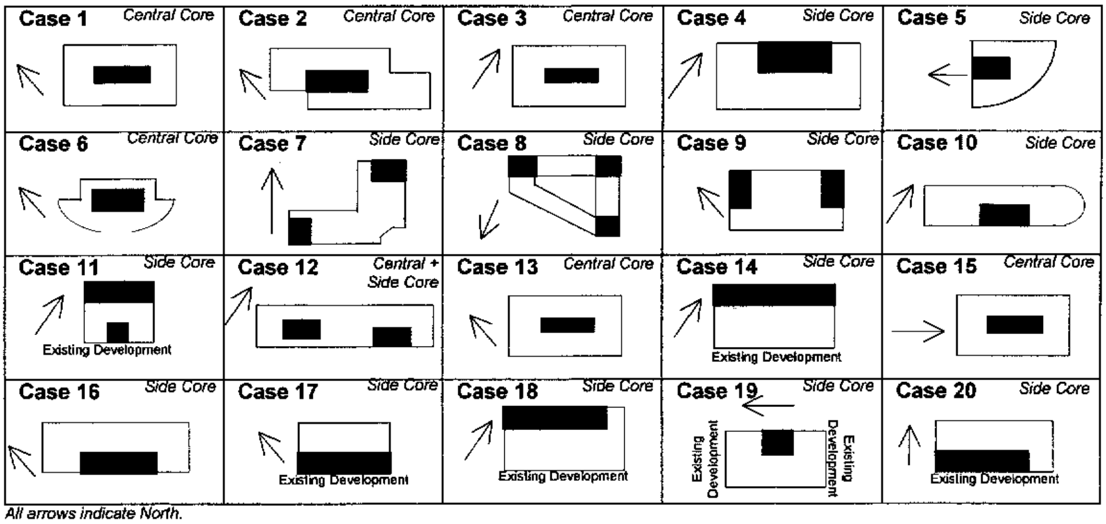
Envelope Attribute	N	NE	E	SE	S	SW	W	NW
$\text{OTTV}_{\text{Facade}}$ (W/m^2)	39.6	39.0	37.0	40.6	42.6	36.7	37.6	36.9
$\text{WWR}_{\text{Facade}}$ (%)	45.6	46.6	41.1	49.5	47.0	45.3	39.0	47.1
TT_F ($\text{W/m}^2\,{}^\circ\text{K}$)	70.2	60.8	71.3	71.1	75.6	66.1	71.3	65.9
TT_W ($\text{W/m}^2\,{}^\circ\text{K}$)	15.1	15.6	14.4	13.5	13.3	13.0	14.4	12.7

Table 4.3. Mean Value of Façade Attribute According to Orientation

4.1.3. Analysis

4.1.3.1. Building Shape, Orientation and Placement of Service Core

From the database of 27 buildings, information relating to shape and layout was found to be available for 20 (Appendix A2: Summary of 27 Buildings Surveyed via Archival Search). These are summarised in the Table 4.4.



All arrows indicate North.
Dark insert indicates a building's service core.

Table 4.4. Building Shape, Orientation and Placement of Service Cores

These plan configurations are compared with the Bioclimatic ideal. In Section 2.2.2, this was represented by an elongated plan-outline facing N-S, with an aspect ratio of 1:3 and service cores situated against E and W orientations (see Figure 2.5). In the comparison, it emerges, first, that the overwhelming majority of buildings (15/20) have an orthogonal geometry that faces NE/SE/NW/SW. Seven out of twenty have central cores. Of the remainder with side cores, only two (Case 7 and 19) are situated E and W. It is unclear if these side-placed cores were intended to act as solar buffers as they do not extend across the full length of the façade.

In terms of shape, orientation and core placement, none of the buildings show a response that is consistent with the Bioclimatic ideal. The question asked then is whether such a response was possible in the context of the building's site.

To answer this, three levels of freedom are defined:

- *Minimum Freedom*: building abutting one or more existing developments
- *Some Freedom*: site with adjacent buildings
- *Maximum Freedom*: stand-alone site

This classification is premised on the principle that a building with adjacent buildings, particularly if it physically abuts another development, is more restricted that one that without. Table 4.5 assigns a level of freedom to each building, based on a review of site drawings from the records.

	Site	**Minimum Freedom**	**Some Freedom**	**Maximum Freedom**
Case 1	52-storey tower & podium in high-density area within CBD		X	
Case 2	16-storey tower in high-density area in the CBD		X	
Case 3	30-storey tower in high-density area in the CBD		X	
Case 4	20+-storey development in high-density area within CBD		X	
Case 5	20+-storey development in high-density area within CBD		X	
Case 6	32-storey tower & podium on stand-alone site in the West			X
Case 7	Podium development in medium-density area in the West		X	
Case 8	Podium development in medium-density area in the West		X	
Case 9	16-storey tower & podium in high-density area within CBD		X	
Case 10	12-storey tower & podium on stand-alone site just outside CBD			X
Case 11	14-storey tower in high-density area within CBD – one façade abutting an existing building	X		
Case 12	7-storey podium in high-density area within CBD		X	
Case 13	5-storey podium in medium-density area within CBD		X	
Case 14	6-storey podium in medium-density area within CBD – one façade abutting an existing development	X		
Case 15	8-storey podium in medium-density area in the East		X	
Case 16	18-storey tower in high-density area in the CBD		X	
Case 17	6-storey podium in medium-density area within CBD – one façade abutting an existing development	X		
Case 18	4-storey podium in medium-density area within CBD – one façade abutting an existing development	X		
Case 19	4-storey podium in medium-density area within CBD – two façades abutting existing developments	X		
Case 20	11-storey tower in high-density area within CBD – one façade abutting an existing development	X		

Table 4.5. Summary of Freedom

It is noteworthy that of the fourteen buildings that have *Some* or *Maximum Freedom*, none opt for a profile consistent with the Bioclimatic ideal. The prevalence of NE-SW/SE-NW orientation appears to relate with location. In the Central Business District (CBD), where many of the buildings are located, building plots are predominantly oriented NE-SW/SE-NW, consistent with the urban grid of streets.

The fact that so many buildings do the same suggests that in a dense urban setting, the choice of orientation is often dependent on context, i.e. street alignment and adjacent buildings.

Significantly, in the two buildings with *Maximum Freedom*, neither opted for a Bioclimatic profile. These buildings have unusual plan shapes with curvilinear geometry, suggesting, perhaps, that the approach was one of crafting an aesthetic statement.

4.1.3.2. Envelope Variables

The comparison of envelope attributes asks if behind the single OTTV figure for the building lies a wider range of values for its facades. Figures 4.1 and 4.2 show $OTTV_{Facade}$ and $WWR_{Façade}$, juxtaposed with the corresponding range for the building.

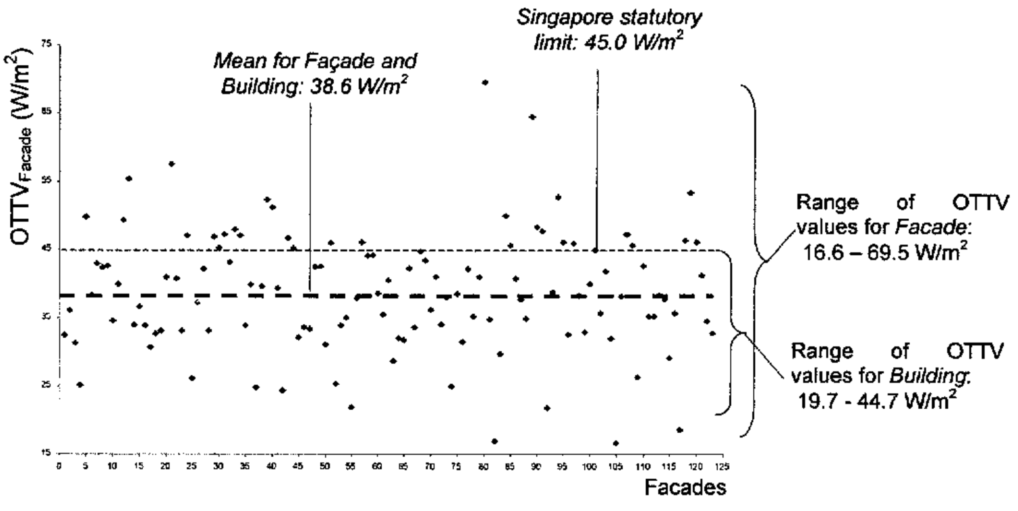


Figure 4.1. $OTTV_{Façade}$

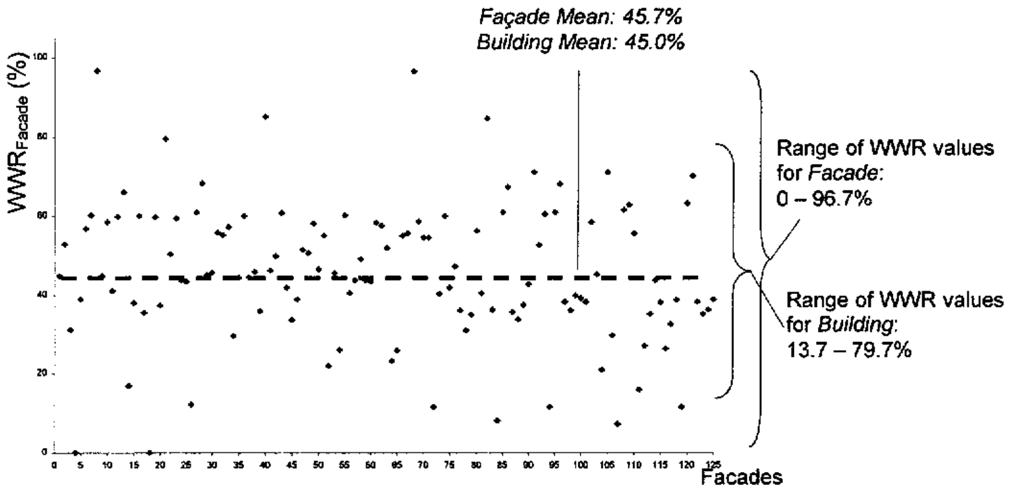


Figure 4.2. $\text{WWR}_{\text{Facade}}$

Even though the mean OTTV and WWR values for buildings and façades are identical, or near identical, the ranges are significantly different. OTTV for the building is constrained by the statutory code limit of 45W/m^2. With $\text{OTTV}_{\text{Facade}}$, however, this limit does not apply and it ranges from $16.6\ \text{W/m}^2$ to $69.5\ \text{W/m}^2$.

In the case of WWR, for which there is no restriction in the code, the range of $\text{WWR}_{\text{Facade}}$ spans 0% to 96.7% whilst that of building ranges from 13.7% to 79.7%. It was noted from the drawings that a facade with no windows (i.e. 0% WWR) often abuts or overlooks an adjacent development. It is harder to explain WWR that is in excess of 80%. A high WWR most likely reflects a preference of the designer and/or owner for view or a sense of openness.

In Figure 4.3 the mean values of the four key façade envelope variables are plotted according to orientation. To evaluate climatic response, these are cross-referred with the Solar Spindle presented in Section 3.4.1 (see Figure 3.3). As mentioned in Chapter 3, a similarity between a plot and the spindle suggests that solar load was a design consideration for that particular attribute.

Of the four variables, only $\text{WWR}_{\text{Facade}}$ appears to bear some semblance to the spindle. The plot suggests that windows are typically smallest when facing E and W. Mann-Whitney U tests were carried out on the difference between mean values for the various orientations to determine statistical significance[1]. No significance at $p<0.05$, was found between WWR_{Facade} of N and S against those facing NE, SE, NW and SW. For facades facing E and W against the remaining six orientations, results bordered on significance giving a z= -1761 and p=0.078.

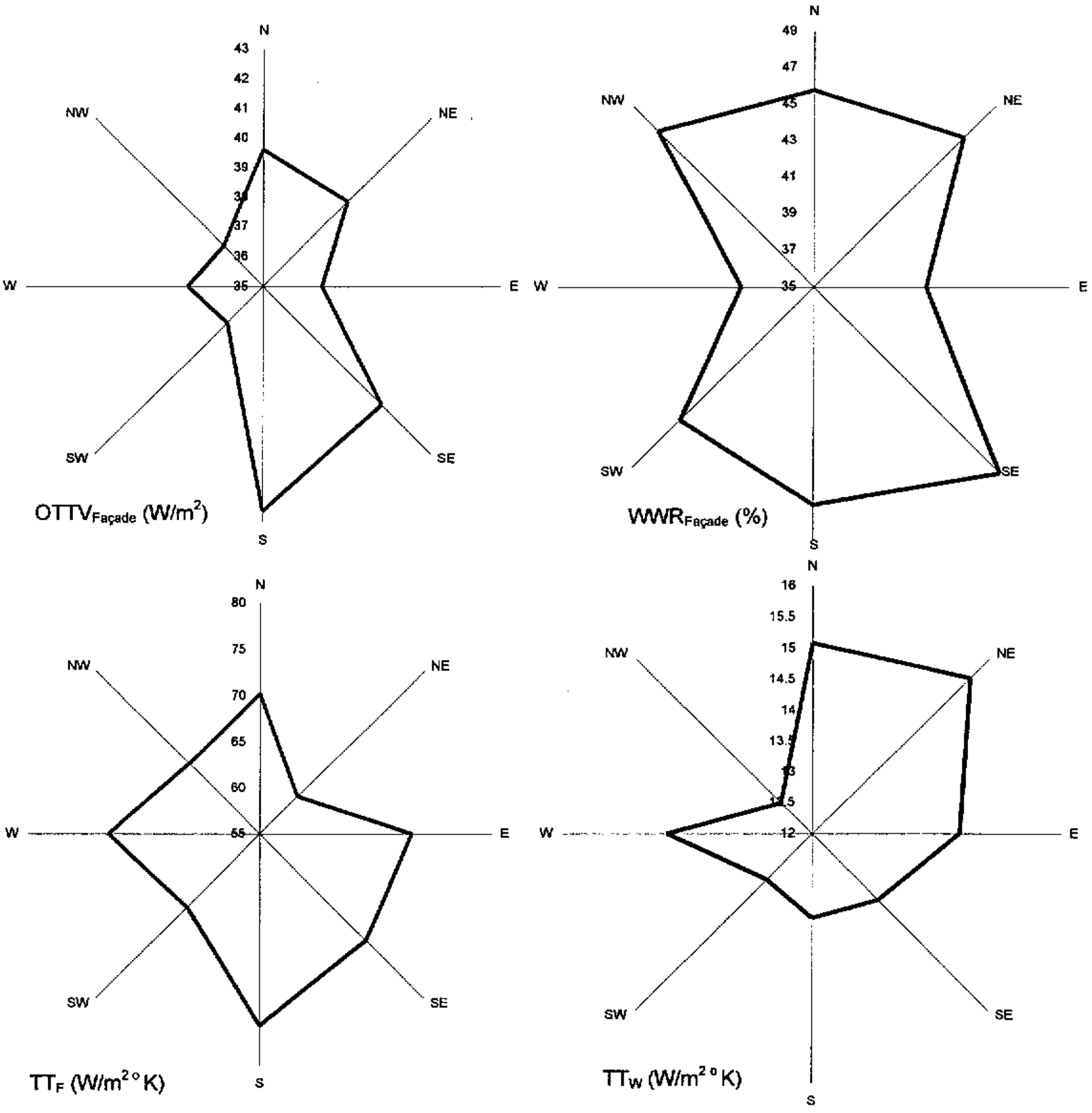


Figure 4.3. Mean $OTTV_{Facade}$, WWR_{Facade}, TT_F and TT_W according to Orientation

The results suggest that designers may be wary of window size for E and W orientations. They do not appear to exercise similar discretion with WWR for the remaining 6 orientations.

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[1] For all statistical tests in the present thesis, the cutoff for significance is $p<0.05$.

Finally, it is speculated that if a climatic approach existed, it would be applied simultaneously to the design of fenestration and walls. TT_F and TT_W are found, however, to be unrelated. A Pearson's Correlation test, performed on the two variables, yielded r (125) = -0.096 at $p>0.05$. This suggests there is no consistency in the way that walls and windows are designed, at least in terms of their thermal performance.

4.2. Review of Indoor Conditions

4.2.1. Overview

The preceding section looked broadly at the shell of the office building; the present section examines indoor conditions through onsite observations and logging. The objective is to get a representative picture of the conditions found inside office buildings and to establish compliance with the Singapore statutory codes.

A second set of observations, presented at the end of this section, pertains to the shell of these buildings and their internal layouts. This is intended to supplement the preceding section (4.1) that focussed on the shell but relied on archival data.

Ten buildings were selected for this study of which nine were from the list of case studies of the preceding section[2]. The buildings picked were from two locales; in each, they were within walking distance of each other. Seven were from a central part of Singapore, three from the west in a business park[3].

Most of the spaces surveyed, with the exception of Offices, were accessible to the general public. In each building, one or more tenants were identified at random from the listing at the building's reception area and approached for permission to log their premises. Where permission was denied, another tenant was selected from the directory. The survey of each building took approximately 45 minutes. Weather

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[2] Revenue House is the new building introduced here. It was not reported in the previous section on the envelope, because its OTTV records could not be found.

[3] Business parks are out-of-city hubs that are home to multinational corporations.

conditions before and after each survey were noted, so as to ensure that no significant extraneous change had taken place during the period of logging.

4.2.2. Results

Table 4.6 summarises the data gathered for each environmental condition logged. For a more detailed summary, see Appendix A3: Summary of 10 buildings surveyed for indoor conditions.

	IAT* (°C)	RH (%)	Light (Lux)
Atrium			
Mean +/- Std. Dev. (N)	23.3 +/- 1.5 (8)	61+/- 5.4 (8)	481+/- 120 (8)
Min. - Max	20.8 – 25.0	50 -68	120 - 350
95% Confidence Interval	22.0 – 24.5	56 - 65	380 - 582
Lift Lobby			
Mean +/- Std. Dev. (N)	22.9 +/- 0.7 (9)	61+/- 6.3 (9)	153 +/- 105 (10)
Min. - Max	21.8 - 24.0	50 – 68	50 – 380
95% Confidence Interval	22.4 – 23.5	56 - 66	78 - 228
Cafeteria			
Mean +/- Std. Dev. (N)	22.4 +/- 1.0 (4)	63 +/- 4.4 (4)	170 +/- 26 (3)
Min. - Max	21.0 - 23.1	57 – 67	50 – 380
95% Confidence Interval	20.9 – 23.9	55 - 69	104 - 235
Offices			
Mean +/- Std. Dev. (N)	22.6 +/- 1.0 (10)	61+/- 5.7 (10)	480 +/- 150 (10)
Min. - Max	21.3 - 23.7	53 – 75	175 – 670
95% Confidence Interval	22.0 – 23.3	57 - 65	373 - 587
Toilet			
Mean +/- Std. Dev. (N)	26.4 +/- 1.5 (9)	59 +/- 10.3 (9)	191+/- 126 (8)
Min. - Max	24.5 - 28.5	50 – 80	50 – 340
95% Confidence Interval	25.3 – 27.6	51 - 67	86 - 296

** This summary of IAT covers only air-conditioned spaces.*

Table 4.6. Indoor Conditions Surveyed in 10 Office Buildings

It should be noted that there were only four cafeterias found in the ten office buildings surveyed. This sample size is likely to affect how representative the data is with regard to this particular space type.

4.2.3. Analysis

4.2.3.1. Indoor Air Temperature

The conditions logged show that, in general, office buildings are cooled to temperatures well below that which is required by the Singapore statutory codes (see Figure 4.4). The means and lower limits of all spaces, with the exception of Toilets[4], were close to, or well below, the specified minimum of 23°C.

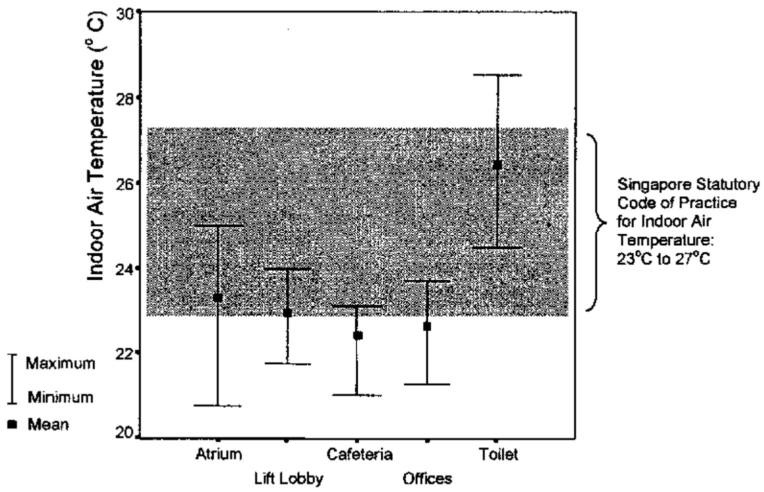

Figure 4.4. IAT and the Singapore Statutory Code

The temperature means show a consistency across almost all the spaces which supports the idea that a building's mechanical and electrical systems are designed to deliver uniform conditions, irrespective of use or location.

The bandwidths of temperature are fairly tight, between 1 to 2.5 K (defined by the 95% confidence intervals) for all spaces, excluding toilets. The Singapore statutory code allows a range of up to 4K, 23°C to 27°C, for AC spaces.

Almost all of the spaces surveyed were reliant on AC with the exception of two atria, one of which clearly relied on natural ventilation (Case 5) whilst the other (Case 4) appears such because of poor AC distribution and seepage of cold air to the outdoors. Only one lift lobby was found to be mechanically ventilated (Case 8).

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[4] In the case of the Toilet, the higher temperatures recorded are probably due to the requirement for air-exchange rates. The PWD Handbook for Energy Conservation in Buildings and Building Services (1983) stipulates that Toilets must provide a minimum of 10 air-changes/hour (p. 32). An Office, which can have 6 if mechanically ventilated, or a minimum of 13 m^3/hour per person if operated with AC.

4.2.3.2. Relative Humidity

The distribution of relative humidity shows that almost all spaces were below the 75% upper limit prescribed by the statutory codes (see Figure 4.5). The mean values tend to cluster around the 60% mark, with RH as low as 50% in some spaces. There is, however, no lower limit in the code for RH.

As with IAT, the consistency of RH across different space types suggests a consistency due to the building's electro-mechanical systems.

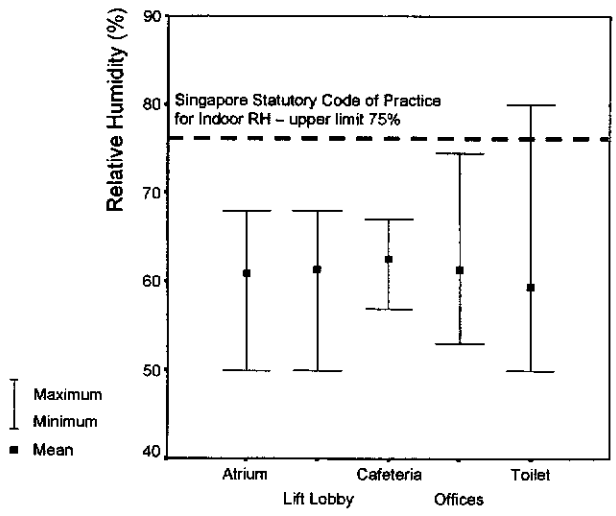

Figure 4.5. RH and the Singapore Statutory Code

4.2.3.3. Illuminance

With illuminance, the picture is more complex, both in terms of onsite conditions and codes. The code for lighting permits varying bandwidths of illuminance levels, depending on the nature of the space.

Readings of the five spaces surveyed show a wide range of conditions (see Figure 4.6), often beyond the limits prescribed for its respective category. This variability is sometimes due to the presence of daylight, which could not be measured independent of electrical light in the context of the present study.

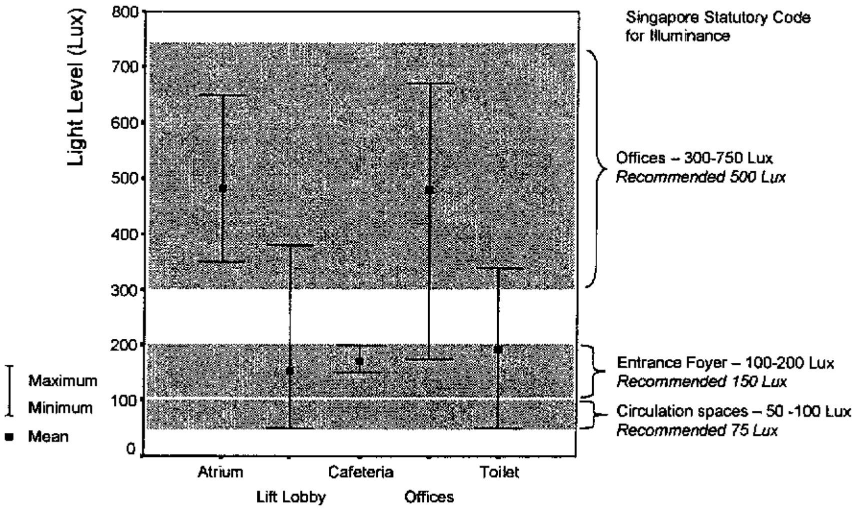

Figure 4.6. Illuminance and the Singapore Statutory Code

An overview of the visual condition is shown in Table 4.7 the Atrium, Cafeteria and Offices each had substantive access to natural light. In the Lift Lobby and Toilet, daylight was often negligible or absent.

	Electrical Light	**Daylight**
Atrium	Mostly large downlights.	Extensive glazing on periphery, sometimes around 3 sides of the atrium. Two case buildings (JTC and URA) had skylights as well.
Cafeteria	Fluorescent lights concealed within decorative ceilings plus downlights.	Windows and skylights were present in all cases except one (RevH).
Lift Lobby	Fluorescent lights concealed within decorative ceilings plus downlights.	Seven out of ten buildings did not have windows. Of the remaining three, two had small openings that let in low levels of natural light.
Offices	Ceiling grids of fluorescent lights in almost all cases. The sole exception (RevH) had task lighting at occupant's desk to supplement lower levels of ambient light from ceiling-mounted fluorescent fittings.	Most workspaces had access to windows. The buildings were often designed with large windows that let in substantial amounts of natural light. However, daylight distribution was seen to be impeded by two factors: • Placement of floor-to-ceiling partitions near the building envelope • Occupants who kept blinds/shades drawn
Toilets	A combination of concealed fluorescent fittings and downlights	Six of the nine toilets surveyed had no windows. Of the remainder, two had small windows that let in minimal daylight.

Table 4.7. Electrical and Natural Light Provisions

4.2.3.4. Appearance and Layout

Of the ten buildings visited, only one had external sunshades and setbacks for windows (see Table 4.8). Façade treatment did not vary with orientation for any of the ten; none had a side-placed core.

Whilst each building appeared different, there emerged a stylistic consistency that could be broadly labeled Modern or International Style[5]. All buildings were generally without ornamentation, with strong geometric forms and uncluttered facades. Seven of the ten relied on curtain wall envelope systems that gave the exterior an uninterrupted, smooth finish.

	External Shading	**Façade Varies with Orientation?**	**Use of Service Core as Thermal Buffer**	**Style, Appearance and *Layout***
Case 1	X	No	X	International Style Curtain wall exterior *High partitions on plan perimeter*
Case 2	X	No	X	International Style Curtain wall exterior *Full height partitions on plan perimeter*
Case 3	X	No	X	International Style Curtain wall exterior *Full height partitions on plan perimeter*
Case 4	X	No	X	International Style Curtain wall exterior *High partitions on plan perimeter*
Case 5	X	No	X	International Style Curtain wall exterior *High partitions on plan perimeter*
Case 6	X	No	X	International Style Curtain wall exterior *Full height partitions on plan perimeter*
Case 7	X	No	X	Modern *High partitions on plan perimeter*
Case 8	X	No	X	Modern
Case 9	✓	No	X	Modern *High partitions on plan perimeter*
Case 10	X	No	X	International Style Curtain wall exterior *High and full height partitions on plan perimeter*

Table 4.8. Building Appearance

In terms of internal layout, the most significant observation was that daylight entry was obstructed by high and/or full-height partitions situated at the perimeter zone. It was noted that these served to delineate offices for senior staff and meeting rooms.

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[5] Refer to Section 2.1.3 for elaboration of these two styles, as they apply to the Office Building.

4.3. Detailed Passive and Active Logging

4.3.1. Overview

Whereas the preceding section relied on spot readings of indoor conditions across a spectrum of case studies, this present section relies on data from a select group of buildings, carried out over a longer period of logging. This will be reviewed to ascertain the dynamic interaction between a building's shell and its systems.

Four buildings make up the case studies here (see Table 4.9). Two were selected from the earlier list of buildings surveyed for indoor logging; the remaining examples are from Malaysia[1].

The Singapore case studies, URA Centre (URA) and Revenue House (RevH), were picked because they deploy state-of-the-art intelligent systems and energy conservation measures (Cooke, 2000; Gwee, 1999). They represent a progressive and contemporary approach to office building design.

The Malaysian examples, Menara Mesiniaga (MES) and Menara UMNO (UMNO), were picked because they are well known examples of the Bioclimatic approach[2] as it is applied to office buildings in the hot humid climate (Pearson, 1993; van Schaik, 1998).

A summary description of all four buildings is presented in Appendix A4 (Summary of 4 Buildings Surveyed for Passive and Active Logging) followed by the weather conditions under which they were logged (Appendix A5: Summary of Weather for Period of Logging).

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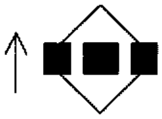
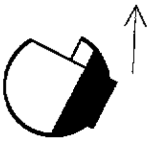
[1] There are seasonal differences between Singapore and Malaysia with regard to the periods of rainfall but the two countries have similar diurnal and annual ranges for solar radiation levels, dry bulb temperature, relative humidity and wind speeds (Pearce & Smith, 1990).

[2] There are no known examples of 1990s-built Singapore office buildings that were designed to be Bioclimatic, nor any that specifically embody a strategic approach to climate.

Table 4.9 summarises what was logged and when. It should be noted that logging was confined to specific office floors[3], and included their lift lobbies and service areas.

Building *Year Completed* *Location*	**Design Emphasis**	**Period of Logging**	**Passive Readings**	**Active Readings**	**Energy Consumption**
URA *1997* *Singapore*	Active-run. Emphasis on building intelligence 	10 – 20 March 2000	EST, IAT, MRT	EST, IAT, MRT, RH, Air, Light	For the Year 1999
RevH *1995* *Singapore*	Active-run. Emphasis on energy efficiency 	26 October – 9 November 1999 29 January – 3 February 2000	EST, IAT, MRT, RH, Air, Light	EST, IAT, MRT, RH, Air, Light	
MES *1992* *Kuala Lumpur, Malaysia*	Bioclimatic design. Predominantly active-run 	19 – 25 January 2000	EST, IAT, MRT, RH, Air, Light	EST, IAT, MRT, RH, Air, Light	
UMNO *1998* *Penang, Malaysia*	Bioclimatic design with passive and active mode options 	5 – 15 May 2000	EST, IAT, MRT, RH, Air, Light	EST, IAT, MRT, RH, Air, Light	

Arrows indicate North. Dark insert indicates the building's service core.

Table 4.9. Summary of Passive and Active Logging

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[3] The building manager would decide on the level of access granted. This ranged from a single floor (URA) to the entire building (MES). Constraints on access affected the range and frequency of monitoring, particularly in the case of URA where passive readings on weekends were not permitted.

4.3.2. Results

Table 4.10 summarises the range of all temperatures recorded during the period of logging. Subsequent tables do the same for RH (see Table 4.11), Air (see Table 4.12) and Illuminance (see Table 4.13). The data presented here is from office spaces only; a more comprehensive summary of data gathered for each building is presented in Appendices A6 to A9.

	EST$_{Glass}$ Range* (°C)	IAT Range (°C)		MRT Range (°C)		Outdoor DBT and MRT** (°C)
		Passive	*Active*	*Passive*	*Active*	*During period of logging*
URA	26.2 - 38.5	25.1 – 26.2	22.0 – 23.0	24.7 – 27.2	22.3 – 23.3	DBT: 23.5 - 33.0 MRT: 21.8 – 47.2
RevH	28.4 – 40.0	24.9 – 29.4	19.6 – 24.3	24.3 – 29.0	21.9 – 24.1	DBT: 22.9 – 35.0 MRT: 21.6 - > 41.3
MES	32.6– 50.0	25.6 – 33.7	21.5 - 28.3	25.5 – 35.5	23.9 – 29.5	DBT: 23.5 – 34.5 MRT: 22.7 – 44.8
UMNO	31.2 - >41.3	28.0 – 38.5	21.3 – 24.5	27.4 – 41.2	Not Available	DBT: 23.7 – 33.5 MRT: 24.5 - >41.3

The upper limit for some temperature loggers was 41.3°C. Where entry is indicated as '>41.3', it implies the logger had reached its upper limit.

** These temperatures were recorded around the building perimeter during the period of logging. For detailed meteorological data, refer to Appendix A5 (Summary of Weather for Period of Logging)*

***This range represents the high-end EST recorded for each façade during daylight hours.*

Table 4.10. EST, IAT and MRT across all buildings

	Indoor RH Range (%)	Indoor RH Range (%)	Outdoor RH Range (%)*
	Passive	*Active*	*at time of active readings*
URA	Not available	57 - 67	69 - 82
RevH	79 - 84	53 - 56	66 - 78
MES	52 - 75	51 - 60	55 - 65
UMNO	59 - 75	59 - 72	65 - 77

** These RH values were recorded around the building perimeter during the period of logging. For detailed meteorological data, refer to Appendix A5 (Summary of Weather for Period of Logging)*

Table 4.11. RH across all buildings

	Range of Indoor Air Speeds* (m/s) *Active*	**Range of Indoor Air Speeds (m/s)** *Passive*	**Outdoor Wind Conditions** (direction and speed in m/s)** *at time of passive logging*
URA	Below instrument sensitivity	Passive readings not permitted	
RevH	0.0 – 0.1	<0.3 to > 5.0	From S and SW, 0.5 (AM) to 2.0 (PM)
MES	Below instrument sensitivity	<0.3 to 3.0	From W (PM only), 0.0-2.7
UMNO	0.0 – 0.1	<0.3 to 5.0	From N (AM), 2.3-4.4 From SW (PM), 0.7-3.3

**The VelociCalc Air Meter, which could record air speeds below 0.3 m/s, was available only for certain periods of logging (see Appendix A1: Summary of Instruments and Instrumentation). Where entry indicates <0.4, the Kestrel wind meter was used.*
*** Data from the Singapore and Malaysia Meteorological Offices. It was not possible to record wind speed around the building perimeter as these proved to be erratic and highly variable.*

Table 4.12. Air speeds across all buildings

	Range of Illuminance Levels (Lux) *Active*	**Range of Illuminance Levels (Lux)** *Passive*
URA	540 - 990	Passive readings not permitted
RevH	110 - 1160	20 - 470
MES	300 - 770	50 - 4000
UMNO	300 - 700	57 – 15400

It was not possible to record illuminance levels around the building perimeter as these proved to be erratic and highly variable. No data from the Meteorological Offices was specific to illuminance.

Table 4.13. Illuminance across all buildings

	Energy Consumption for the Year 1999 (kWh/m²/year)
URA	238.5
RevH	124.1
MES	245.0
UMNO	353.0

Refer Appendices A6 to A9 for monthly breakdowns of energy figures for each building.

Table 4.14. Energy consumption in all buildings for the Year 1999

4.3.3. Analysis

Analysis of data is presented as follows:

- Impact of passive features
- Proximity to the envelope
- Type/degree of indoor variability
- Passive and active modes

It should be noted that all analysis is confined to intra-building comparisons for same-day readings. This is to minimise any confusion that might arise from outcomes due to differing weather conditions experienced by each of the buildings during same period of logging, or by the same building on different days.

4.3.3.1. Impact of Passive Features

Four passive variables are reviewed here:

- Orientation
- External Sunshade
- Transitional Space
- Material Attribute

The graphs presented in this section attempt to isolate the impact of each variable. This impact is inferred from comparisons made between ESTs of different facades and IATs at various locations within the context of a single building and on the basis of simultaneous readings. The graphs are extracted from logging that often lasted two or more days; data not shown here can be viewed in Appendix A10 (Logging Data in Detail).

As an example of inference from a set of same-day readings, the first graph shown here is of EST_{Glass} readings taken on a single floor in UMNO. On this floor the building has transitional spaces facing NE, sunshades on the NW façade and no solar protection on the W. Figure 4.7 shows EST_{Glass} readings for each surface.

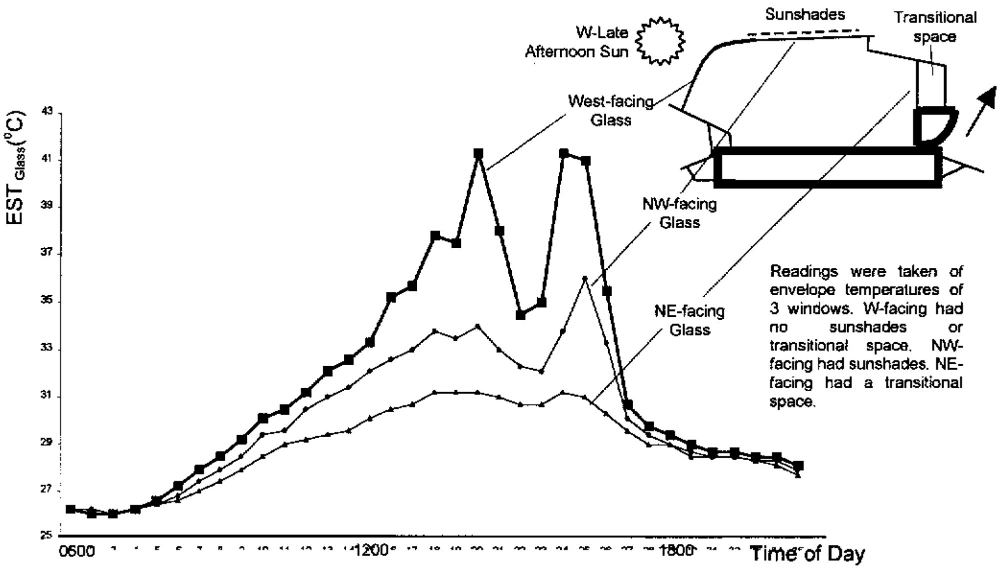

Figure 4.7. EST_{Glass} of UMNO with varying combinations of passive features

Of the three facades, NE performs 'best' because it has the lowest surface temperatures throughout the day. The 'mid-way' option is NW, which receives some incident sunlight, but is partly protected by its sunshades. The 'worst' is W, which receives high levels of direct solar radiation in the afternoon, but has no sunshade or transitional space. The divergence of EST_{Glass} starts early in the day and peaks in the late afternoon when the difference between NE and W surface temperatures amounts to 10K[4]. In reviewing the graph, it was not possible to isolate the impact of each. The next set of graphs will attempt this.

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[4] The margins of temperature difference reported here should not in themselves be viewed as absolute indicators of performance. They should be seen, rather, as signifiers of the impact of a variable, or combination of variables, at a point in time.

Orientation

It was observed that office buildings often have identical façade treatments irrespective of orientation. In comparing ESTs of two facades of identical design, the impact of their respective orientations can be gauged.

Figure 4.8 contrasts EST_{Glass} for the N and S-facing envelope of RevH. At the time of logging, the building was receiving direct sunlight on its southerly facades. Each facade has the same glass type, a transitional space and no sunshades. The difference in surface temperatures was observed to reach 5.3K during afternoon peaks, with S-facing glass the hotter of the two.

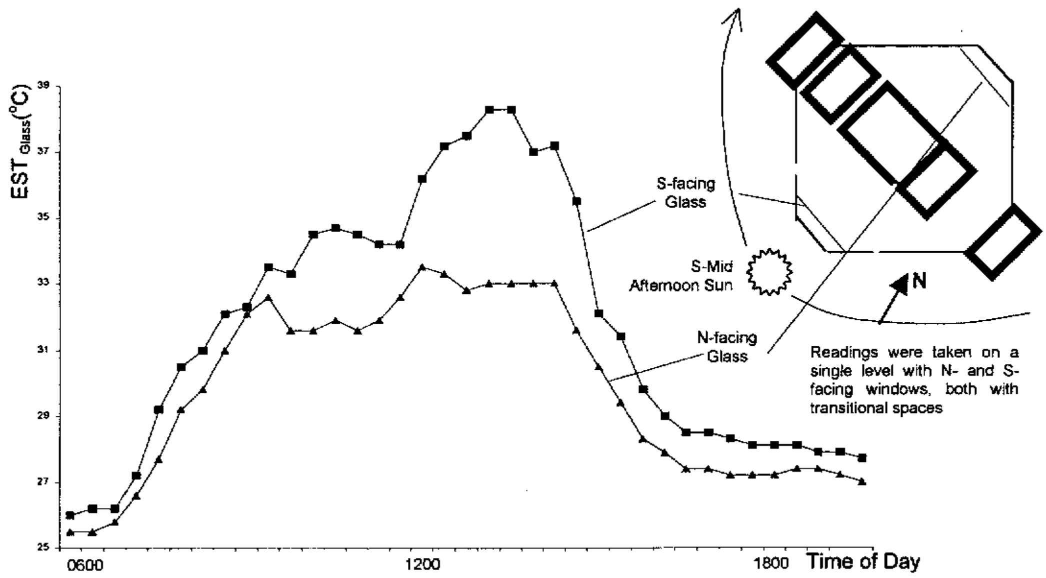
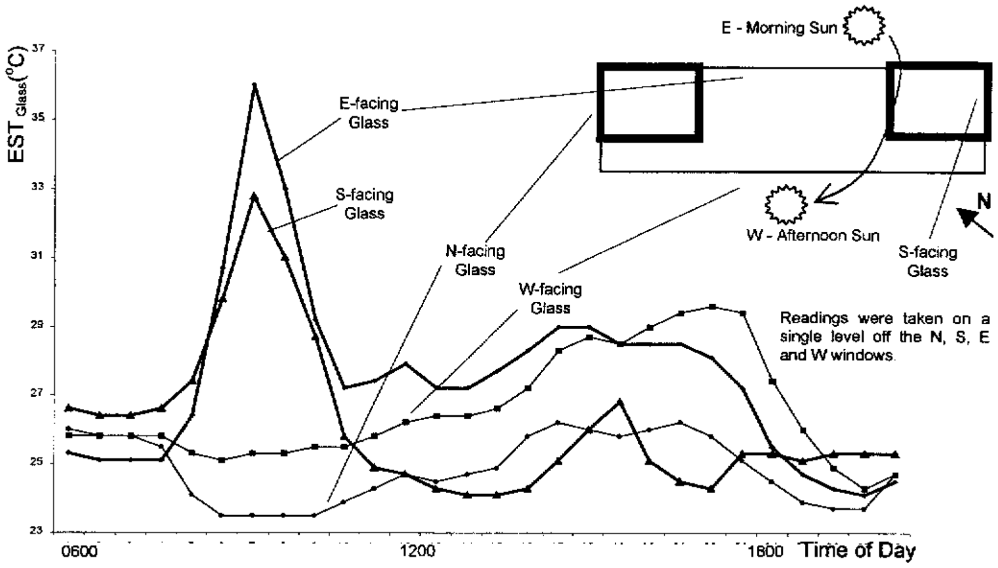


Figure 4.8. N- and S-facing EST_{Glass} of RevH for impact of orientation

URA was the only Singapore case study observed to have external sunshades. Its orientation is primarily N-S, E-W, with the longer facades getting the full impact of the morning and afternoon sun. At the time of the study, the sun was in the southern hemisphere of the sky.

Figure 4.9 compares EST_{Glass} across all four facades of the URA where it is shown that the S and E facades behave significantly different from the E and N facades.



Readings were taken on a single level off the N, S, E and W windows.

Figure 4.9. N, S, E and W-facing EST_{Glass} of URA for impact of orientation

E and S peak in the mid-morning hours with temperature differences of more than 10K higher than W and N. The afternoon peaks are not as pronounced due to hazy conditions that occurred later in the day.

External Sunshades

The impact of external sunshade is illustrated with MES, which has two types: light and heavy[5]. In the two figures that follow, EST_{Glass} of a façade with sunshade is compared with that of another without. Both facades are otherwise identical in terms of orientation and tint.

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[5] See Appendix A4 for details on the MES sunshades.

Figures 4.10 and 4.11 show the impact of light and heavy sunshades respectively. Readings were taken on the two 'hot' elevations, NE and W, which were most exposed to direct solar radiation. The impact of sunshades was found to be particularly notable during peak periods when sunlight was incident on the windows. It is evident that both sunshades make a difference of at least 5K on EST_{Glass}.

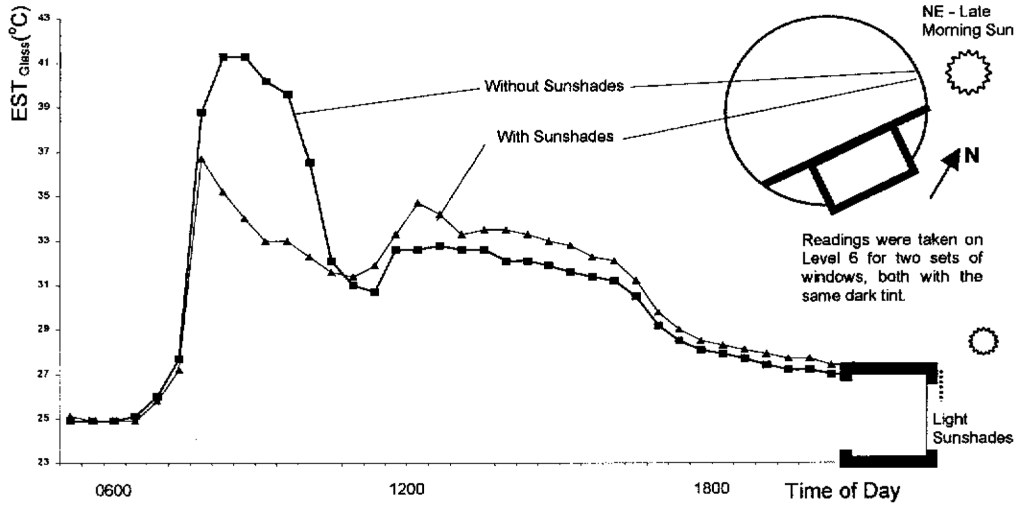


Figure 4.10. N-facing EST_{Glass} of MES for impact of light sunshade

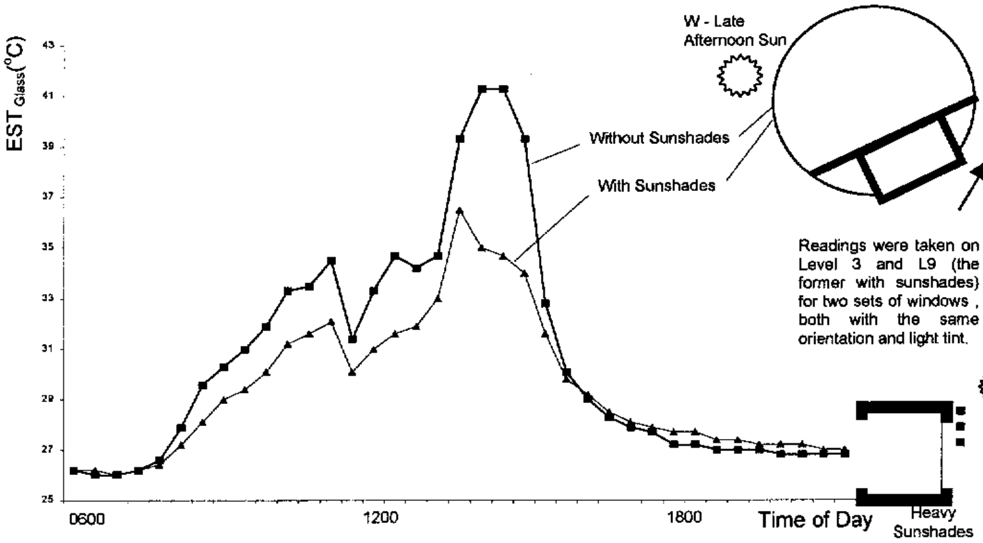


Figure 4.11. W-facing EST_{Glass} of MES for impact of heavy sunshade

The sunshades appear also to have an impact during periods when the windows were not subject to direct radiation. Differences then amounted to as much as 2.5K. This suggests that sunshades may play a part in reducing the effect of indirect radiation.

Transitional Space

The impact of transitional space on EST_{Glass} is shown here for two buildings: UMNO and MES.

UMNO was designed with W-facing transitional spaces on some floors, but not on others. These transitional spaces, when present, result in an envelope setback of 8.2m at the widest point. Figure 4.12 contrasts EST_{Glass} on two floors, one with and the other without transitional space.

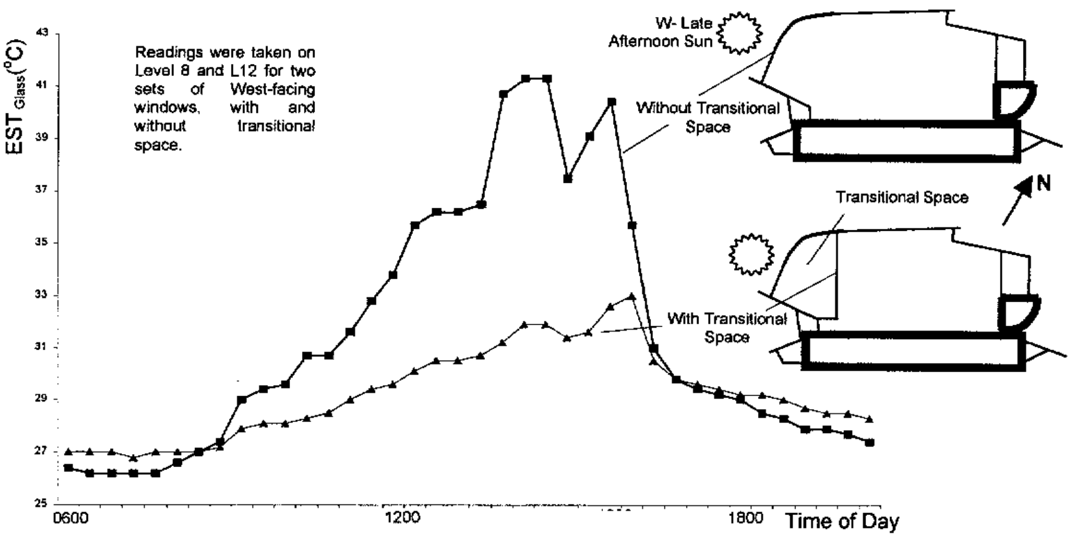


Figure 4.12. W-facing EST_{Glass} of UMNO for impact of transitional space

The gap between the two begins early in the day and widens progressively to a late-afternoon peak of more than 9K.

In MES, the transitional space faced S and therefore did not receive much direct sunlight for the period of logging. Figure 4.13 contrasts two floors, one with and the other without a transitional space. The graph shows a difference in EST_{Glass} of almost 4K.

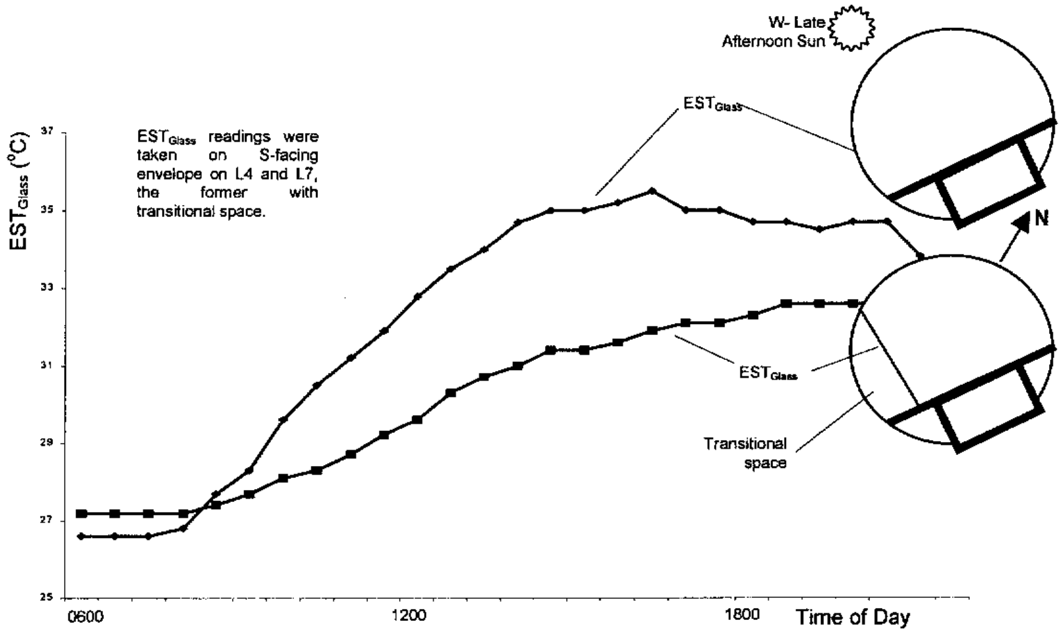


Figure 4.13. S-facing EST_{Glass} of MES for impact of transitional space

The EST_{Glass} curve in MES, as compared with that for UMNO's W-facing facade, is more rounded, without the sharp peaks of the latter. This appears to be because of the level of direct solar radiation received by the UMNO facade.

Material Attribute

In the years since MES was completed, tenants progressively installed layers of solar tints in a bid reduce glare. In so doing they altered the envelope's material attributes. Three types of tints are evident: *light*, *dark* and *extra dark*. These are reviewed here for their impact on EST_{Glass}.

Figures 4.14 and 4.15 contrast EST_{Glass} of two sets of windows. The first pair, facing W, has a *light* and *dark* tint. The second pair, both windows NE-facing, has *dark* and *extra dark* tint. None of the windows have external sunshades.

The first graph suggests that having a light or dark tint amounts to difference 1-2K surface temperature. In the morning, without incident light on the facades, the light tint is the warmer of the two. In the afternoon, the dark tint becomes warmer than the light.

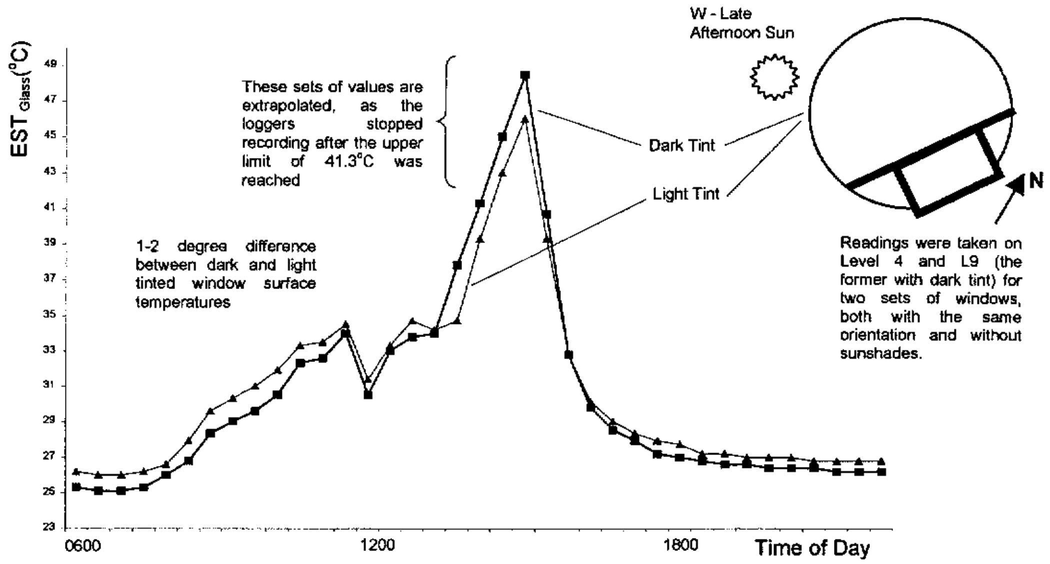


Figure 4.14. W-facing EST$_{Glass}$ of MES for impact of solar tints

The second graph suggests that the difference between dark and extra dark is far more substantial. The gap in surface temperatures widens during the late morning peak, reaching an estimated 10K.

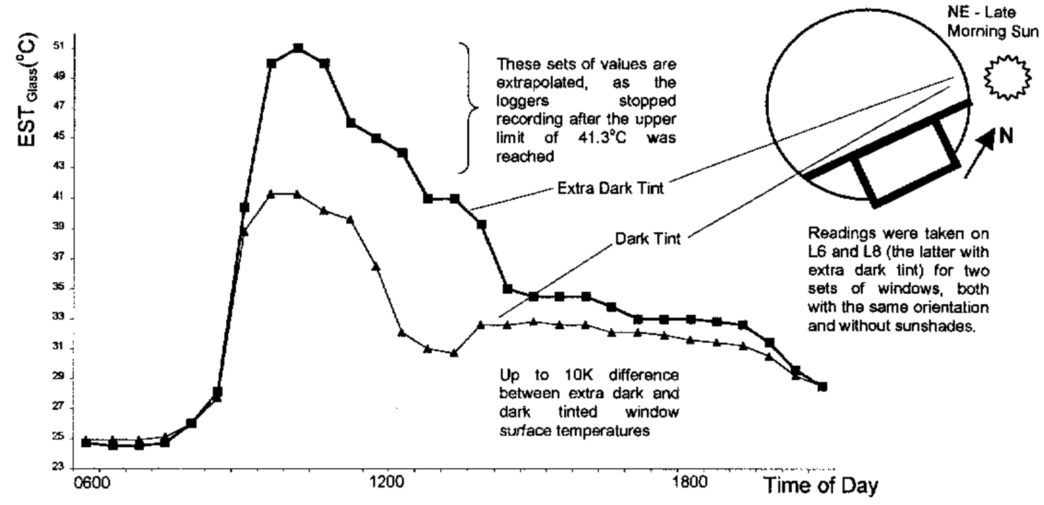
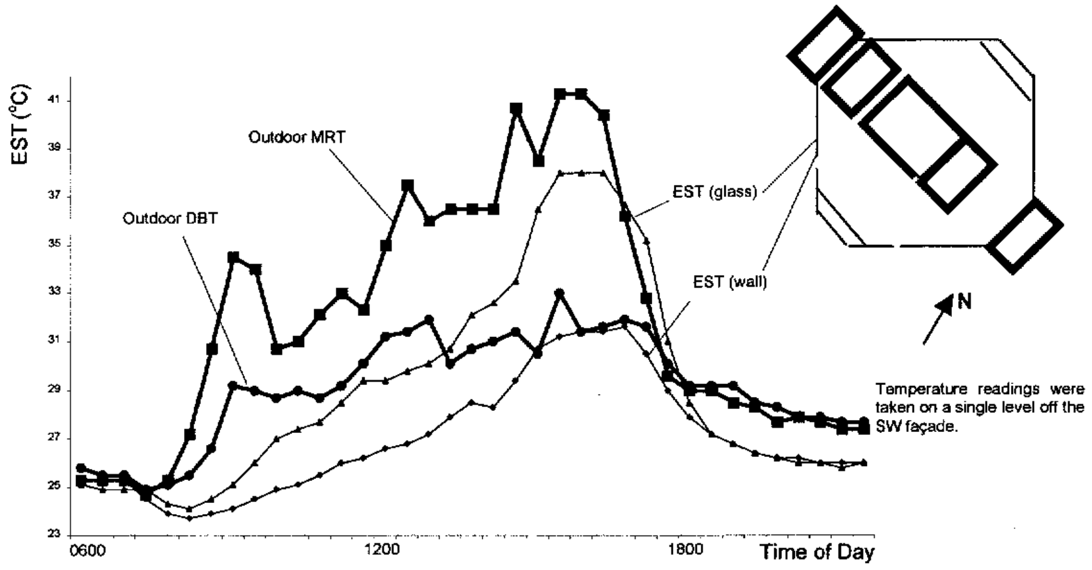


Figure 4.15. NE-facing EST$_{Glass}$ of MES for impact of solar tints

4.3.3.2. Proximity with Envelope

The envelope, as it is delineated by the OTTV equation, has two constituents: *fenestration* and *wall*. Fenestration typically offers lower thermal resistance than walls because of its transparency and material make-up (see Section 4.1.2, Table 4.2).

Figure 4.16 contrasts EST of envelope glass and wall in a set of readings for RevH. The walls here are made of a composite layer of brick and aluminum cladding; the windows are double-glazed tinted with a 19mm air gap. The graph shows two things. First, that glass reaches temperatures that are far higher than wall. Second, that both ESTs appear to reflect movements in outdoor MRT more so than that outdoor DBT.



Temperature readings were taken on a single level off the SW façade.

Figure 4.16. SW-facing ESTs at RevH

The same patterns are evident in Figure 4.17 from the URA. The graph shows ESTs of the wall and fenestration for the E facade. In this building, which has granite cladding instead of RevH's aluminium, EST_{Wall} appears virtually unaffected by outdoor conditions.

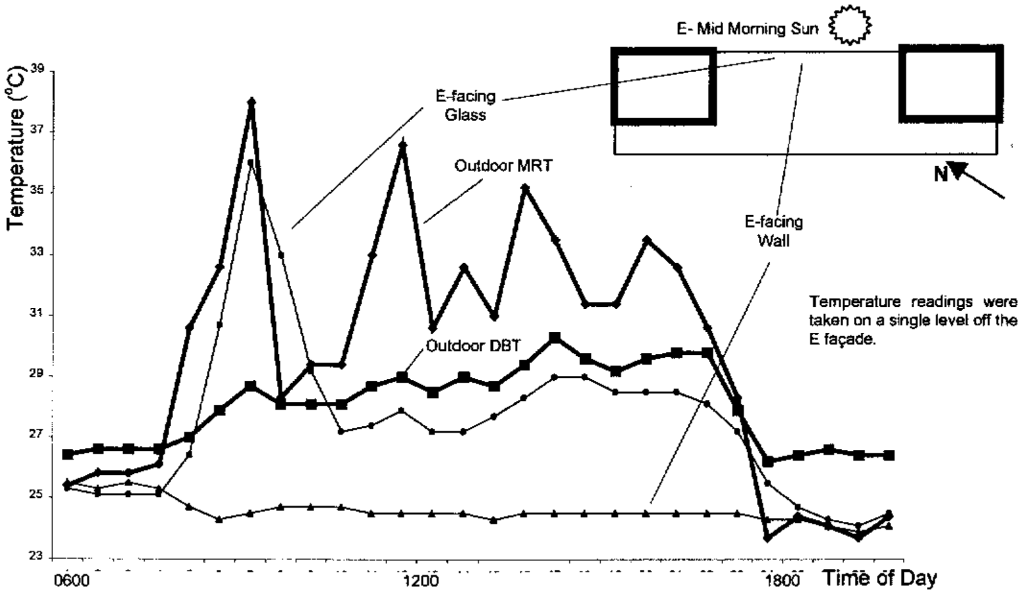


Figure 4.17. E-facing ESTs at URA

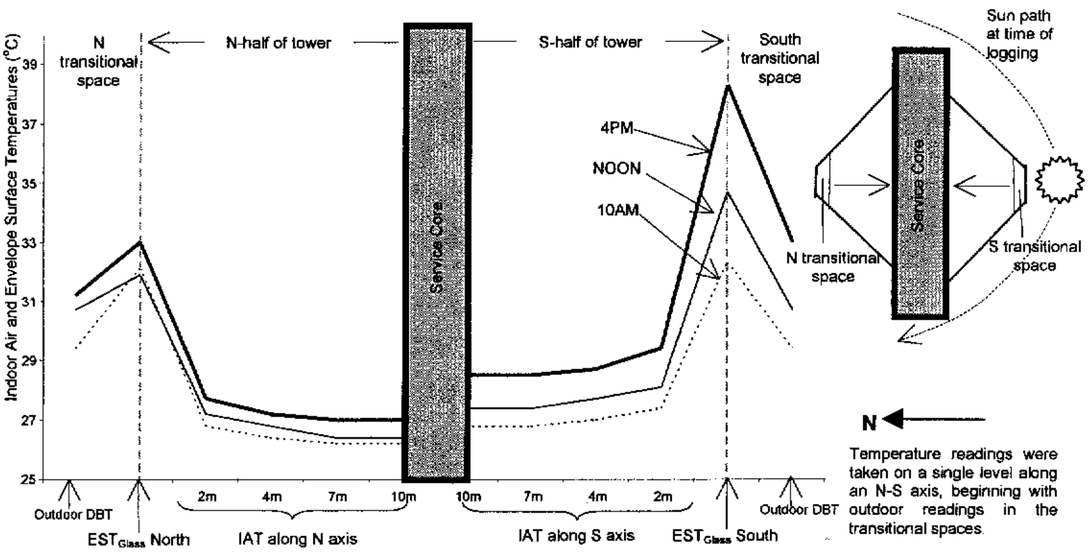
It is noteworthy that in both RevH and URA, the surface temperature of glass often reaches levels far higher than outdoor DBT.

Clearly a poorly shaded façade is likely to generate high surface temperatures. The question arises if this is likely to affect indoor air and radiant temperatures. The following set of figures will examine this carryover effect.

The first example of indoor temperature gradients is RevH. Its IAT and EST_{Glass} were logged at intermittent points along an N-S axis. This was done three times in the day: 10AM, Noon and 4PM for three consecutive passive-run days.

The building is symmetrical across its E-W axis in the way that the envelope is designed and detailed. The key difference, at the time of logging, was that the S half was exposed to the sun, whilst the N half was in perpetual shade.

Figure 4.18 shows temperatures logged from envelope to plan centre, including EST_{Glass} and Outdoor DBT, recorded at the N and S transitional spaces. It shows, first, that indoor conditions are generally warmer on the S half and, second, that they descend from warmer conditions nearest the envelope to cooler conditions near the plan centre.



Temperature readings were taken on a single level along an N-S axis, beginning with outdoor readings in the transitional spaces.

Figure 4.18. Temperatures along N-S axis of RevH *(passive mode)*

The figure confirms that EST_{Glass} is consistently higher than outdoor DBT. It is suggested here that this difference is more pronounced for a façade without shade.

Figure 4.19 shows IATs in UMNO logged with reference to two floors: one with transitional space and one without. The data suggest two things: that transitional spaces affect the thermal condition and that the temperature gradients are steepest when there is no transitional space. IAT on the periphery of the floor without a transitional space reached temperatures in the high 30s; IAT on the floor with one was about 8K cooler.

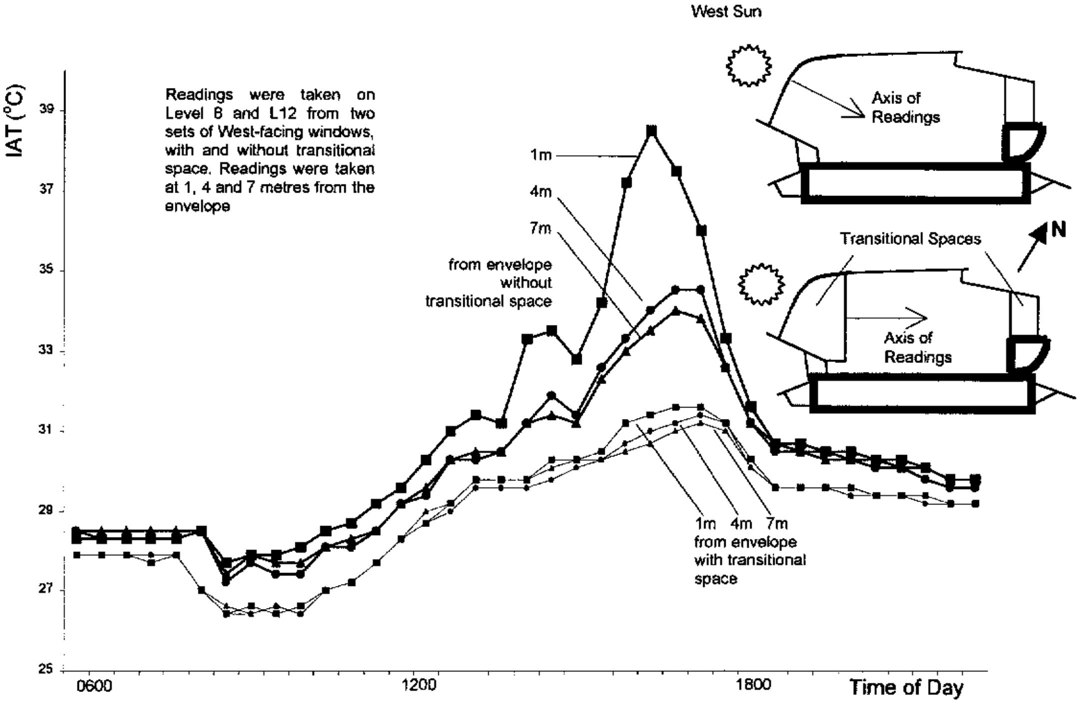


Figure 4.19. IATs from W-facing façade in UMNO *(passive mode)*

Furthermore, the floor without a transitional space exhibits a greater contrast between temperatures at its the perimeter and inner zones.

This pattern was also found in readings taken in MES, for S-facing elevations, with and without a transitional space. The data in Figure 4.20 compares IAT and MRT at 1.2m and 2.4m from the envelope on two floors.

The graph suggests that conditions are generally warmer on the floor without a transitional space. While the temperatures on the floor without a transitional space are closely bunched together, on the floor with, they exhibit a consistent gap throughout the day, with IAT loggers at 2.4m showing conditions 0.5K lower than IAT loggers at 1.2m.

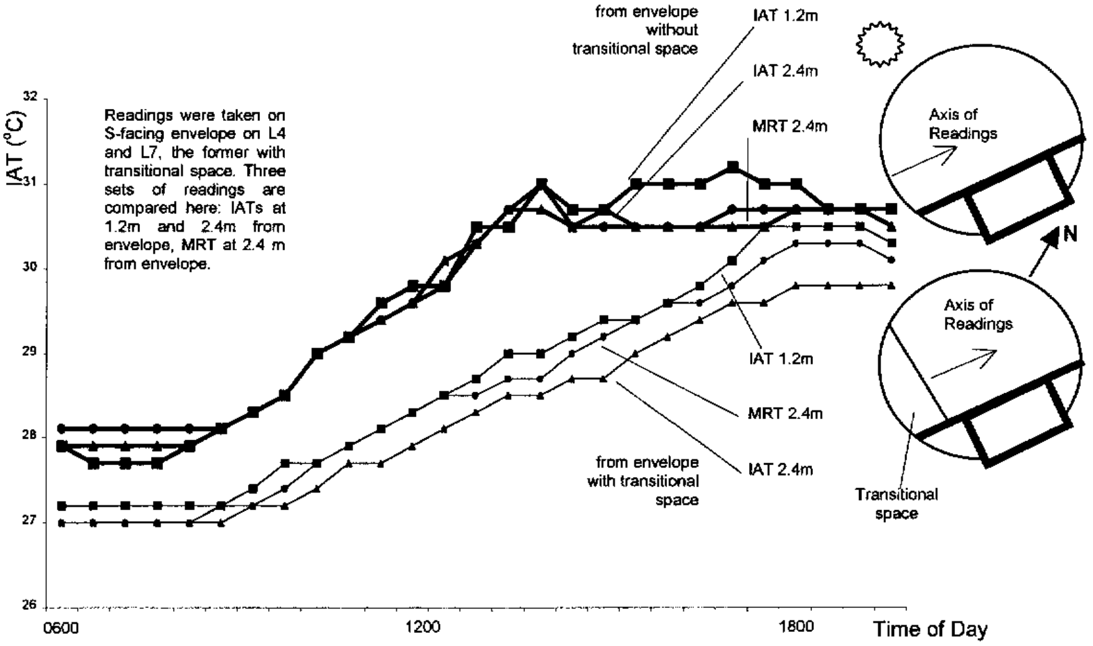


Figure 4.20. IATs from S-facing façade in MES *(passive mode)*

Table 4.15 summarises temperature gradients across all four case studies. The gradients are significantly sharper in the two Bioclimatic buildings, suggesting a greater contrast between thermal conditions in the perimeter zone and those areas further in.

	Temperature Gradients
URA	IAT - 0.6 K drop from 2.3 to 8.7 m MRT – 0.6 K drop from 2.3 to 8.7 m
RevH	IAT – 1.9 K drop from 1m to 16m MRT – not available
MES	IAT - 3.3 K drop from 1m to 11.5m MRT – 3.8 K drop from 1m to 11.5m
UMNO	IAT – 7.4 K drop from 1m to 16m

Table 4.15. Temperature gradients across all buildings *(passive mode)*

The difference between perimeter and centre is summarised here for natural ventilation (see Table 4.16) and daylight (see Table 4.17). In both cases, and for all buildings, a consistent pattern emerges of higher levels in the perimeter zone. Relative humidity is not shown as no significant patterns were noted in any of the buildings. Indoor RH levels were generally on par with outdoor conditions, with only a marginal difference between the two sets of readings (see Appendices A9 - A9).

All entries are in m/s	**Plan Perimeter**		**Plan Centre**	
	Maximum	*Minimum*	*Maximum*	*Minimum*
URA	Passive readings not permitted			
RevH	> 5.0	0.3	2.0	< 0.3
MES	3.0	0.5	0.5	< 0.3
UMNO	5.0	0.5	1.0	< 0.3

Table 4.16. Air movement across all buildings *(passive mode)*

	Maximum Illuminance at plan periphery (Lux)	**Minimum Illuminance at plan centre (Lux)**
URA	Passive readings not permitted	
RevH	1,800	<100
MES	5,600	<100
UMNO	>10,000	<100

Table 4.17. Natural light levels across all buildings *(passive mode)*

UMNO is briefly reviewed independent here in terms of NV as it was specifically designed to function in the passive thermal mode. Figure 4.21 summarises airflow patterns from several days of logging (see Appendix A9: Summary of Menara UMNO data). It suggests that the pattern of air movement is affected by the building's wind wing-walls and openings. These generate a stronger airflow, particularly on the plan periphery. In a large portion of the plan, however, air speeds are low.

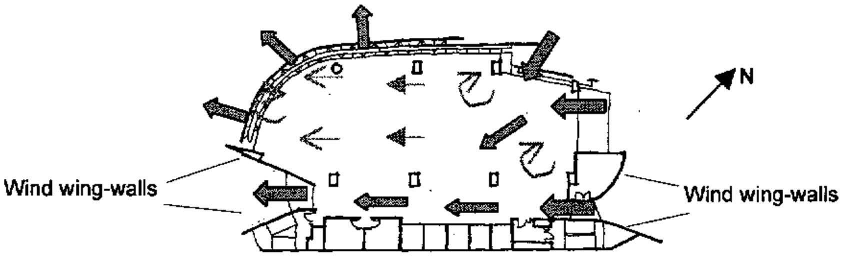


Figure 4.21. Pattern of passive air flow through UMNO

The wing-walls, in a sense, allow air to move from one end of the plan to the other, without really achieving an even distribution across the floor plan.

4.3.3.3. Indoor Variability

Indoor variability is reviewed here under three headings:

- Non-uniformity across the *Plan*
- Variability due to *Time of Day*
- Variability due to *Weather*

A fourth factor, variability due to *Time of Year*, could not be evaluated as logging was confined to periods of up to only two weeks.

The data presented here focuses on IATs and ESTs. Variability of Air and Light typically varied with proximity with envelope, which has been covered in Section 4.3.3.2. Variability of RH was not significant in the passive and active modes

Non-uniformity across the plan

A review of IATs shows that the differences evident in the passive mode tend to persist in the active mode, even if they are somewhat dampened. These gradients and asymmetries appear in relation to the envelope and/or AC supply outlets.

Of the four buildings, URA had the smallest margin of variability (see Figure 4.22) and is coolest at the plan centre. Its NW corner suffered from higher than average temperature differentials. This corner also had the higher WWR: 80% as compared with 40% for the rest of the facades. A patch of warmth also showed up along the E façade, but only in the active mode. This was found to be due to a door left open between warmer service areas and the cooler office space.

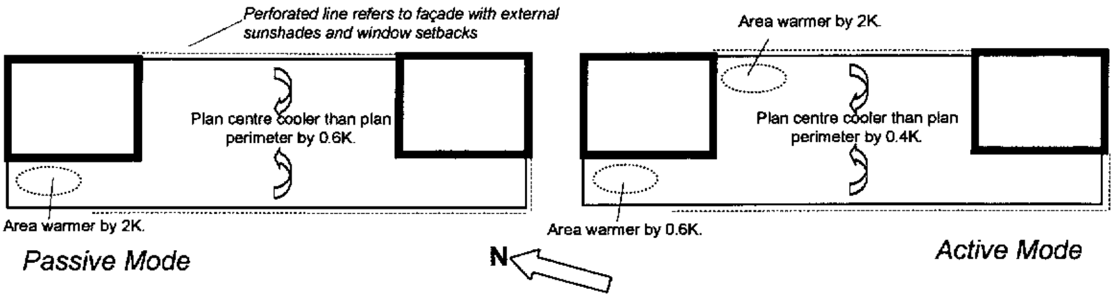


Figure 4.22. Non-uniformity in URA under passive and active modes

RevH showed a consistent difference between N and S halves of the plan, the S warmer in both passive and active modes (see Figure 4.23). This is probably due to its higher solar exposure. A cold patch appeared in the active mode in the vicinity of an AC supply outlet.

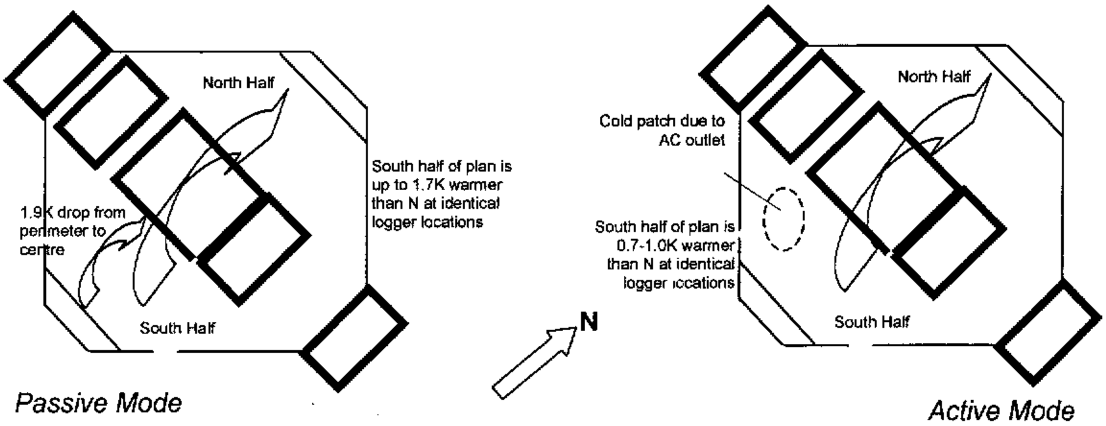


Figure 4.23. Non-uniformity in URA under passive and active modes

MES showed higher differentials than the two preceding buildings. 'Hotspots' occurred adjacent to NE and W facades (see Figure 4.24). These differentials increased in the active mode, as temperatures in S half of the building dropped due to AC supply, whilst those in the NE and W continued to be affected by high EST_{Glass}.

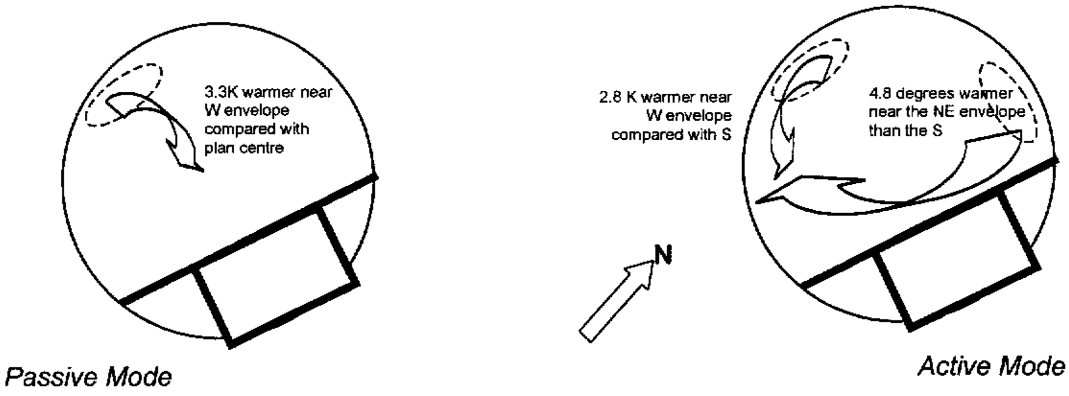


Figure 4.24. Non-uniformity in MES under passive and active modes

UMNO had similar solar-load induced differentials, the most striking occurred in areas near the W façade (see Figure 4.25). In the active mode, the differentials flatten out to a 0.5K margin. This may have been due to the fact that active logging was only carried out on a floor that had a W-facing transitional space[1].

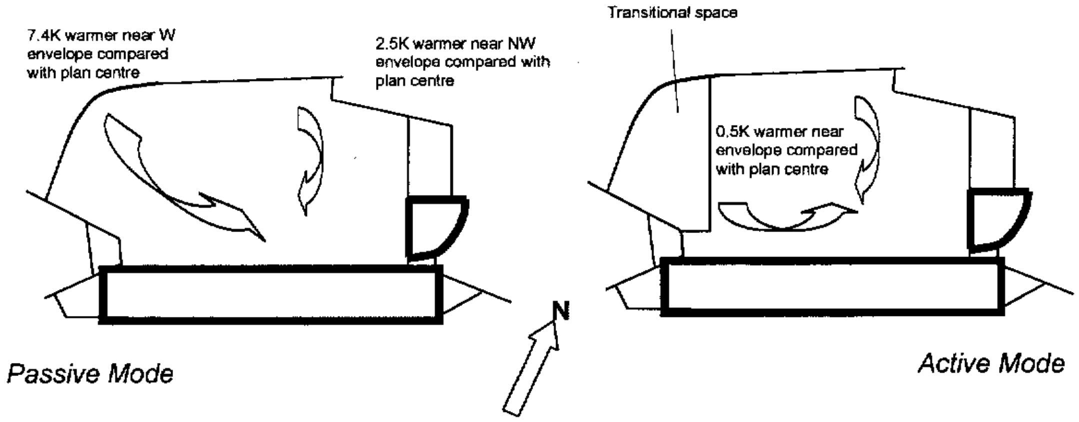


Figure 4.25. Non-uniformity in UMNO under passive and active modes

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[1] In UMNO, the active-run for which access was granted, had a transitional space.

Variability due to Time of Day

Indoor variability due to time-of-day appears to relate with sun-path. URA, which is E-W oriented, showed a clear shift in IAT and EST_{Glass} between the morning and afternoon (see Figure 4.26).

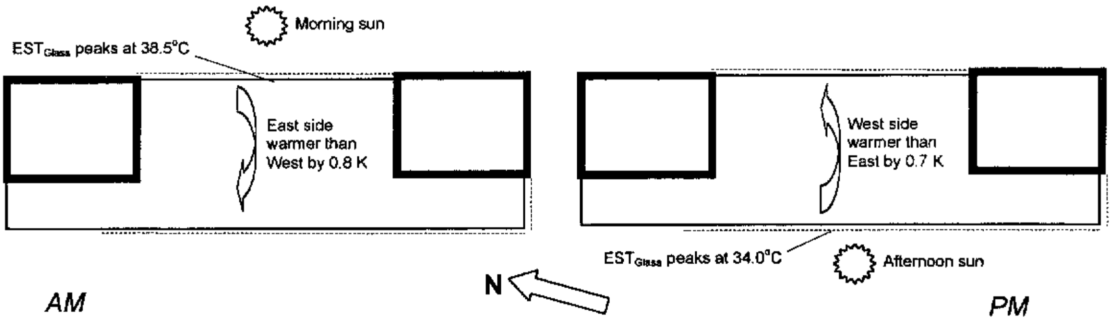

Figure 4.26. Indoor variability *(in passive mode)* at URA due to time of day

RevH, which was N-S oriented, showed the same shifts from E- to W-facing elevations (see Figure 4.27). This affected only the S half of the plan, suggesting that these shifts are contingent on degree of solar exposure.

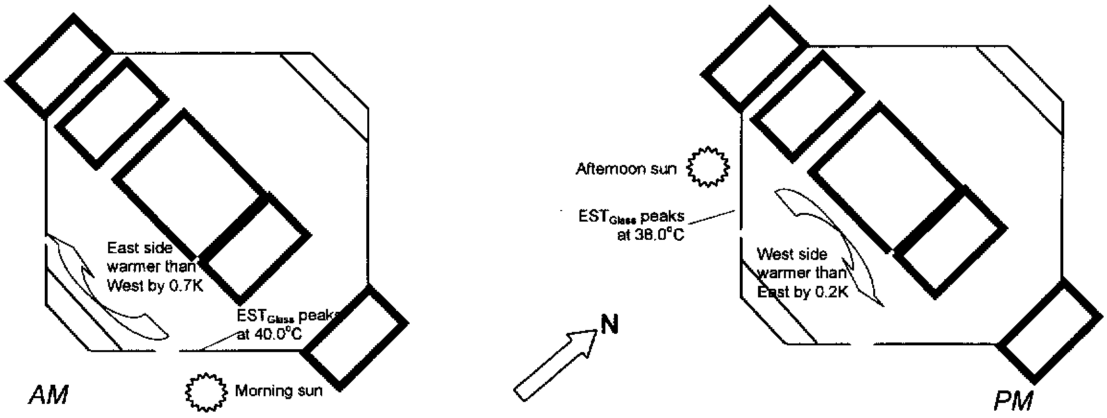

Figure 4.27. Indoor variability *(in passive mode)* at RevH due to time of day

MES had higher EST_{Glass} values than the two preceding case studies (see Figure 4.28). High temperatures were recorded in the late morning on the NE façade and late afternoon on the W façade. These appeared to have an effect on IAT (see Figure 4.24).

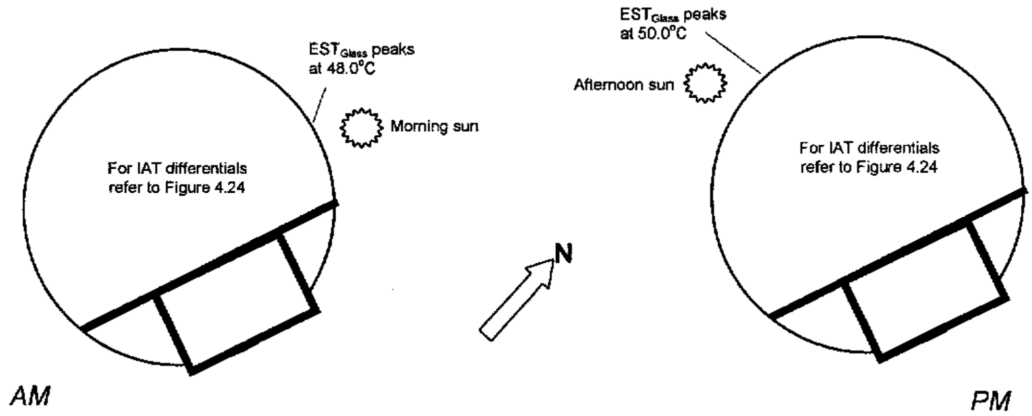

Figure 4.28. Indoor variability *(in passive mode)* at MES due to time of day

UMNO shows similar highs in EST_{Glass} for the afternoon; the morning peaks reached 33.3°C (see Figure 4.29). It was not possible to determine the maximum temperature in the afternoon as the logger in this instance had an upper limit of 41.3°C.

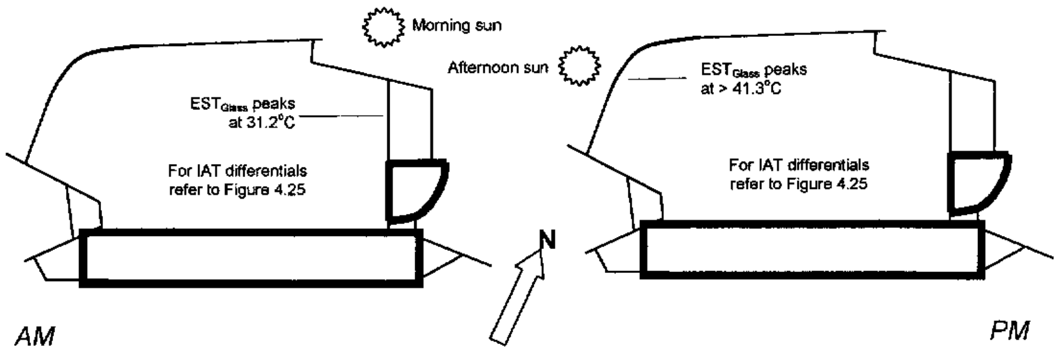

Figure 4.29. Indoor variability *(in passive mode)* at UMNO due to time of day

In a separate, one-off study of temperature changes due to time of day, an extensive survey was carried out at RevH. IAT and RH readings were taken at five locations on each floor (see Figure 4.30), once in the morning and again in the afternoon[2].

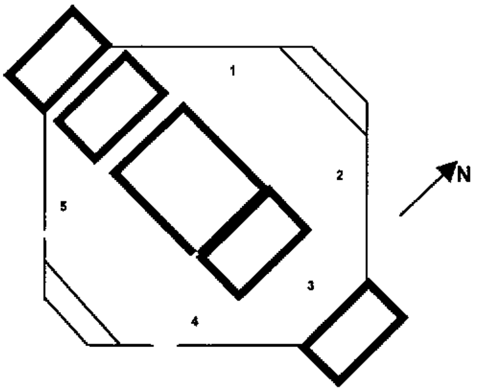

Figure 4.30. Location of readings at RevH

Table 4.18 shows the conditions logged in the offices. The weather for the day was generally consistent, with no periods of rainfall.

	Indoor Air Temperature (°C)			**Relative Humidity (%)**		
	AM *Overall Mean +/- Std. Dev. (Range)*	**PM** *Overall Mean +/- Std. Dev. (Range)*	**AM/PM Difference** *(Range of differences for individual floors)*	**AM** *Overall Mean +/- Std. Dev.(Range)*	**PM** *Overall Mean +/- Std. Dev.(Range)*	**AM/PM Difference** *(Range of differences for individual floors)*
Offices *N=65* *(13 floors x 5 readings per floor)*	22.2 +/- 0.5 (21.5-23.5)	22.4 +/- 0.4 (21.8-23.5)	+ 0.25K (-0.3 to + 0.9)	55 +/- 4.7 (49-67)	52 +/- 3.1 (44-60)	-3.0 (-7.0 to +0.6)

Table 4.18. IAT and RH shifts in RevH across AM and PM hours *(active mode)*

The comparison shows a rise, between AM and PM IAT readings, of 0.25K, whilst RH dropping by 3%. In the themselves these overall fluctuations may seem minimal, however, a floor by floor comparison suggests that some office spaces experience a rise of up to 0.9K in the course of a day, with others experiencing drops in RH of up to 7%.

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[2] The logging were carried out by two teams who took two hours to log the entire building each time.

Variability due to Weather

Data presented here consists of post-hoc observations of periods of logging when rainfall occurred. In order for such observations to be meaningful, periods are shown when inclement weather alternated with periods of sunshine (as opposed to protracted rainfall through the day). This resulted in a sudden shift in conditions to which the building's response could be observed.

Two days during the logging of RevH fulfilled this requirement. In the data from these, it was noted that outdoor changes were experienced indoors in the passive and active modes, both in the perimeter and centre zones. The patterns of change suggested that these outdoor changes were 'transmitted' indoors via EST_{Glass}, which was most influenced by outdoor MRT.

Figure 4.31 shows the first period of these two periods, for conditions logged in the passive mode. The wet weather occurred in the late morning and straddled two periods of high solar radiation. The graph shows that IATs at the perimeter zone and plan centre were affected by the weather. The swings in EST_{Glass} appear synchronous with outdoor MRT. IAT appears to rise and fall with EST_{Glass}, with its amplitude of variability greatest in areas near the envelope (1m).

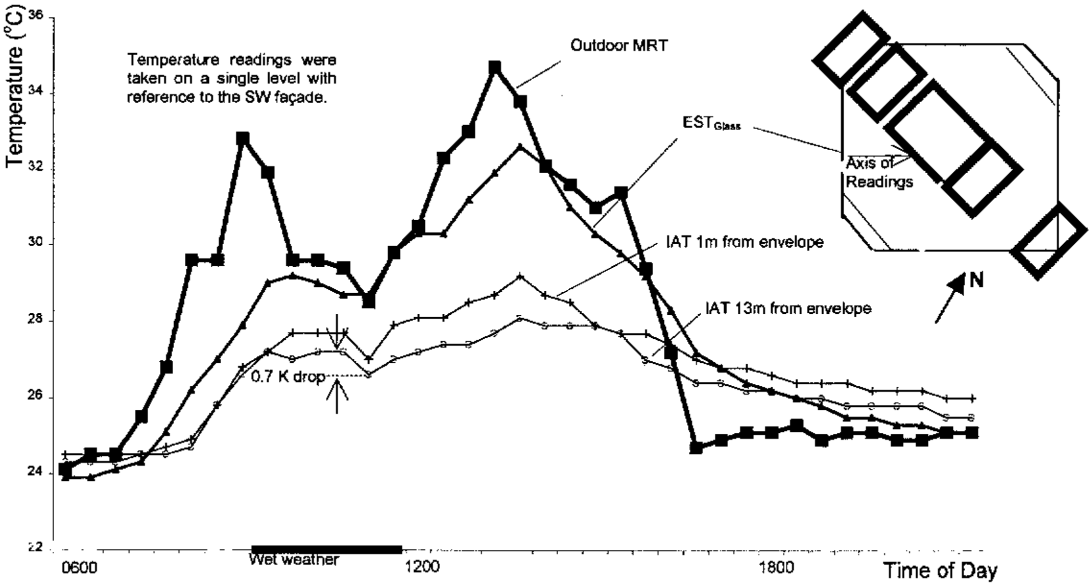
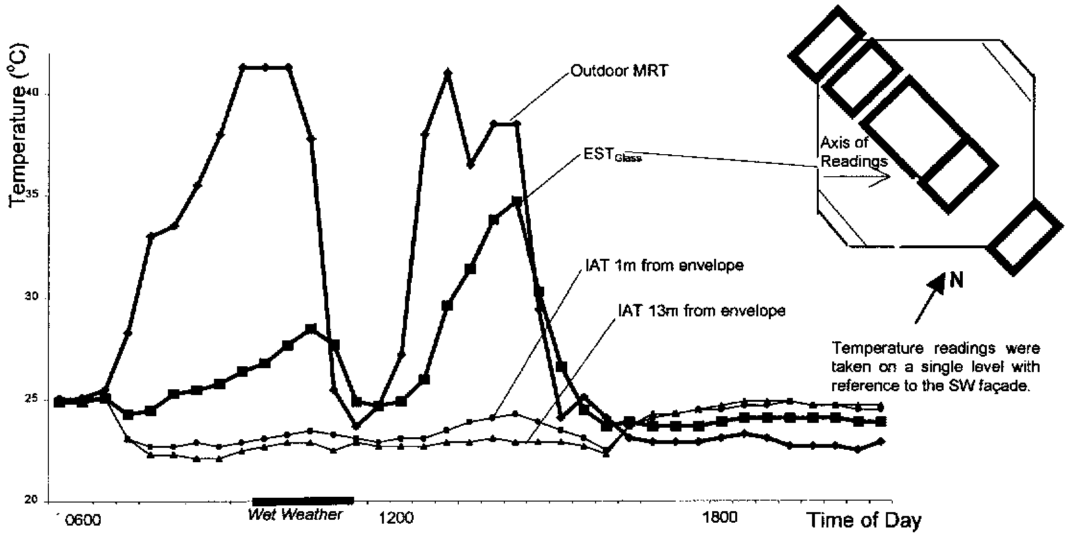


Figure 4.31. SW-facing IATs at RevH *(passive mode)*

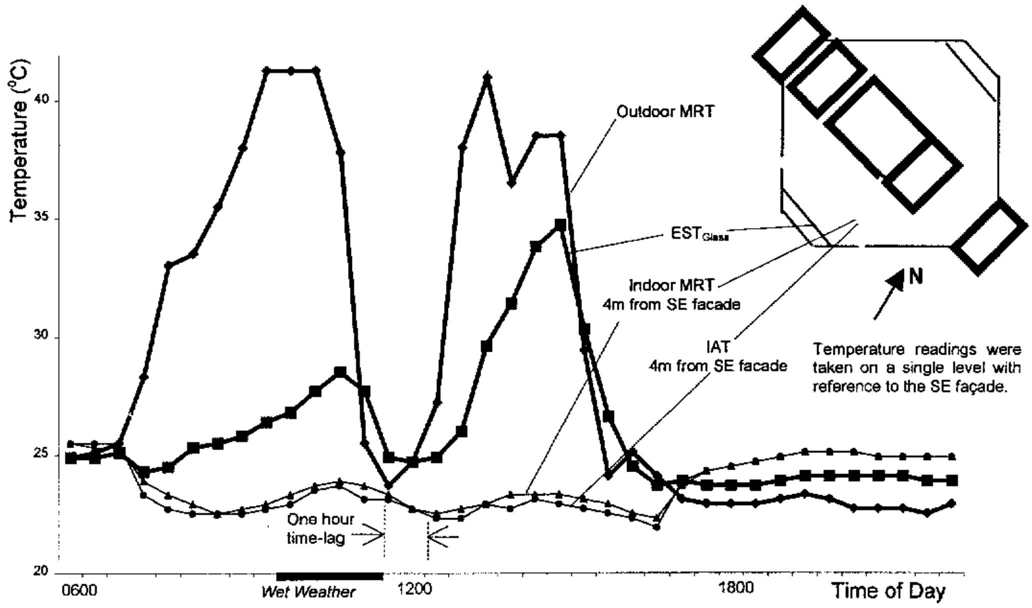
On a separate day of logging, in the active mode, a similar pattern was observed. Figure 4.32 summarises this day's readings and shows the link between EST_{Glass} and IAT. IAT closest to the envelope (1m) appears to move with outdoor conditions; IAT further in (13m) appears nearly less affected.



Temperature readings were taken on a single level with reference to the SW façade.

Figure 4.32. SW-facing EST_{Glass} and IATs at RevH *(active mode)*

In a separate set of readings for the same period of logging, the impact of weather on the perimeter zone is shown for both IAT and indoor MRT. Noteworthy in this graph (see Figure 4.33) is that the time lag between indoor and outdoor peaks and troughs is approximately one hour.



Temperature readings were taken on a single level with reference to the SE façade.

Figure 4.33. SE-facing IAT and indoor MRT at RevH *(active mode)*

4.3.3.4. Passive and Active Modes

UMNO presented the opportunity to log two separate floors simultaneously in passive and active modes. Figures 4.34 and 4.35 show IAT and EST_{Glass} readings respectively, taken at two identical floors, one occupied and operated with AC, the other unoccupied and monitored in NV.

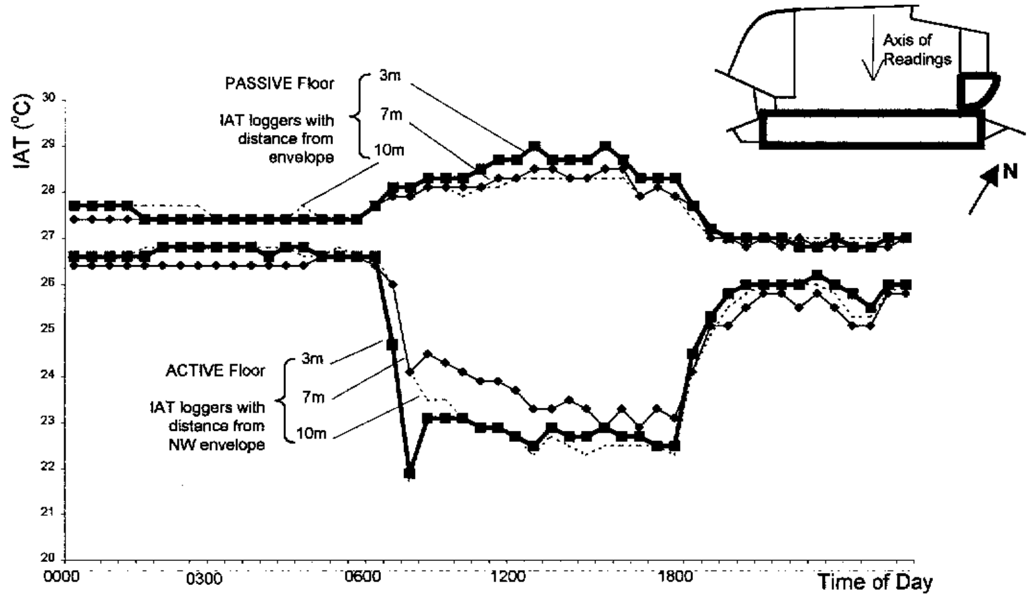


Figure 4.34. IATs for passive- and active-run floors in UMNO

IATs recorded on the two floors illustrate the 'work' that AC system must perform. In the gap between active and passive readings for loggers at the same distance from the envelope, it is evident the fabric load is highest in the areas immediately next to the envelope (3m). The impact of the AC system does not, however, create temperature gradients seen with NV. The logger at 7m location suggests the warmest conditions, whilst those at the 1m and 10m show cooler conditions. This may have been due to the location of AC source, notably at the perimeter of the space

It is also interesting that temperature differences between the two floors persist into the night, suggesting that the building, its structure and elements, retain the 'coolness' generated by the AC system.

The EST_{Glass} shows daytime differences of up to 1.6K between loggers mounted at the same location on the two floors. The envelope surface temperature of AC floor is persistently cooler than the NV floor.

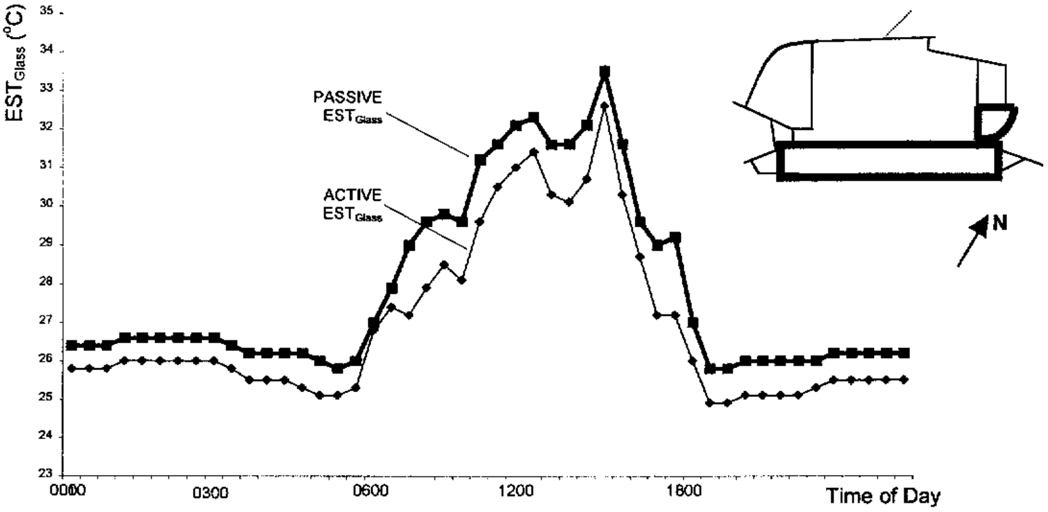


Figure 4.35. ESTs for passive- and active-run floors in UMNO

As with the IATs, the difference between the floors persists into the night, albeit at smaller margins of up to 0.8K.

4.4. Summary of Findings

The main thrust of the findings from this chapter is twofold. First, office buildings in Singapore appear to be climate rejecting in terms of their shells, and striving for uniform, stable conditions through their electro-mechanical systems. Second, indoor variability, despite these intentions, is an inevitable outcome of the building-climate interaction. This is more so in Bioclimatic buildings than the Conventional, and at the perimeter zones of all buildings.

The specific findings as they pertain to the various sections of this chapter are as follows:

4.4.1. Envelope Review

- The Bioclimatic approach to plan shape, orientation and core-placement is not evident in office buildings in Singapore. Its application, were it intended, would be constrained by site and context. It would also compete with the designer's aesthetic preference, in terms of decisions made about the external appearance of the building.
- The aesthetic choices in the buildings observed seem to relate to the question of style. The Modern and International styles were found to be most prevalent.
- The Bioclimatic prescriptions for façade design, vis-à-vis sun-path, are not evident either. This was confirmed, first, by the observation that buildings do not vary in terms of façade design across different orientations, nor do they deploy solar control devices such as external sunshades.
- Despite the seeming consistency of façade appearance in the 10 office buildings observed, the range of WWR_{Facade} and TT_F values found in the sample of 125 facades suggests that some facades are significantly more permeable to light and heat than others. The OTTV, as an index averaged across the entire building envelope, permits tradeoffs at the level of the façade design.
- The façade WWR gets some consideration with regard to the size of windows facing E and W. In general, however, WWR_{Facade} does not vary in a manner that is consistent with solar load. There appears also to be no strategy linking window and wall permeability (TT_F and TT_W) to the climate, nor to each other.

4.4.2. Indoor Conditions

- The passive- and mixed-mode options are rarely applied to the thermal condition; AC appears to be the norm in most spaces found in office buildings.
- Mixed-mode strategies are more readily applied to the visual condition. A combination of natural and electrical light was found in a significant number of spaces. Reliance on natural light, however, is rare. It appears to be negated, particularly in the offices, by occupant behaviour vis-a-vis the use of blinds/shades. Furniture layout and partition deployment, also impede the distribution of daylight. Daylight is generally not deployed in secondary spaces such as the lift lobby and toilet.
- Regulatory controls are generally complied with. There is, however, overcooling in most areas, with IATs that are below the lower limit for AC spaces.

4.4.3. Passive and Active Logging

- In general, all buildings surveyed appeared to be in a state of flux. Indoor variability is most pronounced in the passive mode. In the active mode, it is dampened by a building's electro-mechanical systems. The envelope appears to have a significant impact on indoor variability, largely an outcome of the passive measures in place (such as they might be).
- The two Bioclimatic buildings exhibit greater degrees of indoor variability than the two Conventional buildings.
- The building envelope often reaches surface temperatures significantly higher than outdoor air temperature.
- EST_{Glass} is higher than EST_{Wall} during daylight hours. The range and amplitude of EST_{Glass} is most affected by its exposure to direct solar radiation.
- Passive features and strategies have a significant impact on envelope surface temperatures. Of these, orientation, external sunshades and transitional spaces are effective in cooling the envelope.
- Conditions at the perimeter zone are most sensitive to outdoor fluctuations of light and temperature, the latter typically via fluctuations of EST_{Glass}. The depth of this envelope-sensitive zone depends on the extent to which passive features and strategies are deployed to reduce solar load. In extreme situations, for

instance W-facing elevations with high WWR and no external shading, the perimeter zone can be considerably deeper.

- Changes in outdoor conditions are experienced deep into the building plan, even in active-run buildings. This is despite the presence of AC, which can mask, but not negate, indoor-outdoor connectivity.
- The full impact of a sudden change in outdoor DBT or MRT registers with indoor temperatures typically after a one-hour time lag.
- In the passive modes, the perimeter zone experiences levels of air movement and natural light substantially higher than those found in the plan centre.

Chapter 5. Perception and Behaviour

5.0. Preamble

In Chapter 3, it was proposed that the present thesis would attempt, via occupant surveys, to link attributes of the environment with the perception of comfort. This link, at one level, could be a pattern of response to ambient conditions, for instance, thermal sensation in response to air temperature. At another, more inferential level, it could be about comfort expectations which are formulated over time, but which affect perception and behaviour all the same.

This present chapter follows through on these objectives through the analysis of data from three of the four surveys discussed earlier (see Section 3.4.3). These tools and their objectives are summarised in Table 5.1.

Stage	Approach	Case Buildings	Conditions Logged	Sample Size	Objective
Survey 1 *Cross Sectional Survey*	Cross-sectional survey of thermal and visual comfort. Subjects responded to a questionnaire with rating scales.	URA, RevH, MES, CSC, MND	IAT, RH, Air, Light	n=109	Establish link between ambient environmental condition and occupant response.
Survey 2 *Multiple Sorting Procedure*	Multiple-Sorting Procedure for comfort expectations. Subjects asked to assign 15 labels to three mode options.	RevH, MES, CSC, MND	NA	n=83	Establish the criteria by which subjects decide on comfort mode. Inference is made here on comfort expectations.
Survey 3 *Behavioural Observation*	Subjects observed for behaviour relating to environmental controls, adaptive response and alterations to, and use of, building's systems.	URA, RevH, MES, UMNO, CSC, MND	NA	-	Establish support for findings from Surveys 1 and 2.

Table 5.1. Overview of Chapter 5

Survey 1 adopts the approach of many past comfort studies of simultaneously measuring ambient conditions and soliciting feedback. The objective here is to find a tangible and measurable link between the environment and occupant response. In adopting an established approach, the intent was to position the present study within the context of what is known, particularly with regard to comfort in office buildings in hot humid conditions[1].

Survey 2 takes a tangential approach to the issue of comfort. It seeks to position the present study in the context of comfort expectations by extracting comfort criteria. Subjects were asked to express their preference and tolerance for mode options presented to them in the Multiple Sorting Procedure. This approach attempts to break away from the constraints of semantic rating scales by allowing subjects to freely articulate what they prefer or are prepared to tolerate.

The data from Survey 3, behavioral observations, are reviewed here in the context of results from Surveys 1 and 2. Observations were made specifically of *adaptive* behaviour, to gauge the fit between how a building has been designed and how its occupants respond, thereby shedding light on the human-environment interaction.

In generating data with three survey instruments, the present chapter triangulates findings, one with the other, in a bid to strengthen the conclusions about comfort response and expectations.

5.1. Cross Sectional Survey (Survey 1)

5.1.1. Overview

This section begins by re-stating the objectives of the cross-sectional survey. It had been suggested in Section 3.4.3.1 that this was to generate a 'snapshot' of occupant perception and the indoor conditions that affect it.

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[1] Survey 1 solicited feedback on both thermal and visual comfort. Survey 4, the longitudinal survey summarised in Chapter 6, focused on thermal comfort in greater depth. Several thermal comfort variables, such as clothing insulation and metabolic rates, were not captured in Survey 1 due to time and access constraints. These were subsequently addressed in Survey 4.

This was elaborated further (see Table 3.4) into the following considerations:

- Is there an optimal condition for comfort?
- Does the subject's location, in terms of building and physical proximity to the envelope, affect perception of comfort?
- Is there a link between thermal response and presence of natural light?
- What is the role of environmental controls?

The analysis presented here is carried out largely with non-parametric tests[2]. Response to the various ratings scales is tested against background, building and environmental variables, followed by tests that compare responses on the Thermal, Visual and Control scales to each other. Regression analysis is applied to cases where interval data is tested against ordinal scales. To prepare the data for the regressions, the data is *binned*[3]. A detailed summary of all tests and results carried out is presented in Appendix B2 (Summary of Statistical Tests for Data from Survey 1).

Results are summarised, first, according to Background Variables, followed by Indoor Conditions Logged and Occupant Response. Subsequent analysis is presented in the following order:

- Impact of Background Variables
- Occupant Sensitivity to Ambient Conditions
- Impact of Building Variables
- Thermal Comfort and Natural Light
- Environmental Controls

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[2] The data was tested for normality using the Kolmogorov-Smirnov and Shapiro-Wilks tests using SPSS. It was found that no group gave a Lillefors significance level of greater than 0.05 on any of the scales, suggesting the absence of normality.

[3] Binning is a procedure for data handling for the purpose of analysis, whereby occupant response to ordinal rating scales is averaged within certain temperature, humidity and light intervals. In the case with IAT, for instance, all occupant response to thermal sensation scale for temperatures at half-degree intervals between, say, 22.25°C to 22.75°C might be averaged. This mean value, if represented by sufficient votes, would be said to reflect occupant response at a temperature representing this interval 'bin', for example, 22.50°C.

The margin of the intervals depends on the data, accuracy of instruments and variability of the environment. Binning for data analysis in Survey 1 was carried out at half-degree intervals for IAT (22.5°C, 23.0°C, 23.5°C, etc.), 4% intervals for RH (53, 57, 61,etc) and 50 Lux intervals for Light (450, 500, 550,etc.). A bin with less than 4 votes was excluded on grounds that it may not be representative of the broader population response to that specific condition.

5.1.2. Results

5.1.2.1. Background Variables

Table 5.2 summarises background variables of all subjects surveyed, with regard to gender, age, ethnicity and job.

	RevH *(n=24)*	URA *(n=21)*	MND *(n=20)*	CSC *(n=20)*	MES *(n=24)*	Total *(N=109)*
Gender						
Male - 1	8	7	3	5	11	34 (31)
Female – 2	16	14	17	15	13	75 (69)
Age						
under 20 - 1	-	-	1	-	-	1 (1)
20-29 - 2	11	6	9	12	11	49 (45)
30-39 - 3	9	5	5	5	11	35 (32)
40-49 - 4	4	8	4	3	2	21 (19)
50 & above - 5	-	1 *1 missing value*	1	-	-	2 (2) *1 missing value*
Ethnicity						
Chinese - 1	20	19	17	13	12	81 (75)
Malay - 2	3	2	-	2	10	20 (18)
Indian - 3	1	-	3	5	2	8 (7)
Eurasian - 4	-	-	-	-	-	-
Others – 5	-	-	-	-	-	-
Job						
Professional - 1	14	6	2	3	7	32 (29)
Managerial - 2	-	-	2	4	6	12 (11)
Technical Support - 3	1	13	-	2	6	22 (20)
Administrative Support - 4	9	2	14	10	3	38 (35)
Others – 5	-	-	2	1	2	5 (5)

Number in parenthesis is percentage of total sample size.

Table 5.2. Background variables from Survey 1

In general, the sample from the Singapore buildings appeared to be biased towards Chinese women between the age of 20-39. There was parity with regard to gender and ethnicity in the Malaysian case study (MES), with a near equal number of Chinese and Malay, male and female respondents. The demographics of Singapore explain the bias of ethnicity[4] in the Singapore buildings. The gender figures for the Malaysian case study also corresponded with national figures. With regard to gender bias for the Singapore buildings and ethnicity bias for Malaysia building, however, the samples do not correspond with national demographics. They may,

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[4] According to the Singapore Department of Statistics (2000) the following figures apply to the population as a whole (figures in parenthesis are from survey sample in the present study) :

• Male/Female breakdown	-	50.15/49.85% (37%/73%)
• Ethnic breakdown	-	Chinese / 77%, Malay / 14%, Indian / 7.7% (Chinese / 81%, Malay / 8.2%, Indian / 10.3%)

According to the Malaysian Department of Statistics (2000), the figure for Malaysia are as follows: (figures in parenthesis are from survey sample in the present study) :

• Male/Female breakdown	-	50.5%/49.5% (45.8%/54.2%)
• Ethnic breakdown	-	Chinese/ 25.3%, Malay/66.1%, Indian/ 7.4% (Chinese/ 50%, Malay/41.7%, Indian/ 8.3%)

however, be representative of the particular organisations found in these buildings. With the Singapore buildings, these were primarily government or quasi-government bodies with an administrative role. In the case of the sole Malaysian building (MES), the owner-occupant was a computer sales and distribution company.

5.1.2.2. Indoor Conditions Logged

Table 5.3 summarises the four environmental variables that were logged at the end of each survey. These readings were taken in the active mode, with the exception of some subjects who had access to a mix of DL and EL.

	RevH	**URA**	**MND**	**CSC**	**MES**	**All Buildings**
IAT (°C)						
Mean +/- Std. Dev.	22.5 +/-0.6	23.3 +/- 0.7	23.8 +/- 0.5	22.9 +/- 0.5	24.7 +/- 0.8	23.4 +/- 0.9
Min. to Max.	21.0 - 23.5	22.0 - 24.5	23.0 - 25.0	22.0 - 23.5	22.0 - 26.5	21.0 - 26.5
RH(%)						
Mean +/- Std. Dev.	57 +/- 2.6	62 +/- 2.2	62 +/- 3.3	72 +/- 2.4	60 +/- 3.7	63 +/- 4.7
Min. to Max.	54 - 66	57 - 71	53 - 68	65 - 78	53 - 70	53 - 78
Light (Lux)						
Mean +/- Std. Dev.	358 +/- 71	574 +/- 75	451 +/- 147	320 +/- 64	367 +/- 85	421 +/- 111
Min. to Max.	240 - 600	300 - 750	250 - 720	235 - 523	130 - 540	130 - 720
Air (m/s)	< 0.3*					<0.3

Air speed was below instrument capability.

Table 5.3. Indoor conditions logged during Survey 1

The summary suggests that RevH was the coolest of the five buildings with lows of 21.0°C IAT and a mean of 22.5°C. MES was warmest with highs of 26.5°C and mean of 24.7°C. This is consistent with readings from earlier logging of these buildings (see Section 4.3.2, Table 4.10). A comparison of IAT readings across the 5 buildings has been carried out using the Kruskal-Wallis Test which yielded a χ^2 (4, N=109) = 56.61, p<0.001, suggesting that the difference in IAT between buildings is of high statistical significance.

Of the five buildings, RevH was the least humid, with mean RH of 57%. The most humid appeared to be CSC, which had a mean of 72%. A comparison of RH readings across the 5 buildings was carried out using the Kruskal-Wallis Test which yielded a χ^2 (4, N=109) = 55.83, p<0.001, again affirming the difference between the buildings.

In terms of light, MES, CSC and RevH were the dimmest with means below 400 Lux and lows of 130 (MES). URA was brightest with mean above 500 Lux and highs of 750 Lux. A comparison of illuminance readings across the 5 buildings was carried out using the Kruskal-Wallis Test. The difference yielded a χ^2 (4, N=108) = 31.97, p<0.001.

Having established that the 5 buildings are significantly different for each of three environmental variables, the question that follows is if occupant response will likewise differ.

5.1.2.3. Occupant Response

Tables 5.4, 5.5 and 5.6 summarise occupant response. In general, thermal conditions were perceived to be the coolest in RevH and warmest in MES. This is consistent with IAT readings for these buildings (see Table 5.3). Mean thermal comfort vote was lowest for MES and highest in URA suggesting that these were least and most comfortable respectively. Perception of RH did not vary much; means were generally close to 'Neutral' in all case buildings. Meanwhile, response to the Air Movement Scale suggests that RevH, MND and MES were perceived to be more still than URA and CSC.

	RevH	URA	MND	CSC	MES	Total
	(n=24)	*(n=21)*	*(n=20)*	*(n=20)*	*(n=24)*	*(N=109)*
Thermal Sensation - ASHRAE Scale ***at time of interview***						
Cold - 1	-	-	-	1	-	1 (1)
Cool - 2	10	1	1	5	-	17 (16)
Slightly Cool - 3	11	12	4	5	7	39 (35)
Neutral - 4	1	8	6	6	9	30 (27)
Slightly Warm - 5	2	-	7	2	4	15 (14)
Warm - 6	-	-	2	1	3	6 (6)
Hot - 7	-	-	-	-	1	1 (1)
Mean Vote	2.8	3.3	4.3	3.3	4.3	3.6
Thermal Sensation - ASHRAE Scale ***in general***						
Cold - 1	2	-	-	1	-	4 (4)
Cool - 2	8	2	2	4	1	17 (16)
Slightly Cool - 3	5	7	5	2	4	23 (21)
Neutral - 4	6	10	8	9	10	43 (39)
Slightly Warm - 5	2	1	4	2	7	16 (15)
Warm - 6	-	-	1	1	2	4 (4)
Hot - 7	-	-	-	-	-	-
		1 missing value		*1 missing value*		*2 missing values*
Mean Vote	2.8	3.5	3.9	3.5	4.2	3.6
Relative Humidity ***at time of interview***						
Much Too Dry - 1	-	-	-	-	-	-
Too Dry - 2	2	-	1	1	1	5 (4)
Slightly Dry - 3	8	6	9	5	5	33 (30)
Just Right - 4	14	13	8	11	13	59 (54)
Slightly Humid - 5	-	1	2	3	5	11 (11)
Humid - 6	-	-	-	-	-	-
Much Too Humid - 7	-	-	-	-	-	-
		1 missing value				*1 missing value*
Mean Vote	3.5	3.8	3.6	3.8	3.9	3.7
Air Movement ***at time of interview***						
Much Too Still - 1	2	-	-	1	3	6 (5)
Too Still - 2	5	1	2	2	1	10 (11)
Slightly Still - 3	7	10	14	10	11	52 (48)
Just Right - 4	9	9	4	5	9	36 (33)
Slightly Breezy - 5	1	1	-	-	-	2 (2)
Too Breezy - 6	-	-	-	2	-	2 (2)
Much Too Breezy - 7	-	-	-	-	-	-
Mean Vote	3.1	3.5	3.1	3.4	3.1	3.2
Thermal Comfort Scale ***at time of Interview***						*N=85*
Very Uncomfortable - 1		-	-	-	1	1 (1)
Moderately Uncomfortable - 2		-	1	-	-	1 (1)
Slightly Uncomfortable - 3	Not Surveyed	-	3	2	8	13 (15)
Slightly Comfortable - 4		6	4	6	6	22 (26)
Moderately Comfortable - 5		13	10	9	7	39 (46)
Very Comfortable - 6		2	2	3	2	9 (11)
Mean Vote		4.8	4.5	4.6	4.0	4.5
Thermal Comfort Scale ***In general***						*N=85*
Very Uncomfortable - 1		-	-	-	1	1 (1)
Moderately Uncomfortable - 2		-	-	2	-	2 (2)
Slightly Uncomfortable - 3	Not Surveyed	-	3	2	6	11 (13)
Slightly Comfortable - 4		6	1	4	6	17 (20)
Moderately Comfortable - 5		13	14	9	10	46 (54)
Very Comfortable - 6		2	2	3	1	8 (8)
Mean Vote		4.8	4.8	4.4	4.1	4.5

Number in parenthesis is percentage of total sample size.

Table 5.4. Occupant response to thermal, humidity and air movement scales

There was not much difference in response to Overall Perception of Light across the 5 buildings (see Table 5.5). Mean votes were generally close to 'Just Right' (4); this is despite significant differences between buildings in terms of their indoor illumination levels.

	RevH *(n=24)*	URA *(n=21)*	MND *(n=20)*	CSC *(n=20)*	MES *(n=24)*	Total *(N=109)*
Overall Perception of Light						
Too Dim - 1	-	-	-	-	-	-
Dim - 2	-	-	2	-	-	2(2)
Slightly Dim - 3	9	4	1	2	5	21(19)
Just Right - 4	10	14	15	17	17	73(67)
Slightly Bright - 5	4	3	1	1	-	9(8)
Bright - 6	1	-	1	-	2	4(4)
Very Bright - 7	-	-	-	-	-	-
Mean Vote	3.9	4.0	3.9	4.0	3.9	3.9
Perception of Natural Light						
None at all - 1	7	-	5	3	2	17(16)
Very Dim/Negligible - 2	6	2	6	3	11	28(26)
Soft and Diffused - 3	8	8	6	11	8	41(38)
Strong and Direct - 4	3	1	3	3	2	12(11)
Very Bright and Direct - 5	-	-	-	-	-	-
Variable - 6	-	10	-	-	1	11(9)
Mean *Vote (excluding Variable votes)*	2.3	2.9	2.4	2.7	2.4	2.5
Preference – Natural Light						
Decrease It - 1	4	4	4	1	4	17(16)
No Change - 2	6	17	10	13	12	56(51)
Increase It - 3	14	3	6	6	7 *1 missing value*	35(32) *1 missing value*
Percentage* voting for 'No Change'	25	81	50	65	50	51
Does daylight affect thermal comfort?						*N=85* *(excl. RevH)*
Yes - 1	Not Surveyed	6	6	2	11	25 (29)
No - 2		15	9	16	10	50 (59)
Not Applicable – 3		-	5	2	3	10 (12)
Overall Satisfaction with Light						*N=85* *(excl. RevH)*
Very Dissatisfied - 1	Not Surveyed	-	2	-	-	2(2)
Moderately Dissatisfied - 2		-	-	-	-	-
Slightly Dissatisfied - 3		-	-	-	1	1(1)
Slightly Satisfied - 4		7	2	4	4	17(20)
Moderately Satisfied - 5		12	10	9	12	43(51)
Very Satisfied - 6		1 *1 missing value*	6	7	7	21(25) *1 missing value*
Mean Vote		4.7	4.8	5.2	5.0	4.9

Number in parenthesis is percentage of total sample size.

** Preference Scale for Natural Light is a nominal scale, hence the use of percentage.*

Table 5.5. Occupant response to visual scales

In terms of the Perception of Natural Light, URA and CSC have the highest mean vote, with URA subjects also saying that they have the most variable levels of daylight.

On the Preference scale for Natural Light, occupants of RevH were least satisfied, with only 25% opting for 'No Change'. Occupants of URA were most satisfied, in spite of the variability experienced, with 81% voting 'No Change'. Perceived impact of natural light on thermal comfort is most evident in MES, where 46% said 'Yes', and least evident in MND where only 10% said 'Yes'.

On the question of Overall Satisfaction with Light, the difference between means of the buildings is small, with a majority of subjects in each building voting 'Moderately Satisfied'. This suggests that, in general, there appears to be no significant difference in Overall Satisfaction with Light across the five buildings.

Table 5.6 suggests that the two most prevalent extraneous factors affecting thermal comfort were 'Time of Day' and 'Outdoor Weather'. Time of Day refers to difference between morning and afternoon hours, Outdoor Weather to when it rains. This supports findings in the previous chapter in which it was found that indoor variability often resulted from daily shifts and inclement weather (see Section 4.3.3.3).

The most common adaptive response to thermal discomfort was 'Adjustment to Clothing', followed by 'Consumption of a Warm or Cold Drink'. The least common response related to adjustments made to natural light level.

	RevH *(n=24)*	URA *(n=21)*	MND *(n=20)*	CSC *(n=20)*	MES *(n=24)*	Total *(N=109)*
Thermal Comfort depends on						
Time of Day - 1	7	10	13	7	14	41(38)
Outdoor Weather - 2	21	13	18	16	18	86(79)
Outdoor Temperature - 3	-	1	4	2	3	10(9)
Day of Week - 4	5*	-	-	-	-	5(5)
Likely Adaptive Response						
Alter Clothing - 1	17	11	15	18	11	72(66)
Alter Activity - 2	2	4	5	4	11	26(24)
Alter Natural Light - 3	1	2	3	-	-	6(6)
Consume Cold or Warm Drink - 4	9	13	14	13	10	59(54)
Use Fan - 5	1	1	9	1	9	21(19)
Environmental Control	Not Surveyed					N=85 *(excluding RevH)*
Availability *those saying they have access to the following environmental controls*						
Blinds - 1		13	9	12	NA	34(56)**
Thermostat - 2		-	-	-	-	-
Light Switches - 3		3	1	4	4	12 (14)
Frequency of Use *those saying they use the controls available to them*						
Blinds - 1		2	2	1	NA	5(15)
Thermostat - 2		-	-	-	-	-
Light Switches - 3		1	-	-	-	1(8)
Satisfaction with Control						
Very Dissatisfied - 1		-	1	-	1	2(2)
Moderately Dissatisfied - 2		-	-	-	2	2(2)
Slightly Dissatisfied - 3		5	7	7	5	24(28)
Neutral - 4		6	6	10	12	34(40)
Slightly Satisfied - 5		6	4	1	2	13(15)
Moderately Satisfied - 6		3	2	2	2	9(12)
Very Satisfied - 7		1	-	-	-	1(1)
Mean Vote		4.5	3.9	3.9	3.8	3.8

Number in parenthesis is percentage of total sample size.
** Day of Week affected occupants of RevH because of reduced occupancy in this particular building on Mondays and Saturdays.*
*** N=61 - excludes MES which does not have blinds for its windows.*

Table 5.6. Occupant response to environmental variability and control

On the subject of environmental control, 56% said they had access to blinds; of this only 15% said they exercised control. Of those that had access to light switches, only 8% said they exercised control. No one had control over thermostats.

Mean satisfaction with control was generally just below 'Neutral' (4.0), suggesting neither dissatisfaction nor satisfaction. Of the four buildings, subjects in URA were most satisfied with a mean response of 4.5.

5.1.3. Analysis

5.1.3.1. Impact of Background Variables

Of the four background variables recorded, the following were found to relate with response on thermal/visual rating scales[5]:

- Gender with Thermal Sensation *(in general)*
- Job with Daylight Preference

Gender and response to the ASHRAE scale were tested with the Mann-Whitney U-Test which yielded $z = -1.966$ at $p<0.05$, suggesting a difference in thermal sensation between male and female subjects. In general, women tended to feel slightly cooler than men, with a mean vote of 3.44 compared with 3.97 for men. This response might, however, be connected to differences in clothing ensembles worn by the two groups. The Clo value for each individual had not been calculated here. Based on observation, however, it appeared that the male attire tended towards higher levels of insulation with long sleeve shirts and trousers as compared with skirts and blouses worn by the women. This observation, and its inference, is confirmed in Survey 4 for which Clo values were computed (see Chapter 6).

Job and Daylight Preference were tested using the Chi-Square test, the results for which were χ^2 (8, N=108) = 20.43 at $p<0.01$. This finding that Job affects Daylight Preference might be explained by the fact that a subject who was senior in the organisation was more likely to be situated near the window than someone in a clerical and/or junior position. Seniority was therefore likely to affect the access to natural light. Proximity to envelope and perception of thermal and visual comfort are further explored in Section 5.1.3.4.

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[5] For more detailed summary of tests, see Appendix B2: Summary of Statistical Tests for Data from Survey 1.

5.1.3.2. Occupant Sensitivity to Ambient Conditions

Two questions are asked here: is there a relationship between occupant response and ambient condition? And if so, is it possible to predict an optimal condition for comfort? The first question is explored by linking subject response with environment variable. The second question examines the pattern that emerges, to speculate on what constitutes an optimal ambient condition. Response to all scales is plotted against pertinent ambient conditions, namely IAT, RH and Light.

Indoor Air Temperature

On the question of thermal response, the data yields a highly significant correlation between Thermal Sensation *at time of interview* and IAT. Figure 5.1 shows that occupant response exhibits a linear relationship with IAT, with an $R^2=0.95$ at $p<0.001$.

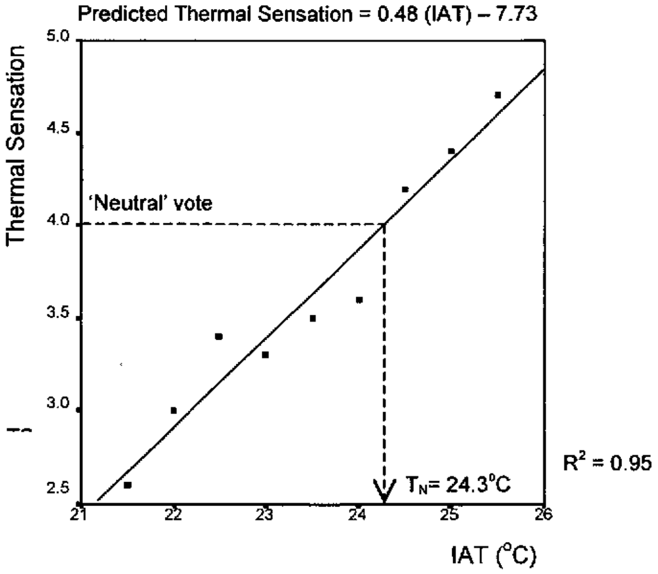

Figure 5.1. Thermal sensation *(at time of interview)* against IAT

Neutral temperature (T_N), earlier defined as the condition at which thermal sensation is neither one of warmth nor coolness, occurs at 24.3°C.

The relationship between response on the Thermal Comfort scale *(at time of interview)* and IAT is an inverted U-shape, with R^2=0.96 at $p<0.001$, and an F value of 70.3 (df=2).

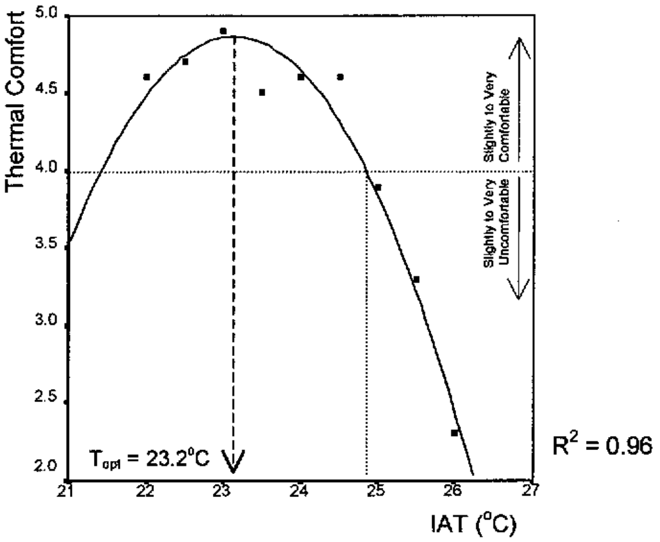

Figure 5.2. Thermal comfort *(at time of interview)* against IAT

The curve peaks, and comfort vote is at its highest, at 23.2°C. This is defined as T_{Opt} (Optimal Temperature), the ambient condition at which thermal comfort is most likely to occur.

It is noteworthy that discomfort on this scale (i.e. response lower than a vote of Slightly Comfortable/4) is cited mostly for temperatures near or above 25°C. Temperatures as low as 22°C, below the Singapore code of 23°C (PWD, 1983), appear not to cause discomfort. At the upper limit of Code, 27°C, response was clearly on the side of discomfort.

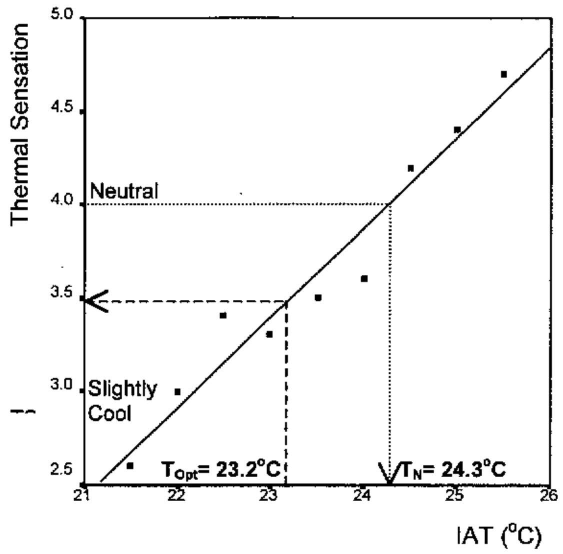

Figure 5.3. Relationship of thermal comfort and thermal sensation

It is noteworthy that there is a 1.1K difference between conditions defining T_N and $T_{Opt.}$ When T_{Opt} is scaled off the Thermal Sensation/IAT graph, it intersects the Y-axis at 3.5, implying that thermal comfort most likely occurs between sensations of 'Neutral' (4) and 'Slightly Cool' (3).

Relative Humidity

Occupant Perception of Humidity shows no relationship to RH levels (see Appendix B3: Regressions for Data from Survey 1). It is noteworthy that responses on the Thermal Sensation and Thermal Comfort scales show no relationship of significance (at $p>0.05$) with RH either.

These results suggest, first, that occupants are not able to discern accurately the level of the humidity to which they are exposed. This may, however, be due to the narrow bandwidth found in the buildings here (53% to 78%) within which its potential effect on perception of Thermal Sensation and Comfort may be minimal. Alternatively, the absence of a link between RH and perception of comfort may be due to other comfort-related variables such as air movement and mean radiant temperature, which were not recorded.

Light

On the question of Light, Perception of Overall Light Level relates poorly with illuminance level (see Appendix B3: Regressions for Data from Survey 1). This is also the case with Satisfaction with Light. Given that there is a significant difference in illumination levels between buildings (see Section 5.1.2.2), this may be because the bandwidths are too narrow to affect response significantly, or because adaptation, in some form, counters ambient condition.

5.1.3.3. Impact of Building Variables

Two building-related variables are hypothesised to relate with occupant response: 'Proximity to Envelope' and 'Building'. The former refers to a subject's location in relation to the building envelope. The latter refers to which of the five buildings, s/he works in. Proximity to Envelope results in a division of all subjects into two groups: those sitting next to a window and those further in. The criterion of Building results in a division of subjects into five subgroups.

It was speculated that both thermal and visual responses would vary between perimeter and inner zones. It had been shown in the preceding chapter that the perimeter zone has the highest levels of daylight and temperature (see Section 4.3.3.2). The influence of Building was premised on the idea that differences in ambient conditions, earlier shown to be significant, are likely to generate a difference in response.

Statistical tests[6] carried out on the data show that the following relationships have significance at $p<0.05$:

- Proximity to Envelope to Perception of Daylight Level and Daylight Preference
- Building to Thermal Sensation (both *at time of interview* and *in general*)
- Building to Daylight Preference

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[6] For a detailed summary of results, see Appendix B2: Summary of Statistical Tests for Data from Survey 1.

On the question of envelope proximity and daylight level, results from the Mann-Whitney U-Test yielded z=-4.3 at $p<0.001$. A comparison of means between the two subgroups shows that subjects who are next to the envelope claim they get more daylight than subjects who are further away.

On the link between proximity and daylight preference, a Chi Square test yielded χ^2 (2, N=108)=8.156 at $p<0.05$. Predictably, daylight preference shows an inverse relationship, with those further away from the window saying they want more daylight than subjects who were closer to the window.

It is noteworthy that the difference between the two groups does not extend to the response on thermal sensation and thermal comfort scales. In the next section on thermal comfort and natural light, this question will be further examined.

The criterion of Building appears to exert influence on occupant response, particularly with regard to Thermal Sensation. On the link between Building and thermal sensation *at time of interview*, a Chi Square test yielded χ^2 (4, N=109)= 29.45 at $p<0.001$. On the link with thermal sensation *in general*, the same test yielded χ^2 (4, N=107) = 20.72 at $p<0.001$.

Table 5.7 suggests that response on the Thermal Sensation scale coincides with higher ambient temperatures, i.e. the warmer buildings (such as MES and MND) have responses that are at the warmer end of the Thermal Sensation scale.

	Mean IAT (°C)	**Mean Thermal Sensation** *at time of interview*	**Mean Thermal Sensation** *in general*
RevH	22.5	2.8	2.8
URA	23.3	3.3	3.5
MND	23.8	4.3	3.9
CSC	22.9	3.3	3.5
MES	24.7	4.3	4.4

Table 5.7. Mean IAT and thermal sensation votes

It is noteworthy that response on the Thermal Comfort scale is not statistically significant across the five buildings. This suggests that whilst subjects feel warmer or cooler, they do not necessarily feel more of less comfortable. This may be due to some adaptive response that intervenes between perceptions of sensation and comfort.

On the link between Building and Daylight Preference, a Chi Square test yielded χ^2 (8, N=108)=15.94 at $p<0.05$. It is not possible to comment on this, as no comparative readings of natural light for the five buildings are available.

5.1.3.4. Thermal Comfort and Natural Light

Response to thermal and visual scales is analysed on the premise that natural light may affect with perception of warmth.

On the question of whether daylight affects thermal comfort, one-third of all subjects surveyed from a sample of 75 said 'Yes'. Of those who answered 'Yes', 84% sat next to the window. The difference between those next to windows and those further in was found to be statistically significant. A cross tabulation of the two groups yielded a χ^2 (1,N=74)=11.21at $p<0.005$, suggesting that the link between natural light and thermal comfort may be due in relation, partly, to the subject's proximity to windows.

Response to the Thermal Sensation and Comfort scales, however, showed little or no relation to the two visual scales[7]. The sole exception was Thermal Comfort *at time of interview* with Overall Light Intensity. A Spearman's Rho test yielded a coefficient of $r_s=0.22$ with N=85 at $p<0.05$. This suggests that an environment seen to be thermally comfortable may also be perceived to be brighter, or vice versa.

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[7] For detailed summary of results, see Appendix B2: Summary of Statistical Tests for Data from Survey 1.

5.1.3.5. Environmental Controls

The role of environmental controls was briefly discussed in the literature review (see Section 2.4.2). In general, it has been argued that the presence of controls improves the perception of comfort and/or satisfaction (Pacuik, 1989; Guedes, 2000; Arens et al., 2001). This section looks at three controls available to occupants of the buildings and asks if these affect their comfort and if they are actually used. The three controls are blinds, light switches and thermostats.

A total of 45% of all surveyed (from N=85) said they had actual control over one or more environmental variable, typically blinds and/or electrical lights. Of those who said they had control, 84% said they never use it. The data is nevertheless tested for the possibility that satisfaction occurs irrespective of the availability of control. This would suggest that the presence of control might, in itself, not be the primary factor affecting perception. A Mann-Whitney U-test carried out on the group with control and the group without, found that the difference in response to the question of Satisfaction with Control was not significant at $p<0.05$. This suggests that the extent to which occupants are satisfied with environmental control is independent of the availability of control.

Analysis shows that the following variables relate with Satisfaction with Control: Thermal Comfort *at time of interview*, Air Movement *at time of interview* and Satisfaction with Overall Light *in general*

Spearman's Rho test was applied to each variable. The coefficient in the case of Thermal Comfort *at time of interview* was $r_s=0.25$ for N=85 at $p<0.05$. In the case of Air Movement, the test yielded $r_s=0.29$ for N=85 at $p<0.01$. With Satisfaction with Overall Light, the test yielded $r_s=0.37$ for N=84 at $p<0.005$. In each case, Satisfaction with Control showed a positive correlation, i.e. satisfaction increased with corresponding increase in response to the three scales.

An interesting question arising is why Satisfaction with Control does not show a significant correlation with Thermal Comfort or Thermal Sensation in general. It would seem that environmental controls are an issue only when discomfort exists. In itself, control may be less critical when ambient conditions are within acceptable limits. In this regard, it is significant that controls, where available, are hardly utilised.

5.2. Multiple Sorting Procedure (Survey 2)

5.2.1. Overview

Comfort expectation is inferred here from the criteria that a subject applies to selecting a mode during MSP. This approach implicitly assumes that a mode of operation, be it passive, active or mixed, represents a type or degree of comfort, and that in opting for one over another, a subject relies on his/her expectations of comfort in the workplace.

It should be noted that this inference, linking choice with expectation, is not about the mode itself; it is about the basis on which the choice is made. If, for instance, a subject says s/he is prepared to accept NV in the evening but expects AC during the daytime, the comfort criterion inferred is 'Time of Day'.

In the MSP, each subject was asked to assign 15 labels to one of 3 mode-options. S/he sorts first according to preference, any space assigned to any mode, and then according to 'preference with a constraint', i.e. 5 spaces to each mode option. This 2-step procedure yielded two types of data: subject verbalisation describing the groupings and a mode-label assignment. The latter was compiled into two matrices, one for each sort. Data from these sorts, each involving 15 labels and over 80 subjects, are summarised in Appendices B6 (Survey 2 Data - Subject Verbalisation) and B7 (Survey 2 Data – Choice of Modes). The present section begins with a summary of background variables, followed by tables summarising breakdowns according to mode and, finally, feedback to the question of whether the modes constitute a degree or type of comfort.

The subsequent analysis is grouped under three headings:

- Content Analysis
- Multidimensional Scaling (MDS)
- Multiple Scalogram Analysis (MSA)

Content Analysis relies on subject verbalisation to generate a list of possible criteria applied to choice-of-mode. The MDS is used to test these criteria, via partitioning of 2-D and 3-D outputs from the Statistical Package for Social Sciences (SPSS). In these plots, each label emerges as a point in space. The analysis procedure was described in Section 3.4.3.2.

The MSA outputs are 2-D plots with each subject indicated as a point in space. These are tested in a second round of partitioning, this time with regard to background and building variables.

5.2.2. Results

5.2.2.1. Background Variables

The breakdowns of gender, age, ethnicity and job for thermal and visual sorts (see Tables 5.8 and 5.9) are not substantially different from that which was observed in Survey 1 (see Table 5.2). This is consistent with the fact that these subjects are from the same case buildings.

There is a single deviation, however, with regard to gender breakdown. With the thermal sorts, there is near parity between male and female subjects. In Survey 1 and with the Visual Sort, the bias was towards female subjects. There is no evident reason for this anomaly; it is assumed to be a chance outcome of a random selection process.

THERMAL SORTING TASKS	RevH *(n=12)*	MND *(n=10)*	CSC *(n=10)*	MES *(n=10)*	Total *(N=42)*
Gender					
Male – 1	6	2	3	7	18 (43)
Female – 2	6	8	7	3	24 (57)
Age					
under 20 – 1	-	-	-	-	-
20-29 – 2	6	5	4	9	24 (57)
30-39 – 3	4	3	3	1	11 (26)
40-49 – 4	2	2	3	-	7 (17)
50 & above – 5	-	-	-	-	-
Race					
Chinese – 1	10	8	6	4	28 (64)
Malay – 2	2	-	1	3	6 (14)
Indian – 3	-	2	3	3	8 (19)
Job					
Professional – 1	7	1	-	4	12 (29)
Managerial – 2	-	1	2	-	3 (7)
Technical Support – 3	1	-	2	3	6 (14)
Administrative Support – 4	4	7	6	3	20 (48)
Others – 5	-	1	-	-	1 (2)

Number in parenthesis is percentage of total sample size.

Table 5.8. Background variables for thermal sorts

VISUAL SORTING TASKS	RevH *(n=12)*	MND *(n=10)*	CSC *(n=10)*	MES *(n=9)*	Total *(N=41)*
Gender					
Male – 1	2	1	2	3	8 (20)
Female – 2	10	9	8	6	33 (80)
Age					
under 20 – 1	-	1	-	-	1 (2)
20-29 – 2	5	4	8	4	21 (52)
30-39 – 3	5	2	2	4	13 (32)
40-49 – 4	2	2	-	1	5 (12)
50 & above – 5	-	1	-	-	1 (2)
Race					
Chinese – 1	10	9	7	3	29 (71)
Malay – 2	1	-	1	6	8 (20)
Indian – 3	1	1	2	-	4 (9)
Job					
Professional – 1	7	1	3	6	17 (41)
Managerial – 2	-	1	2	1	4 (9)
Technical Support – 3	-	-	-	-	-
Administrative Support – 4	5	7	4	2	18 (44)
Others – 5	-	1	1	-	2 (6)

Number in parenthesis is percentage of total sample size.

Table 5.9. Background variables for visual sorts

5.2.2.2. Sorting Tasks

Table 5.10 shows breakdowns according to the mode selected. It should be pointed out that the parity between modes in the second sort merely reflects the procedural constraint, i.e. subjects were told to place exactly 5 of the 15 labels into each mode option.

	Thermal Sorts (%) *(N=100)*		Visual Sorts (%) *(N=100)*	
	1st Sort	2nd Sort	1st Sort	2nd Sort
Passive	15	34	16	33
Mixed	17	32	48	34
Active	68	34	36	33

Table 5.10. Sorting task breakdowns

It is apparent from the breakdown of the 1st sort that the active-mode is preferred for thermal comfort. Sixty eight percent of those surveyed opted for AC. Mixed-mode (FA) gets 17% of the votes. Mixed-mode appears to be the preferred option in the case of visual comfort, although by a lesser margin than with thermal comfort. Forty-eight percent picked mixed-mode (EL+DL), whilst 36% picked the active-mode option (EL).

The passive-mode option is the least preferred with both thermal and visual comfort; NV and DL received only 15% and 16% of the votes respectively.

In the survey, each subject was also asked to differentiate the three modes into 'type' or 'degree' of comfort. S/he made three responses to this question, comparing one pair of modes at a time: AC vs. NV, AC vs. FA and FA vs. NV. Out of a total of 101 responses to this question (see Appendix B6: Survey 4 Data – Subject Verbalisation), the proportion voting type and degree was near equal for both thermal and visual modes (see Table 5.11).

Thermal Modes *(N=101)*		Visual Modes *(N=101)*	
Degree	Type	Degree	Type
47	54	54	47

Table 5.11 Type versus degree of comfort

It is noteworthy that these figures do not reflect a clear bias towards either means of categorisation; there is no evidence to suggest that the question of modes is viewed either a question of type or degree of comfort.

5.2.3. Analysis

5.2.3.1. Content Analysis

The first building surveyed was RevH, after which the method of recording a subject's verbalisation was refined. It was noted in the RevH sorts that the majority of subjects spoke around certain categories. For instance, the preference for EL was cited in relation to the need to *"use of audiovisual equipment"* in the auditorium, or the *"need to concentrate"* on a task in the workplace. In both cases the criterion appeared to be 'Activity'.

Through this initial screening, a preliminary list of criteria was formulated. In all subsequent interviews, when a subject spoke with regard to a particular criterion already on the list, feedback was noted as an affirmation of the criterion. This eliminated the need for verbatim transcribing in the case of each of the 83 subjects. Where comments did not fit a known criterion, however, it was recorded in full. The summary of verbalisation in Appendix B6 (Survey 4 Data – Subject Verbalisation) reflects this method of recording.

In the list presented here, subject verbalisation is collapsed into eight headings:

Duration/Frequency of Use:
These comments typically related to how often a space was visited and how much time one might spend there. In describing a particular preference, a subject was apt to say *"I don't go there often"* or *"I'm only there for a short while."*

There are three subcategories that emerge from this:

- Primary spaces that are visited often and where most time is spent, notably Workspace
- Secondary spaces that are visited infrequently, but where a moderate amount of time might be spent, typically the Gymnasium and Cafeteria
- Tertiary spaces that are visited infrequently and for short periods at a time, notably circulation spaces such as Lift Lobby and Atrium and service areas like Toilets

Activity:

This heading refers to all comments that linked choice of mode with the function or activity of that space/room, with specific reference to density of use, i.e. the number of people at a time, and presence of equipment such as photocopiers and audio-visual equipment. Subjects would also describe a particular mode as affecting one's ability to concentrate on a task, or to relax. This criterion seems to have three sub-groupings:

- Work-related areas, notably Workspace, Meeting Room, Auditorium, Library, Photocopy Room
- Supporting areas, notably Gymnasium, Cafeteria, Day Care Centre
- Transit areas, notably Lift Lobby and Atrium

Health/Hygiene:

The comments that fall under this heading related to the presence of odour and/or food. The primary concern appeared to be that the active thermal mode, AC, was not capable of effectively dealing with these and therefore compromised the health of the building's occupants. Areas mentioned included the Toilet, Cafeteria and Pantry. The heading also included concerns for areas where one was likely to perspire, specifically, the Gymnasium.

Consistency/Control:

This was mentioned with particular reference to DL, which was deemed highly variable. Reliance on daylight was viewed with concern in areas where variability was viewed as a distraction, particularly the Workspace, or where control in itself was deemed to be vital, i.e. Auditorium. In this regard, the question of Consistency/Control appears connected to the criterion of Activity.

Safety:

This was cited only in the context of the Fire Escape Staircase, reflecting a concern for an occupant's ability to see and breathe in the event of an emergency. The passive thermal mode (NV) was most preferred here. It was noted that this issue emerged in response to the label wording, specifically the term 'Escape', which may have triggered a concern for the risk associated with reliance on active modes.

Openness:

This was typically expressed as a preference for views out of the building, which was said to promote *"relaxation."* Conversely, the preference for enclosure, i.e. lack of openness, was expressed in the context of work-related spaces, where it was said to minimise distraction and facilitate *"concentration."* Like the question of Consistency/Control, this appears connected with the question of Activity.

Personal Comfort:

This was expressed primarily as a preference for AC, most frequently in the context of spaces that are used for longer periods, such as the Workspace, or by more people at a time, particularly the Auditorium. It was also the only hint that the modes were seen as a question of degree of comfort, with AC delivering higher level of comfort than NV.

Image:

This was cited in the context of publicly accessible spaces, the Atrium and Lift Lobby, where active modes, AC and EL, were said to create a better impression on visitors. It is unclear why this association was limited to these two spaces, as other spaces in an office building were also accessible to the public. The connection seems to be one linking the presence of these modes with affluence and/or hospitality, offered by the building and, by inference, its occupants. This criterion also covers references to 'mood' created by EL, which was sometimes described as *"cosy."*

It should be noted that some of these criteria might, in fact, overlap. The criteria of Duration/Frequency of Use and Activity, for instance, yield the similar subgroupings. The list of 'work-related' spaces that emerge under Activity is essentially the same as 'primary' spaces under Duration/Frequency of Use; 'support' resembles 'secondary' and 'transit' is similar to 'tertiary'. Consistency/Control also appears to be akin to Openness, in that a space that is more open to the outdoors is likely to offer less consistency/control.

The frequency with which these eight criteria were cited is summarised in Table 5.12.

Criteria cited	Thermal Modes					Visual Modes				
	MES *(n=10)*	RevH *(n=12)*	CSC *(n=10)*	MND *(n=10)*	TOTAL *(N=42)*	MES *(n=9)*	RevH *(n=12)*	CSC *(n=9)*	MND *(n=10)*	TOTAL *(N=40)*
Duration/Frequency	10	12	7	10	39 (1)	5	7	5	5	22 (4)
Activity	9	8	9	6	32 (2)	7	12	8	11	38 (1)
Health/Hygiene	8	9	7	2	26 (3)	1	2	1	2	6 (8)
Personal Comfort	10	8	0	7	25 (4)	1	0	7	1	9 (7)
Openness	3	3	4	4	14 (5)	7	9	9	4	29 (2)
Safety	2	2	4	2	10 (6)	3	6	1	3	13 (5)
Image	4	2	1	3	10 (6)	3	5	1	3	12 (6)
Consistency/Control	1	4	0	0	5 (7)	7	7	8	6	28 (3)

Figure in parenthesis indicates rank order of criterion.

Table 5.12. Frequency and rank order of criteria

A comparison of the criteria and their frequencies shows differences and similarities between the perception of thermal and visual comfort. Duration/Frequency of Use and Activity are prevalent in both thermal and visual sorts. Health/Hygiene and Personal Comfort appear to affect thermal comfort only, whilst Openness and Consistency/Control rank high as criterion affecting visual comfort.

5.2.3.2. Multidimensional Scaling Analysis (MDS)

This section looks at the quantitative data generated by the sorting procedure via a series of 2-D and 3-D outputs using multidimensional scaling analysis on SPSS. Before scrutinising the plots, it is worth reviewing the basis for having two consecutive sorts.

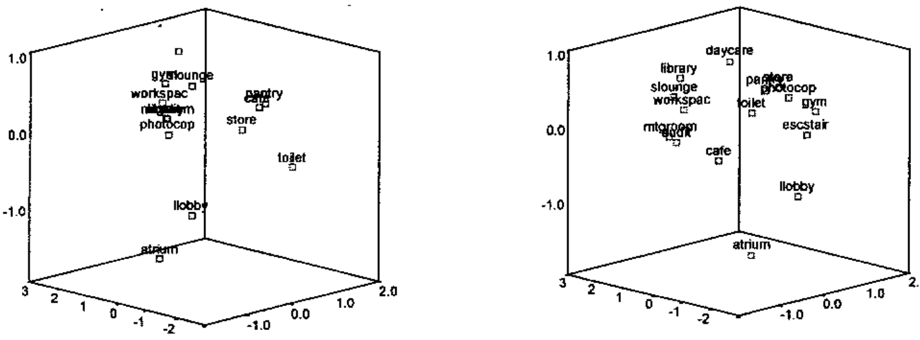
In the studies by Wilson and Canter (1990) and Kraemer (1995), the sorting task procedure relied on 'preference' as a means of triggering evaluation. This same preference-based approach was adopted here, albeit within the context of comfort modes. Subjects were told that they could place labels into whichever mode grouping they preferred.

In the pilot for the sorting procedure (see Appendix B4: Survey 2 - Pilot), it emerged that given carte blanche preference, most subjects placed the majority of the labels into a single category, particularly AC, in an unthinking manner. They exercised discretion only in the case of a few spaces where AC was patently an odd choice, for instance, fire escape staircase and toilet.

A second sort was introduced, asking subjects to sort according to 'preference with a constraint'. The objective was to compel subjects to make an assessment, as with real-world constraints, and to force a consideration of all mode options. It was found that this yielded more meaningful data, particularly subject verbalisation.

The bias of the first sort can be seen in the summary of sorting task breakdowns (see Table 5.10) in which AC and EL+DL emerged the dominant choices for thermal and visual sorts respectively. In itself, it suggests the relative strength and bias of user preference. It does not, however, say much about what subjects are prepared to tolerate, or simply accept.

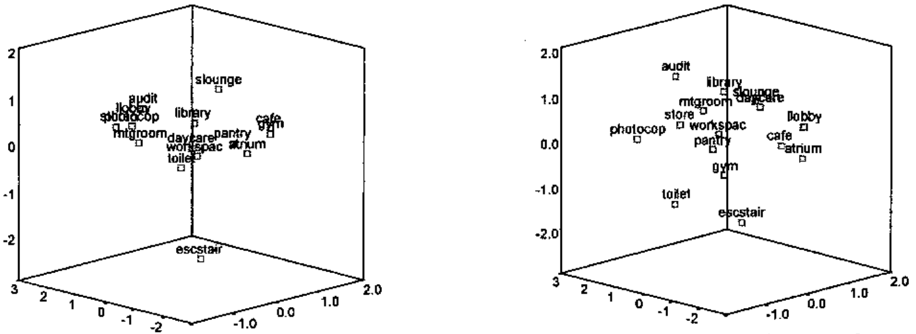
A comparison of the 3-D plots for first and second sorts reinforces this point. Figures 5.4 and 5.5 show that labels[1] tend to cluster together in the first sort. In the outputs for the second sort, they are more clearly distinguishable. Distance between points in MDS plots is an indicator of how similarly they are viewed by the subjects (Wilson, 1995). The closer two points are, the more similarly they are perceived. This would suggest that in the context of the present study, subjects began to differentiate critically only during the second sort, when they were compelled to make choices and tradeoffs.



First Sort

Second Sort

Figure 5.4. 3-D plots for thermal sorts



First Sort

Second Sort

Figure 5.5. 3-D plots for visual sorts

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[1] In all MDS plots, the following abbreviations apply (in parenthesis):
Workspace (workspac), Meeting Room (mtgroom), Staff Lounge (slounge), Cafeteria (café), Auditorium (audit), Atrium (atrium), Lift Lobby (llobby), Fire Escape Stairs (escstair), Toilet (toilet), Store Room (store), Staff Pantry (pantry), Photocopy Room (photocop), Health Club/Gymnasium (gym), Library (library) and Day Care Centre (day care).

A decision was made to proceed with a two-sort procedure, instead of just 'preference with constraint'. This was prompted by the observation that the verbalisation between sorts added to the richness of the data.

In reviewing MDS, however, it is proposed that only outputs from the second sort will be scrutinised. In a sense, they represent the question of *tolerance*, as well as *preference*. They reflect a deliberation of the all modes, including the less popular passive options.

2-D Plots

In the Wilson and Canter study (1990), the structure within the data was 'uncovered' by the successful partitioning of 2-D outputs. In the present study, analysis begins with the similar 2-D outputs. Figures 5.6 and 5.7 show that partitioning supports two criteria identified during Content Analysis. The plots can be divided according to *Activity*, with groupings of Work, Support and Transit spaces. In the case of the thermal plot, the Support zone can be further subdivided according to the criterion of *Health and Hygiene*.

The Work zone consists of Workspace, Meeting Room, Auditorium and Library. Support consists of Day Care Centre, Staff Lounge, Photocopy Room, Cafeteria, Pantry, Toilet, Store and Gymnasium. Transit consists of Atrium, Lift Lobby and Escape Staircase. The question of *Health/Hygiene* applies to the Cafeteria, Pantry, Toilet, Store and Gymnasium within the Support zone.

The one anomaly within the Health/Hygiene grouping is the Store, which was not verbalised as one in which this was a concern.

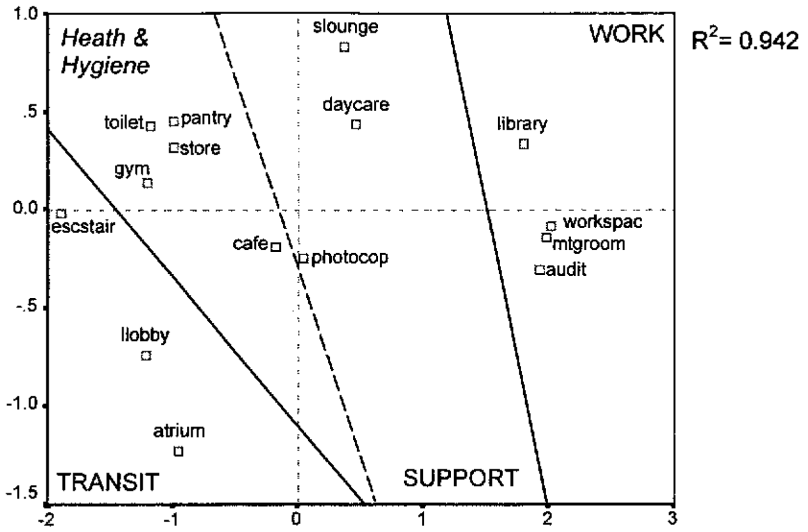

Figure 5.6. 2-D MDS output for thermal sort

The Coefficient of Determination, R^2, for the thermal output is 0.942, which represents a good fit. The Coefficient for the visual sort is 0.873. Whilst not ideal, it can nevertheless be viewed as a good interpretation of the data (Stalans, 1995).

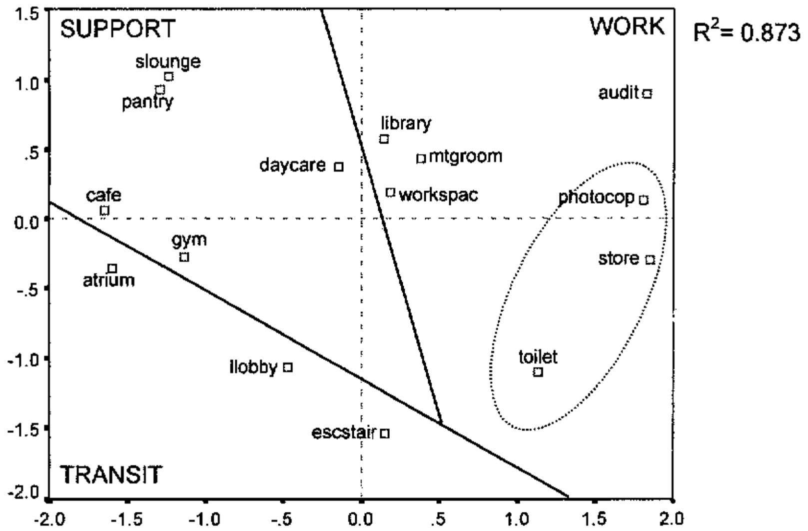

Figure 5.7. 2-D MDS output for visual sort

In the visual sort, a second anomaly is observed in the three groupings. Three labels, which, in the thermal sort were found in the Support zone, are here found in the Work zone: Photocopy Room, Store and Toilet. The question of whether the Photocopy Room and Store represent work or support-based activities is open to interpretation. The Toilet, however, should logically belong in the Support zone.

3-D Plots

To study the data in greater depth, 3-D outputs are generated from the same thermal and visual data matrices. In Kraemer's study (1995), she generated 2-D and 3-D plots, the latter revealing added constructs and affirming the ones found in the former.

The construct of 'Privacy', uncovered by her analysis, will be tested here as it emerged briefly in verbalisations during visual sorts (refer Appendix B6: Survey 2 Data – Subject Verbalisation; see tables summarising RevH and CSC). It had been mentioned by only 3 subjects and as such was not included in the earlier summary of criteria (see Table 5.12) under a separate heading.

It should be noted that all the 3-D plots presented here do not have a satisfactory Coefficient of Determination. The data matrices had insufficient observations (subjects=42) against parameters (15 labels x 3 mode options = 45) for a reliable 3-D output. The plots are nevertheless discussed here, first, as a means of establishing support for the criteria already identified in the 2-D analysis and, second, for any evidence of other criteria.

Figure 5.8 shows the 3-D thermal and visual sorts. In the figures that follow, two axes of each plot are reviewed.

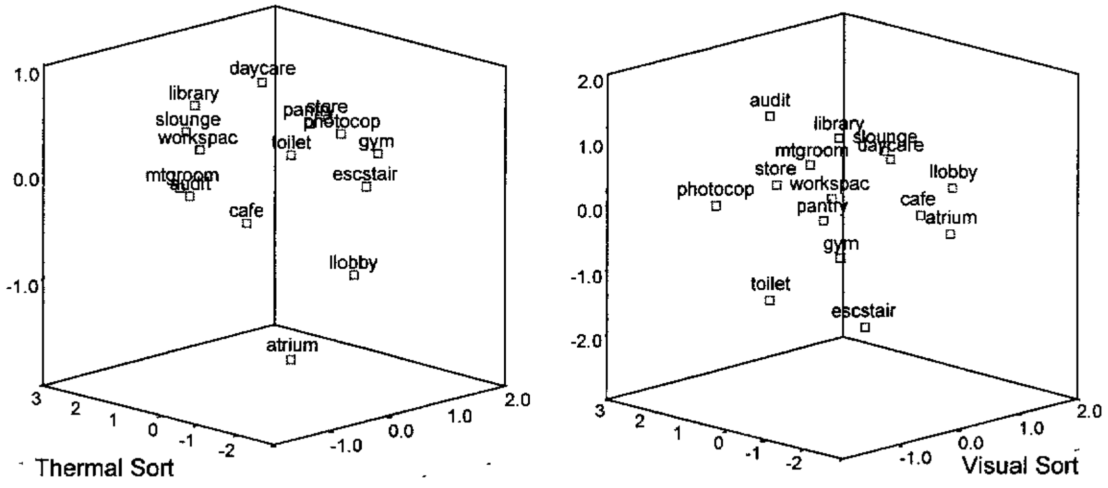

Figure 5.8. 3-D MDS output for thermal and visual sorts

In the three elevations from the thermal sorts, the criteria of Activity, Health/Hygiene and Consistency/Control are supported. Figure 5.9 shows all three elevations and their partitions. The X-Y axis reveals the same basic groupings found in the 2-D plots. Activity is the main criterion; Health/Hygiene emerges as a sub-grouping within the Support zone.

In the X-Z axis, the distribution of labels appears to suggest a gradation of Consistency/Control. Spaces for which control was deemed to be critical, i.e. Workspace, Meeting Room, Auditorium and Library, are situated at the top end of the plot. The space where Control was least critical, Fire Escape Staircase, is situated at the bottom. A scrutiny of mode selection (refer Appendix B7: Survey 2 Data – Choice of Modes) suggests that the way in which spaces are positioned here reflects a progressive shift of preference from NV to AC.

It should be noted that despite the grouping of work-related spaces at the top, partitioning of this plot according to Activity is not possible. Spaces associated with Transit cannot be isolated from those associated with Support.

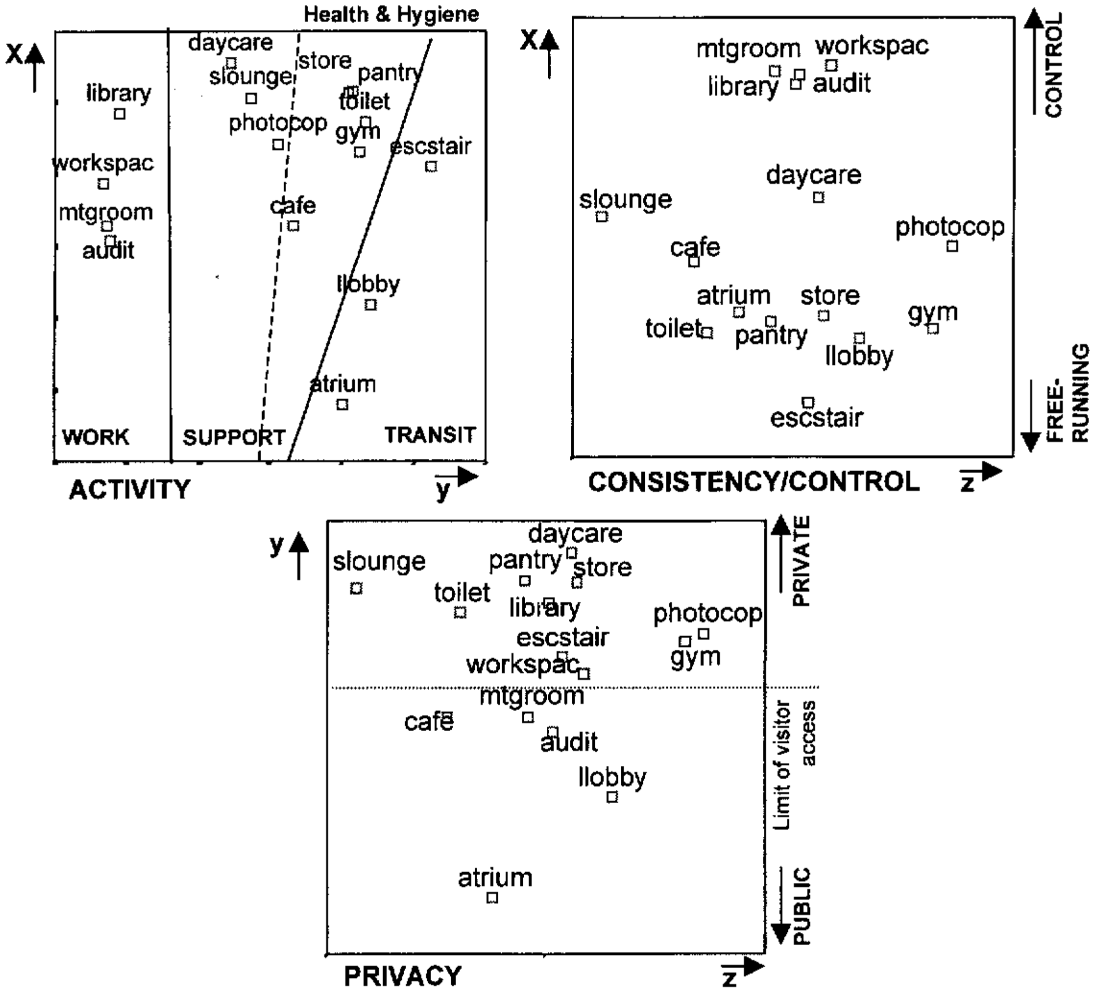

Figure 5.9. Elevations of the thermal plot

The Y-Z elevation appears to reflect the criterion of Privacy. Public access in most office buildings is progressively restricted from the Atrium, Lift Lobby, Auditorium, Cafeteria to Meeting Room, in that order. Beyond this limit of public access, a second gradation exists whereby the most private spaces are increasingly restricted. The most private of these, Day Care Centre, Staff Pantry, Store and Staff Lounge, emerge at the top end.

With regard to Privacy, the Toilet and Fire Escape Staircase merit mention as they emerge in the 'private zone' when these spaces might well be considered public amenities. In the case of the Toilet, an instruction had been given to each subject that the label referred specifically to *Staff* Toilet, so as to minimise confusion arising from the presence of public toilets (see Appendix B4: Survey 4 - Pilot). In the case of the escape stairs, these were observed in most buildings to be situated near workplace or service areas, often off-limits to the public for reasons of security.

In the plots for visual comfort, the criteria of Activity and Consistency/Control are supported. Figure 5.10 shows two elevations in which partitioning was possible. The third, Y-Z, is not shown here as no evident criterion was found (see Appendix B8: Survey 2 Analysis – MDS Plots)

In the X-Z elevation the distribution of spaces is similar to that of the 2-D visual plot earlier (see Figure 5.7) The Work zone is well defined even though it includes the Photocopy Room, Store Room, and Toilet. These had earlier been found in the Support zone for Thermal Comfort. The partition between Support and Transit zones is weaker here than with the 2-D plot, as the Day Care Centre is situated in the Transit zone.

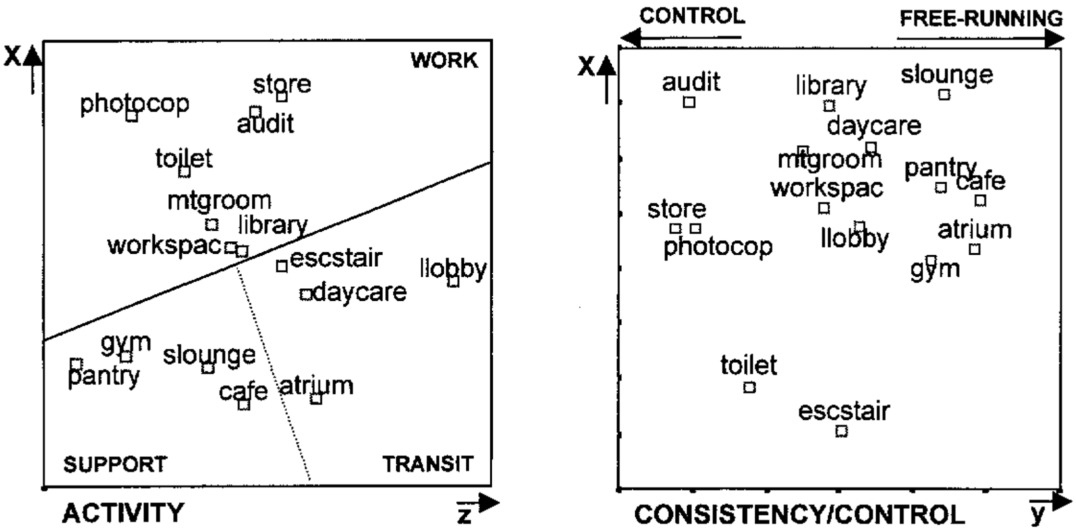

Figure 5.10. Elevations of the visual plot

In the X-Y elevation, the criterion of Consistency/Control emerges, as it did in the thermal plot, this time moving from right to left (passive to active).

To test the robustness of these findings, MDS analysis was carried out on each of the four buildings separately. The objective was to review each criterion found in the present section. These analyses are presented in Appendix B8 (Survey 2 Analysis – MDS Plots). They confirm that the results, in general, are robust, that plots for individual buildings can be partitioned on the basis of the same criteria that emerged here for combined sample. Some minor differences emerge, however, but appear to relate to differences in the layout of the buildings themselves. This suggests that familiarity with a particular environment may play a part in shaping comfort expectations. The building and other subject-related variables are analysed in the next section.

5.2.3.3. Multiple Scalogram Analysis (MSA)

Of the environment and subject-related variables tested - Building, Gender, Job, Age and Ethnicity - only Building appears to be a factor affecting visual sorts. Figure 5.11 shows the partitioning that supports this. In this plot, all MND subjects are found to be grouped at around the bottom half of the plot, clearly separable from the rest. A secondary, weaker cluster, consisting of two thirds of all MES subjects is embedded within the CSC and RevH zone. This sub-grouping, marked by a dotted elipse, does not represent an unequivocal partition, but it does suggest that these MES subjects may be responding differently from others. The finding implies that occupants respond according to the building that they inhabit, suggesting in turn that acclimatisation might be factor affecting perception of visual comfort.

The Coefficient of Contiguity for this MSA is 1.0, deemed to represent a good fit of the data (Wilson, 1995).

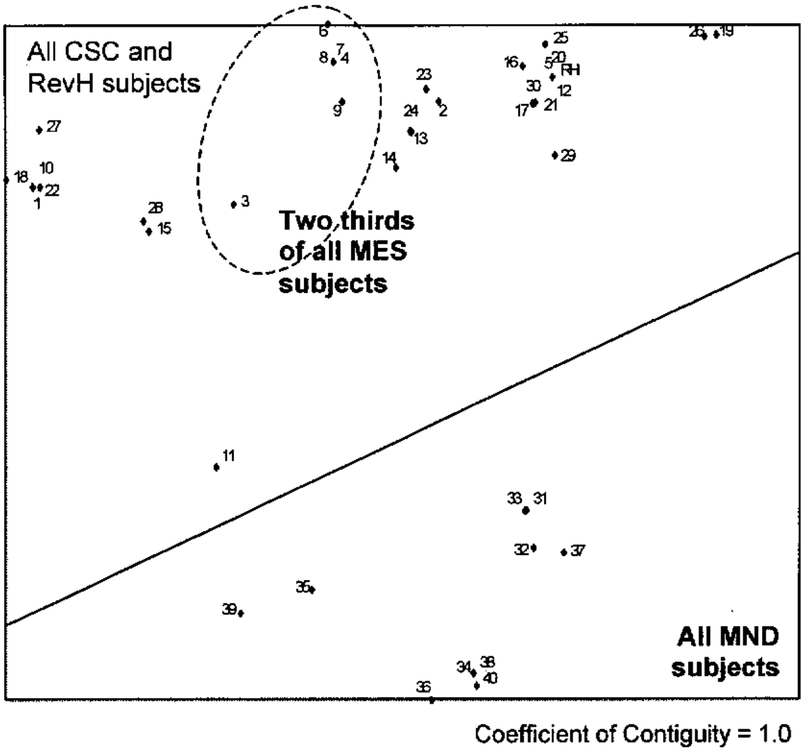

Figure 5.11. MSA plot for visual sorts

The MSA for thermal sorts, which shows no successful partitions on any of the background or case building variables, is shown in Appendix B9 (Survey 2 Analysis – MSA Thermal Plot). The absence of viable partitions seems to imply that occupants respond do not perceive thermal comfort on the basis of any of criteria being tested.

5.3. Behavioural Observations (Survey 3)

5.3.1. Overview

This section on behaviour is meant to support findings from Surveys 1 and 2, particularly with regard to adaptive behaviour, the use of environmental controls and comfort expectations. The raison d'être for this instrument, as cited in Chapter 3 (Section 3.4.3.3), is that it is less intrusive; the researcher does not interact directly with subjects and is therefore less likely to affect outcome. As a technique, the reliability of its data does not depend on subject cooperation or comprehension of the procedure, as is the case with rating scales and the sorting procedure.

The question of 'what to observe' has been summarised by Brager et al (1993) into a three-step strategy:

- Ask occupants what they do.
- Observe what choices are available to them.
- Observe how they actually behave with regard to these choices.

It was found in Survey 1 that three environmental controls are typically available in office buildings: blinds, light switches and thermostats. The reported rate of usage, in general, was negligible (see Table 5.6). Occupants listed the following adaptive responses with regard to thermal discomfort:

- Alter clothing, i.e. adjust insulation through the use of jackets
- Consume drinks
- Alter activity
- Use fan
- Alter level of natural light, via the opening and closing of blinds

With the exception of drink consumption and activity adjustment, all of the above were observed and are reported here. Consumption could not be verified, as it was difficult to observe systematically. By and large it was noted that most subjects had a drinking cup on their desk. The frequency and volume of drink consumed, however, could not be ascertained. It was not possible to observe activity levels either, in as much as a change in activity reflected a response to discomfort.

It was noted that all of the subjects who wore jackets were women in senior management positions. The men, meanwhile, all wore ties. The choice of attire, it would seem, may have been connected with rank and status, or reflective of corporate culture.

	Percentage who say they keep a jacket at work	Percentage who say they wear a jacket regularly	Mean IAT (°C)
RevH	88	71	22.5
URA	57	33	23.3
MES	29	42	24.7
MND	65	45	23.8
CSC	85	80	22.9

Table 5.13. Ownership and use of jackets (Survey 1)

Observations of jackets worn suggest that it is highly prevalent across all buildings. During observations of RevH, it was noted that, on average, one of out every 2 persons encountered wore a jacket in the workspace. This figure was skewed towards women, whereby two out of every three women encountered wore a jacket.

This high level of jacket ownership and use may offer an explanation as to why thermal discomfort is less likely to occur for lower temperatures (see Section 5.1.3.2, Figure 5.2). It seems to suggest that cooler sensations are easier to manage via adjustments to clothing insulation.

5.3.2.2. Use of Desktop Fans

The most visible means of dealing with 'warm discomfort' was use of fans. The two buildings where desktop fans were most visible were MND and MES. Despite the ties and jackets, over one-third of all occupants in MES were seen to be using portable fans. In MND, where almost half of those observed kept a fan, occupants complained that the air-conditioning system was prone to breakdowns. In other buildings, the figure of fan usage was negligible, amounting to less than 5%.

5.3.2.3. Adjustment to Blinds

Vertical blinds were available in all buildings with the exception of MES. Without fail, and on every floor visited, they were closed. All electrical lights were also switched on, irrespective of proximity to window and access to daylight. In the course of a workday, no occupants were observed to make the effort to adjust blinds with changing daylight conditions.

Feedback from Survey 1 had confirmed the reluctance to use blinds; most of those who said they had control over blinds also said that they did not exercise it (see Table 5.6). Anecdotal evidence suggests that occupants nearest the envelope made the decision on the position of the blinds as they had *'ownership'* of windows. The blinds were then pegged to the worst condition during the day (for instance, late afternoon) and left permanently in that position. This was sometimes moderated by requests from co-workers further in (especially when the occupant next to the window wanted the blinds open) suggesting a kind of consensus-building at work.

5.3.2.4. Switching On/Off of Lights

In all buildings, the operation of ceiling-mounted lights was zoned across large areas of the floor plan. This meant that no individual could switch on/off lights without affecting a significant number of co-workers. In the case of RevH and CSC, however, desktop lighting was provided, complementing lower ambient lighting levels. These were designed to give occupants the freedom to adjust illuminance levels at their desks.

It was observed, however, these lights were generally switched on once, at the start of the workday, and switched off at the end, irrespective of the amount of natural light available to them. In the Survey 1 feedback on lighting, only 8% of all occupants who said they had control also said they exercised it (see Table 5.6).

5.3.2.5. Use of Transitional Spaces

Three buildings have transitional spaces on the floors surveyed. RevH has two per floor, one facing N, the other S. MES has one on each floor, spiraling up the side of the building, varying in orientation, depth and size. UMNO has up to two on every floor, facing NE and SW. In all of the three buildings, these spaces were generally not used.

In MES and UMNO, where the design intention had been to create semi-outdoor settings for relaxation (Khosla, 2000), transitional spaces were observed to be used only by smokers. When occupants were asked about these spaces, most said they did use them because they did not want to step into daytime conditions of heat and humidity.

5.3.2.6. Alterations to Building Envelope

The managers of MES addressed the problem of glare with a radical solution. The building's windows have been progressively and extensively laminated with solar tints (see Appendix B10: Summary of MES Solar Tints). Three shades were used: light, dark and extra dark. At first glance, these appear randomly applied, but a review of tint type against indoor activity showed a combination of criteria. Figure 5.12 shows three floors that illustrate this.

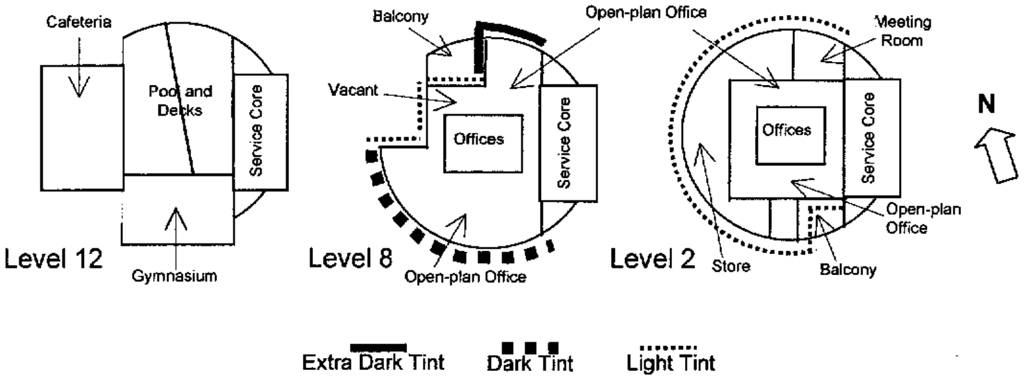

Figure 5.12. Solar Tints applied to the 3 Floors of MES

On level 12, where the cafeteria and gymnasium are located, no tints were added. Windows against service and transit areas, such as toilets and lift lobbies on all floors, were likewise not altered. On level 8, tints were applied around the office spaces, with light tints for windows that are against a transitional space on the outside of the envelope or next to vacant/circulation spaces on the inside. An extra dark tint was applied to the N and W facing windows, where the sun was hottest at certain times of the day (see Section 4.3.3.1, Figures 4.14 and 4.15). On level 2, all windows have the same light tint because the office spaces here are set away from the envelope, buffered by stores and meeting rooms.

In summary, windows next to the workspace get the darkest tints unless they are protected from the sun by transitional spaces. Supporting areas, such as store or meeting room, or where occupants spend less time, such as toilets and lift lobbies, had light or no tints. These interventions appear to *correct* what the building fails to do through passive design, affirming the two criteria of occupant expectations found through Survey 2: *Duration/Frequency of Use* and *Activity* (see Section 5.2.3.1).

5.3.2.7. Reliance on Passive Modes

Tenants of UMNO, when faced with a choice of AC or NV opted for the former. In some instances, they go so far as to install supplementary AC systems, which are able to support activities after hours when the building's central AC system shut down. This observation refutes the expectations of the designer, who had suggested that NV might be useful at cooler hours of the day (van Schaik, 1998).

5.4. Summary of Findings

The main thrust of findings from the present chapter is that occupant comfort expectations are linked with activity zones and the consistency/control available. Acceptance of indoor variability is contingent on task being carried out. This yields a 3-zone division of the building into work, support and transit areas. Other findings pertain to comparisons of responses to the thermal vs. visual environments, perimeter vs. centre zones and Bioclimatic vs. Conventional buildings. These are summarised as follows:

5.4.1. Comfort

- Thermal sensation and thermal comfort appear to relate with IAT. T_N occurs at 24.3°C, approximately one degree higher than T_{Opt}, which occurs at 23.2°C.
- Thermal comfort is likely to occur at thermal sensations ranging from *Neutral* to *Slightly Cool*.
- Thermal discomfort is likely at temperatures near or above 25°C. The lower limit for discomfort was not established. This may have been because of the bandwidth of IATs recorded: 21.0°C to 26.5°C. It is possible also that adaptive response, particularly clothing adjustment, compensates at cooler sensations.
- Relative humidity appears to play a negligible part in influencing thermal comfort. Subjects also seem to lack the ability to gauge the level of humidity. This may have been because of the relatively narrow bandwidth of conditions recorded: 53% to 78%.
- The most common form of adaptive behaviour is adjustment to clothing followed by consumption of a cold or warm drink.
- Extraneous conditions most likely to affect thermal comfort are time of day and outdoor weather.

- Proximity with envelope does not appear to relate with response on thermal scales. It does however, relate with perception of, and preference for, daylight. Those seated next to the envelope say they receive more daylight but would prefer less, as compared with those seated further in. The former group is also twice as likely to say that daylight affects its thermal comfort (i.e. makes them feel warmer) than those further in.

- Perception of Natural Light does not, however, relate, directly with response on any of the thermal scales.
- Overall Perception of Light and Satisfaction with Light does not relate to illuminance levels recorded. Visual comfort involves acclimatisation to conditions found in the building.

- The preferred thermal mode in the workplace is air-conditioning (active mode).
- The preferred visual mode in the workplace is a combination electrical plus natural lighting (mixed-mode), but by a lesser margin than with thermal preference. This mixed-mode, however, appears to be one in which electrical lighting is the larger component, i.e. it is *predominantly* active.
- The passive mode is not the preferred choice of the vast majority of users. Daylight and natural ventilation were picked for only a few secondary spaces.
- Expectation of comfort depends on several criteria. *Activity* and *Duration/Frequency of Use* appear to affect both thermal and visual comfort expectations. These result in three sub-groupings of the office building: Work, Support and Transit.
- The criterion of *Consistency/Control* affects both thermal and visual response.
- *Health & Hygiene* and *Privacy* appear to affect expectations of thermal comfort, but not visual.

5.4.2. Control

- Environmental controls, where available, are generally not used.
- Satisfaction with Control does not relate with availability of control. Rather, it relates with Thermal Comfort and Overall Satisfaction with Light.

5.4.3. Background and Building Variables

- No subject background variable relates with response to thermal, visual or control scales.
- The Building affects response on the Thermal Sensation scale, but not the Thermal Comfort scale. This divergence of response may be because the perception of Thermal Comfort is masked by adaptive behaviour.

- Transitional spaces are not used as intended. Most occupants cite intolerance for daytime outdoor conditions as reason why these spaces are not utilised.
- Corporate/organisational culture appears to affect how people dress and which public areas are deemed to require active modes.
- The Bioclimatic building surveyed (MES) appears to be the warmest and least thermally comfortable. It is also the building where an occupant is most likely to associate presence of daylight with thermal (dis)comfort.

Chapter 6. Delineating Thermal Comfort

6.0. Preamble

It was shown in the earlier part of Chapter 4 that, in general, the Singapore office building exhibits uniformity of indoor conditions across different spaces, particularly with regard to IAT and RH (see Section 4.2.3, Figures 4.4 and 4.5). The *extent* to which uniformity can be meaningfully designed for was subsequently challenged with findings from Section 4.3, where it was shown, through longer periods of monitoring, that a building's indoor conditions are in a natural state of flux. A building's electro-mechanical systems essentially dampen the variability that the buildings exhibit in the passive state. The *need* for uniformity was challenged in Chapter 5 on grounds that the criterion of Activity plays a key role in influencing which conditions are deemed acceptable (see Section 5.2.3). The present chapter asks if the non-uniform building is a tenable proposition and if so, what are the potential energy savings?

This proposition in built on the findings from Survey 2, where it was suggested that an office building could, in theory, be divided into three activity zones, Work, Support and Transit (see Section 5.2.3.3) each operating under different thermal conditions. This proposition will be tested here using the longitudinal survey instrument (Survey 4).

It should be noted that the question of comfort, so far addressed as both visual and thermal comfort, is narrowed here to that of the thermal. There are two arguments for this, the first concerns potential impact, the second, methodology.

With regard to impact, it was suggested in Chapter 2 that AC consumes the largest proportion of an office building's energy load (see Section 2.2.1). In the Singapore context, AC accounts for some 60% of total consumption of an office building (IACEE, 2000) as compared with 5% consumed by electrical lighting (Lee, 1999). Any measure directed at thermal comfort will have the greater impact on energy use.

On methodology, it was shown in Survey 1 that subject response to the thermal condition is predictable (see Figures 5.1 and 5.2), i.e. thermal sensation and comfort relate with IAT at a high level of significance ($p<0.001$). The fact that IAT can be controlled with some certainty via a building's automation system lends itself to testing the hypothesis of 'different conditions for different zones'. Subject response to the visual condition, by contrast, could not be predicted from levels of illuminance. It was later found that this might have been because the perception of visual comfort is specific to building (see Section 5.2.3.3), i.e. it is tempered by the conditions with which subjects are familiar. Also, any attempt at testing a zone-based hypothesis would be handicapped by the difficulty to account for and control daylight.

The central question asked in Survey 4 is if thermal conditions can vary across a building. More specifically, if the three activity zones can be designated different IATs without compromising occupant comfort.

The present chapter consists of two components: the first seeks out, via the longitudinal survey, an optimal thermal condition for each zone. Having established this, the second part involves a re-setting of the building's thermostats in each of the 3 zones while energy consumption is monitored for energy impact. Table 6.1 summarises these two components, along with their approach and objectives.

	Approach	**Case Building**	**Sample**	**Variables Logged**	**Indices**	**Objective**
Survey 4 *Longitudinal Survey*	Survey lasting 3 weeks was carried out in the three activity zones of an office building accompanied by daily adjustments of IAT.	RevH	1000+	IAT, RH, MRT, Air, vertical stratification of temperature. Subject's clothing and chair insulation value, plus metabolic rate.	IAT, ET*, SET*, In/Out Temperature	Test the limits of thermal comfort in each activity-zone.
Energy Impact	Based on the 'upper limit' found in each zone, the entire building's thermostats were re-set. This was accompanied by monitoring of energy consumption.		NA	IAT Daily energy consumption.	NA	Establish energy impact of the 'non-uniform' building.

Table 6.1. Overview of Chapter 6

6.1. Longitudinal Survey (Survey 4)

6.1.1. Overview

The longitudinal survey was described in some detail in Chapter 3 in terms of what was measured and how. In the overview presented here, its objectives and procedures will be examined in greater depth.

This present survey solicited response from occupants in three spaces (see Appendix C1: Survey 4 Questionnaire), each representing an 'activity zone.' While feedback was being gathered, the IAT within each space was adjusted daily. The occupant response collated therefore was made against a bandwidth of temperatures, wider than what was typical for the building. Table 6.2 summarises each zone, its representative space/s and the survey parameters.

Zone	**Location**	**Sample Size**		**Time of Survey**	**Period of Survey**	**Thermostat Adjustments**
Work	Level 3* *(Podium)*	20	These 59 subjects were surveyed repeatedly over 3 weeks resulting in a total of 464 responses	Two slots: 10:30 - 11:30AM 3:00 - 4:30PM	4 days Week 1	None. Left at original setting of 23.5°C
	Level 19 *(Tower)*	20			12 days Week 1 to 3	Daily plus/minus 0.5K in Weeks 2 and 3, up to a maximum of 24.5°C
	Level 23 *(Tower)*	19				None. Left at original setting of 23.5°C
Support	Cafeteria *(Level 2, Podium)*	270		Noon to 2:30PM	12 days Week 1 to 3	Daily plus/minus 0.5 to 1K in weeks 2 and 3; up to a maximum of 26.5°C
Transit	Atrium *(Level 1, Podium)*	290		Two slots: 10:00 - 11:00AM 3:00 - 4:00PM	12 days Week 1 to 3	Daily plus/minus of 0.5 to 1K in weeks 2 and 3; up to a maximum of 28.5°C

** Subjects on this level were surveyed for the first week of the study[1].*

Table 6.2. Overview of Survey 4

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[1] The study had been intended for occupants from two office floors, with one group acting as a 'control' without any adjustments to the thermostat on their level. The building's manager requested that L3 be included for Week 1 of the study, as there had been past complaints of discomfort here. No cause for these complaints was identified and data from this floor was included in the database for analysis.

The survey lasted three weeks, during which temperature adjustments were made in Weeks 2 and 3. Week 1 acted as a 'control' during which the variability of subject response and indoor conditions were monitored. The twenty subjects per office floor were nominated by the building's manager and were surveyed repeatedly. In the Atrium and Cafeteria, each subject was surveyed once. S/he was randomly selected and the group consisted mainly of people entering or leaving the spaces.

A concern arose from the repeat surveys of office subjects, namely the extent to which they responded in a candid manner. This has been described in the literature as the Hawthorne effect[2]. Table 6.3 summarises some of the cautionary measures that were taken with regard to this group.

Concerns with repeat-response subjects	**Measures**
Familiarity	Nominated subjects were informed by email of the survey. During the first encounter with each subject, each subject was given details about the procedure and informed that the survey would be repeated daily over three weeks. They were not informed of the imminent adjustments to the building's temperature settings. The subject was then given a choice to opt out of the exercise. None opted out, however one subject was eliminated from the original list of 60 due to his apparent frustration with the survey procedure.
General Dissatisfaction	Of the subjects surveyed, those who consistently complained about work conditions, responded too quickly or appeared disinterested were noted.
Flexibility	Half the office subjects are approached in the morning and the rest in the afternoon. The question of who was surveyed when was decided at random, often depending on whether the subject was available at the time that s/he was approached.

Table 6.3. Repeat-response considerations

In addition to these measures, the procedure also incorporated observations of extraneous factors that might potentially affect comfort perception. In Survey 1, several variables had been noted to affect perception of thermal sensation and comfort in RevH (see Table 5.6).

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[2] The Hawthorne Effect refers a situation when subjects in an experiment respond to the fact that they are being observed rather than to the experimental changes being tested (Bell et al. 1996, p. 439).

Table 6.4 summarises these extraneous variables and the measures taken to account for them in the analysis.

Variable affecting Thermal Comfort	Measures
Proximity to Envelope	The location of each office worker was noted on plan.
Weather	Outdoor conditions were noted 3 times a day.
AM vs. PM	Half of the surveys were approached in the morning; half were approached in the afternoon. Time of Survey was noted for each subject.
Last Exposure to Outdoors	Office subjects were surveyed at time slots when they were likely to have been indoors for at least two hours.
Saturday and Monday	No survey or adjustment to temperature was carried out on Saturdays and Mondays

Table 6.4. Extraneous factors

Results from Survey 4 are summarised under the following headings:

- Background variables
- Variables affecting thermal comfort
- Indoor conditions
- Occupant response
- Screening of subjects

Analysis begins with a review of the impact of background variables via a series of non-parametric statistical tests[3], the summary of which is presented in Appendix C5 (Summary of Statistical Tests for Data from Survey 4). This is followed by regression analysis of occupant response to the four rating scales.

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[3] The data was tested for normality using the Kolmogorov-Smirnov and Shapiro-Wilks test using SPSS. No group gave a Lillefors significance level of greater than 0.05 on any of the scales, suggesting the absence of normality.

To prepare the data for the regressions, occupant responses to each scale were binned. For each bin, a representative value of occupant response was found. This value consisted of the following:

- *Means* for Thermal Sensation and Comfort, which are ordinal scales with 7 and 6 points respectively.
- *Percentages* for Thermal Preference and Acceptability scales, which are 3 and 2 point nominal scales respectively. The percentage refers to the proportion of those who picked the options of 'No Change' and 'Acceptable'.

The approach to regression analysis here bears comparison with Survey 1 where it was found that occupant response to the Thermal Sensation and Thermal Comfort scales, when plotted against IAT yielded a linear or quadratic outcome (see Section 5.1.3.2, Figures 5.1 and 5.2). From the plots for these scales, two reference temperatures were extracted: T_N (Neutral Temperature) and T_{Opt} (Optimal Temperature).

In the present section, the approach is essentially the same, except that the breadth of data, in terms of scales and indices, has expanded. To differentiate thermal response in each zone, T_N and T_{Opt} are used. It is predicted that if non-uniformity is acceptable to the occupants, analysis will yield different values for each of the three spaces. If non-uniformity is not tenable, T_N and T_{Opt} will not differ significantly with zone; i.e. response in all spaces should essentially be the same.

Four key differences between Surveys 1 and 4 need to be pointed out:

- In addition to IAT used in Survey 1 regressions, three additional indices are introduced here: ET*, SET* and In/Out Temperature. ET* and SET* were discussed in Chapter 2 (see Section 2.3.1); the premise for In/Out Temperature was covered in Chapter 3 (see Section 3.4.3.1). The objective behind these additional indices is to ensure inclusion of known variables affecting thermal comfort, i.e. mean radiant temperature, air movement, clothing and chair insulation value, metabolic rate and outdoor conditions.
- In addition to the Thermal Sensation and Thermal Comfort Scales used in Survey 1, Thermal Preference (McIntyre) and Acceptability Scales were introduced in Survey 4. The new scales are expected to shed further light on the perception of thermal comfort.

- In keeping with the objective of testing the 'Activity' criterion, the Survey 4 was conducted in three spaces. In addition to Offices, which had been the sole focus of Survey 1, subjects were approached in the Cafeteria and Atrium.
- The data here are binned at two temperature intervals: quarter and half degree[4]. In Survey 1 binning was carried out at ½ degree intervals only. The two bin intervals here are to test the possibility that some scales will yield improved regressions at one interval more than the other. If so, it would suggest that certain scales are more sensitive to ambient condition than others. This analysis offers the possibility of delineating the various types of subject responses, i.e. sensation, comfort, preference and acceptability.

The regression analysis presented begins with outcomes for each of the three scales, IAT, ET* and SET*, at quarter and half degree bins. This is followed with plots for In/Out Temperature (see Section 6.1.3.2).

In the last analysis shown here (see Section 6.1.3.3), the data is examined in terms of the comfort response in each space. Means and distributions across the three spaces are compared and the difference tested for statistical significance.

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[4] It is not possible to test the data at smaller or bigger temperature intervals. The sling hygrometers were sensitive to ¼ degree differences (see Appendix A1: Instruments and Instrumentation). Binning with at intervals greater than ½ degree would significantly reduce the number of data points in the regression plot.

6.1.2. Results

6.1.2.1. Background Variables

Table 6.5 summarises background variables of all subjects surveyed.

	Office *(n=464*)*	Cafeteria *(n=270)*	Atrium *(n=290)*	Total *(N=1024)*
Gender				
Male - 1	43 (9.3)	116 (43.0)	186 (64.1)	345 (33.7)
Female - 2	412 (88.8)	150 (55.6)	104 (35.9)	666 (65.0)
	9 missing values (1.9)	*4 missing values (1.4)*		*13 missing values (1.3)*
Age				
under 20 - 1	0 (0)	23 (8.5)	13 (4.5)	36 (3.5)
20-29 - 2	226 (48.7)	104 (38.5)	89 (30.7)	419 (40.9)
30-39 - 3	124 (26.7)	78 (28.9)	73 (25.2)	275 (26.9)
40-49 - 4	80 (17.2)	47 (17.4)	70 (24.1)	197 (19.2)
50 & above - 5	25 (5.4)	18 (6.7)	45 (15.5)	88 (8.6)
	9 missing values (2)			*9 missing values (0.9)*
Staff or Visitor				
Staff - 1	464 (100)	109 (59.6)	28 (9.7)	601 (58.7)
Visitor - 2	0 (0)	161 (40.4)	262 (90.3)	423 (41.3)
Race				
Chinese - 1	407 (87.7)	226 (83.7)	200 (69.0)	833 (81.3)
Malay - 2	16 (3.4)	27 (10.0)	41 (14.1)	84 (8.2)
Indian - 3	32 (6.9)	9 (3.3)	33 (11.4)	74 (7.2)
Eurasian - 4	0 (0)	0 (0)	4 (1.4)	4 (0.4)
Others - 5	0 (0)	3 (1.1)	9 (3.1)	12 (1.2)
	9 missing values (2)	*5 missing values (1.9)*	*3 missing values (1)*	*17 missing values (1.7)*

Number in parenthesis is percentage of total sample.

**Sample size here and in Table 6.6 refers to combined number of questionnaires collated from repeat surveys across three office floors. For breakdowns, refer to Appendix C3: Survey 4 Data – Breakdown of Repeat Subjects.*

Table 6.5. Summary of background variables

From the data gathered, the Office sample appears biased towards Chinese women in the 20-39 bracket. This is consistent with data from Survey 1 in which the same building was a case study (see Section 5.1.2.1, Table 5.2). In the Cafeteria, the gender bias is less, with 55.6% women, bringing it in line with the demographics of Singapore (Singapore Department of Statistics, 2000).

In the Atrium, the majority of subjects are within the 20-49 age-bracket. The ethnic bias is less with percentage of non-Chinese increasing to 31% as compared with 12-16% in Offices and Cafeteria respectively, better reflecting the Singapore demographics. The percentage of Visitors is highest in the Atrium, at over 90% of all surveyed. This is due to the fact that this survey was conducted at a time when most of the staff were at their workplaces. It is unclear why the Gender bias has moved towards a majority of males.

6.1.2.2. Variables Affecting Thermal Comfort

Table 6.6. summarises variables known to affect the perception of thermal comfort.

	Office *(n=464)*	**Cafeteria** *(n=270)*	**Atrium** *(n=290)*	**Total** *(N=1024)*
Clothing Insulation (Clo)				
Male - 1				
Mean	0.65	0.61	0.59	0.60
Std. Dev.	0.11	0.06	0.09	0.08
Min.	0.40	0.30	0.34	0.30
Max.	0.86	0.85	0.86	0.86
Female - 2				
Mean	0.52	0.50	0.50	0.52
Std. Dev.	0.10	0.09	0.09	0.10
Min.	0.25	0.36	0.30	0.25
Max.	0.75	0.72	0.73	0.75
Overall				
Mean	0.54	0.55	0.56	0.55
Std. Dev.	0.11	0.10	0.10	0.10
Min.	0.25	0.30	0.30	0.25
Max.	0.86	0.85	0.86	0.86
Metabolic Rate (Met)				
Male	1.16	1.49	1.63	1.52
Female	1.39	1.45	1.77	1.46
Overall	1.36	1.47	1.68	1.48
Time since last exposure to outdoors (% of sample)				
just walked in - 1	0.0	10.7	24.1	9.7
<5 minutes - 2	0.0	7.8	11.7	5.4
5-15 minutes - 3	0.0	15.9	23.4	10.8
>15-30 minutes - 4	0.0	9.3	17.2	7.3
>30 minutes - 5	100.0	55.9	23.4	66.7

Table 6.6. Variables affecting thermal comfort

In general, men have a higher Clo value than women for each of three spaces. The difference in the combined sample means - Male/0.60 Clo and Female/0.52 Clo - was tested with the Mann-Whitney U-test which yielded $z=-13.583$ at $p<0.001$. This difference between genders is probably the result of what constitutes typical attire. Men were seen to wear long-sleeved shirts and full-length trousers, whilst women had a wider range of clothing options, such as blouses and skirts, often made of lighter fabrics.

Met rates in the Cafeteria and Atrium were higher than in the Offices. The difference in means across the three spaces was tested using the Kruskal Wallis test. It yielded χ^2 (2, N=1024)= 58.919 at $p<0.001$. The difference is likely to be due to the fact that most people in the Offices were desk-bound. In the other spaces, most had been walking about in the half-hour preceding the interview.

With regard to exposure to the outdoors, subjects in Offices were deliberately surveyed at timeslots when it was certain that they had been indoors at least two hours. This was to ensure that they had settled into a work routine. In the Cafeteria, which had a higher share of Visitors, the time since last exposure to the outdoors averages between >15-30 minutes. In the Atrium, where almost all those surveyed were Visitors, this averages to between 5-15 minutes.

6.1.2.3. Indoor Conditions

Table 6.7 summarises all indoor variables logged during the three-week period. It should be noted that these conditions reflect adjustments made to the thermostats in each space. The exceptions to this are offices on L3 and L23, for which no adjustments were carried out.

	Office				**Cafeteria**	**Atrium**
	L3	**L19**	**L23**	**Total** *(n=464)*	*(n=270)*	*(n=290)*
Indoor Air Temperature* (^{o}C)						
Mean	23.2	23.6	22.9	23.3*	24.6	25.4
Std. Dev.	0.53	0.63	0.58	0.66	0.60	0.68
Min.	22.0	22.0	21.0	21.0	22.5	24.0
Max.	24.0	25.5	24.5	25.5	26.3	27.5
Relative Humidity (%)						
Mean	59	52	54	54	58	57
Std. Dev.	3.4	5.5	3.4	5.1	3.9	4.8
Min.	53	40	40	40	45	48
Max.	65	67	67	67	68	72
Air Movement (m/s)**						
Mean	0.08				-	-
Std. Dev.	0.05				-	-
Range	0.05 – 0.25				0 - 0.04	0.25 – 0.48
Mean Radiant Temperatures* (°C)**	4 m from envelope			10 m from envelope		
Mean Difference between MRT & IAT values	+0.8			+0.5	+0.5	+0.2
Std. Dev.	0.4			0.3	0.2	0.3
25-75% Interquartile Range	0.4 – 1.0			0.4 – 0.6	0.4 - 0.6	0.0 - 0.2

* Mean difference between IAT readings taken at 0.1m and 1.1m above floor level was 0.05 degrees, ranging from 0 to 0.2 degrees. This was recorded with the VelociCalc Meter.

** Readings taken across several days.

*** Values shown here represent the difference between IAT and MRT readings, recorded with paired loggers at 7 locations on an office floor, 2 locations inside Cafeteria and 2 locations within the Atrium.

Table 6.7. Summary of indoor conditions

The data suggest that of the three Office floors, L23 was the coolest (21°C) and had a wide IAT range (3.5K). This is despite the fact that no adjustments were made to its thermostat settings at any point during the three weeks.

MRT readings in the Offices, taken at 4 and 10 m from the envelope, suggested that subjects closer to the envelope were likely to experience an MRT that was up to 1.0K higher than the ambient IAT. Those further in were likely to experience a difference of 0.6K or less.

A mean difference of 0.5K between MRT and IAT was recorded in the Cafeteria. In the Atrium, this margin was 0.2K. It is unclear why the Atrium had such low MRT readings. It may have been due to an error in the readings or atypical conditions during the period of logging.

Air movement in the Atrium was the most variable of the three spaces: between 0.25 and 0.48 m/s. In the Offices and Cafeteria, the bandwidth was much narrower, peaking at 0.25 m/s for the Office and 0.04 for the Cafeteria.

From the summary of representative readings for Air, MRT and vertical stratification of temperature, it could be argued that variability of air movement might affect the thermal response of those in the Atrium. Variability of MRT is likely to affect those seated next to the envelope in the offices. Vertical stratification of temperature does not appear to vary significantly across the building; its relative impact on response should therefore be minimal.

6.1.2.4. Occupant Response

Table 6.8 summarises occupant response to each of the four rating scales.

	Office L3	L19	L23	Total *(n=464)*	Cafeteria *(n=270)*	Atrium *(n=290)*
Thermal Sensation Scale						
Cold - 1	5.8	1.4	2.7	2.6	3.0	3.8
Cool - 2	17.4	10.1	12.9	12.5	16.3	19.0
Slightly Cool - 3	17.4	25.1	34.4	27.8	21.1	17.2
Neutral - 4	47.8	52.2	32.8	43.5	41.1	45.5
Slightly Warm - 5	11.6	9.7	11.3	10.6	14.4	11.4
Warm - 6	0	1.4	5.9	3.0	3.0	2.8
Hot - 7	0	0	0	0	1.1	0.3
Mean Vote	3.4	3.6	3.6	3.6	3.6	3.5
Thermal Acceptability						
Unacceptable - 1	5.6	5.3	18.3	10.6	7.7	6.9
Acceptable – 2	94.4	94.7	81.7	89.4	91.9	93.1
Thermal Preference Scale						
Cooler - 1	15.3	12.1	22.0	16.6	34.8	41.0
No Change - 2	70.8	72.9	60.0	65.9	60.7	56.9
Warmer – 3	13.9	15.0	22.0	17.5	4.4	2.1
Thermal Comfort Scale						
Very Uncomfortable - 1	0.0	0.0	0.0	0.0	0.4	0.0
Moderately Uncomfortable - 2	4.3	1.9	4.3	3.2	3.0	1.4
Slightly Uncomfortable - 3	10.1	11.6	21.0	14.9	8.1	9.7
Slightly Comfortable - 4	15.9	16.9	19.9	17.9	21.5	24.1
Moderately Comfortable - 5	59.4	57.5	44.1	52.8	56.7	46.2
Very Comfortable - 6	10.1	12.1	10.8	11.2	10.4	18.6
Mean Vote	4.6	4.7	4.4	4.5	4.6	4.7

All figures shown are percentages of votes from the total sample for each floor/zone.

Table 6.8. Summary of occupant response

Of the three Office floors, occupant satisfaction seems lowest on L23. It has the highest percentage of subjects who voted 'Unacceptable' and 'Cooler/Warmer', at 18.3% and 44% respectively. In L3, the same votes add up to 5.6% and 29.2% respectively; in L19 it was 5.3% and 27.1% respectively. L23 also has the most number saying they were between 'Slightly Uncomfortable' to 'Very Uncomfortable', 25.3% of the total. In L3 and L19 that figure is between 14.4% and13.5% respectively.

L23 also has the highest proportion of occupants voting on the warm end of the Thermal Sensation scale. Seventeen percent said they were 'Slightly Warm' to 'Hot' here, compared with 11.6% and 11.1% for L3 and L19 respectively.

The mean IAT recorded at L23 (see Table 6.7) suggests that, on the whole, it is the coolest floor. It also has the widest range of IAT, with a margin 3.5K (21.0°C –

24.5°C). The IAT margin for L3, which was kept at a fixed thermostat setting, was 2K (22.0°C – 24.0°C). This suggests that of the three floors, there is a highest naturally occurring variability on L23.

The mean Thermal Sensation and Thermal Comfort votes across the three zones are similar.

6.1.2.5. Screening of Subjects

The analysis of data depends on two factors:

- How candidly each subject voted on the scales
- How accurately the conditions were logged

Of particular concern, with regard to the question of candid response, were subjects from the Office who were repeatedly surveyed for a period of 12 days stretching over three weeks. The database is trimmed of the following:

- *Non-responsive subjects*

  This consists of subjects who appeared disinterested in the procedure and responded in a hasty manner. It was noted during the survey that some did not vary much in their response, voting the same answer irrespective of differences in the ambient condition. These subjects were removed from the database altogether on grounds that they were non-responsive to the spirit of the research. In total, 6 subjects were eliminated for this reason.

- *Hawthorne Effect*

  A review of the 12 days showed that dissatisfaction levels were highest on the first day (see Appendix C4: Summary of Indoor/Outdoor Conditions and Occupant Feedback), a response that had no basis in actual temperatures recorded. It is possible that subjects were only just becoming familiar with the survey protocol. It is likely therefore that their response was not reflective of ambient conditions experienced. All responses from the offices on Day 1 of the study, amounting to 48 entries, were eliminated from the database prior to analysis.

The question of accuracy with which conditions were logged was critical for the three variables for which representative values have been calculated, i.e. MRT, Air and Vertical Stratification of Air Temperature. In the case of the Cafeteria and Atrium, there is no way of gauging the impact of these factors, nor their inherent variability. Subjects were surveyed once and conditions changed rapidly due to opening and closing of doors, particularly in the Atrium. In the Offices, however, conditions were more stable in general and subject location was predictable. Of the three variables here, MRT was found to vary the most. It was noted that subjects sitting next to the building envelope experienced unpredictable levels of MRT. This group of eleven subjects was also removed from the data before analysis commenced.

In total, from a combined total of 464 surveys conducted carried out on the three office floors, the final sample used in the analysis was 245. This was after the above-mentioned screening of subjects for reliability of response and variability of condition. In the Cafeteria and Atrium, from which no subjects could be meaningfully screened, the sample size remained at 270 and 290 respectively.

6.1.3. Analysis

6.1.3.1. Background and Building Variables

The analysis in this section asks if any variables summarised in Tables 6.5 and 6.6 affect a subject's response to the four thermal scales.

It should be noted that of the three spaces surveyed, the sample from the Office is tested for response on individual days, so as not to introduce into the analysis repeat response from same subject[1]. Of the 12 survey days, two from Week 1 are picked for Office analysis. As Day 1 has been eliminated because of suspected Hawthorne effect, Day 2 and 3 are used for analysis.

All background and building variables tested are summarised in Appendix C4 (Summary of Statistical Tests for data from Survey 4). For the Office sample, none of the background and building variables on either of the two days appears to relate with response to the four scales.

In the remaining spaces, the following scales and variables showed significance.

- *Cafeteria:* Staff/Visitor with Thermal Preference
- *Atrium:* Gender with Thermal Comfort; Age with Thermal Comfort; Staff/Visitor with Thermal Comfort and Thermal Preference; Race with Thermal Sensation; Time of Survey (AM vs. PM) with Thermal Preference; Metabolic Rate with Thermal Preference

It is noteworthy that the number of variables is far greater in the Atrium than in the Cafeteria. This may be a chance occurrence or it may suggest something about the former space, which is essentially a transit space through which occupants move rapidly. Subjects here may, therefore, have little time for adaptive response.

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[1] In the Cafeteria or Atrium, this was not an issue as each subject was surveyed only once.

Of the variables that mattered in the Atrium, only Staff/Visitor was also significant in the Cafeteria. In the Atrium, staff were slightly less comfortable (mean vote=4.3) than visitors (mean vote=4.8). A Mann-Whitney U-test performed on the Thermal Comfort response of the two groups yielded a $z=-2.2$ at $p<0.05$. Here, it is found that staff are also slightly more likely to want change on the Thermal Preference scale. A Chi Square test on the two groups with regard to Thermal Preference yielded a χ^2 (2, N=290)=14.83 at $p<0.05$. In the Cafeteria, the order is reversed, i.e. staff are less likely than visitors to want change with a χ^2 (2, N=270)= 6.794 at $p<0.05$.

A possible explanation for the difference these two groups is that Met rate varies significantly. A Mann-Whitney U-test carried out yielded a $z=-4.75$ at $p<0.001$. Visitors have a mean of 1.64 Met compared with 1.39 Met for Staff. This may be explained by the fact that staff are likely to have been at their desks prior to the survey, engaged in low intensity work. All visitors are likely to have engaged in higher levels of activity, such as walking or driving a car.

Of the four other variables to emerge in the Atrium, Gender was found to relate with Thermal Comfort. Women were generally less comfortable (mean vote 4.6) compared to men (mean vote 4.8). A Mann-Whitney U-test on the Thermal Comfort response of the two genders yielded a $z=-2.1$ at $p<0.05$.

With regard to Age, subjects under 30 were least likely to be comfortable (mean vote=4.5), whilst those between 30 and 39 were the most likely (mean vote=5.0). A Chi Square test on Thermal Comfort response of the 5 age groups yielded a χ^2 (4, N=290)=11.189 at $p<0.05$.

Subjects who were Chinese were likely to feel warmer with a mean Thermal Sensation vote of 3.6; Indians were likely to feel coolest with a vote of 3.1. A Chi Square test on three ethnic groups, i.e. Chinese, Malay and Indian, yielded a χ^2 (2, N=274)=10.54 at $p<0.01$. In an earlier study that compared the same ethnic and gender groups in Malaysia (Ismail and Barber, 2001), differences were also found in the way that each responded to the thermal condition. The authors noted, however, that these were possibly due to varying adaptive response.

Thermal Comfort in the PM hours (mean vote=4.6) was slightly lower than in the AM hours (mean vote=4.9) suggesting that subjects were less comfortable in the afternoon than in the morning. A Mann-Whitney U-test on Thermal Comfort response between AM and PM hours yielded $z=-2.86$ at $p<0.005$.

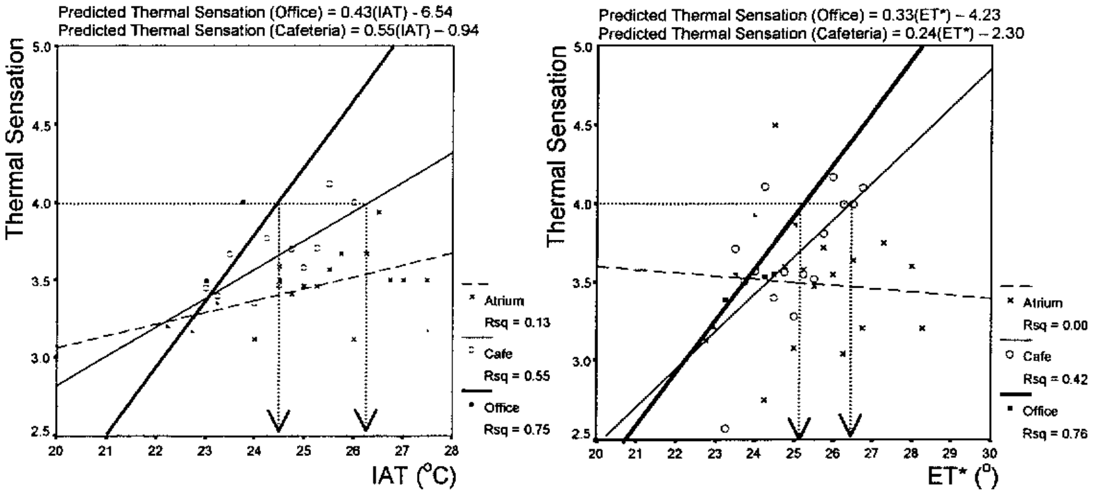
6.1.3.2. Regression Analysis

Each regression plot shows response to a rating scale for each index, with data points representing each of the three spaces. These data points are then highlighted by a line/curve representing the best fit, one for each space. Plots with one or no regressions of significance are found in Appendix C6 (Regressions for Data from Survey 4).

It should be said at the outset that all plots with SET* Index, Preference and Acceptability scales yielded poor outcomes, with one or no fits of significance. Plots shown here, therefore, are primarily for IAT and ET* indices, Thermal Sensation and Thermal Comfort scales. These are grouped according to bin intervals, starting with quarter degree plots.

IAT and ET at quarter-degree bins*

At ¼ bin intervals, only the Thermal Sensation scale yields plots of significance (see Figure 6.1). In both cases, these are for the Office and Cafeteria. With IAT, R^2 for Office is 0.75 at $p<0.001$. Offices give an R^2 of 0.76 with ET* at $p<0.005$. The line for the Cafeteria, by comparison, has a lower R^2 of 0.42 for ET* and 0.55 for IAT, at $p<0.01$ in both cases. The Atrium shows significance within neither IAT nor ET*.

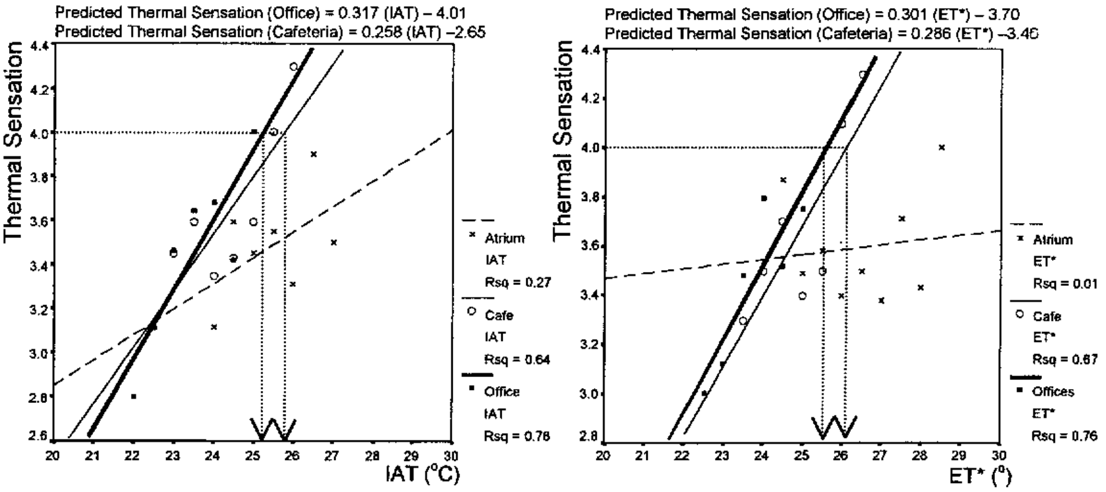


T_N = 24.5°C (Office) and 26.3°C (Cafeteria) **T_N = 25.1° (Office) and 26.5° (Cafeteria)**

Figure 6.1. Thermal Sensation scale at quarter-degree bin intervals

IAT and ET at half-degree bins*

At ½ degree bins, IAT regressions for Thermal Sensation yield an R^2 of 0.76 at $p<0.05$ for Offices. With IAT and the Cafeteria, $R^2=0.64$ at $p<0.05$. The Offices regression for ET* shows R^2 of 0.76 at $p<0.05$. For ET* and the Cafeteria, R2=0.67 at $p<0.05$. The Atrium, again, shows no outcomes of significance (see Figure 6.4).

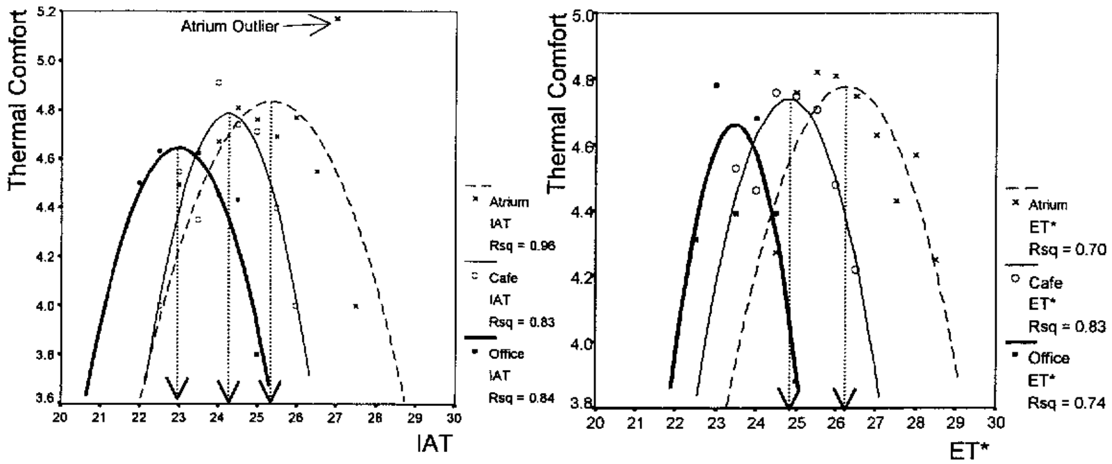


T_N = 25.2°C (Office) and 25.8°C (Cafeteria)

T_N = 25.5° (Office) and 26.2° (Cafeteria)

Figure 6.2. Thermal Sensation scale at half-degree bin intervals

At half-degree bin IAT intervals, the Thermal Comfort scale for Office yields an R^2=0.84 at $p<0.05$ and an F value of 10.26 (df=2). For Cafeteria, R^2=0.83 at $p<0.05$ and an F value of 11.98 (df=2). The Atrium shows an R^2 of 0.96 at $p<0.005$ and an F value of 46.49 (df=2), after exclusion of an outlier (see Figure 6.2).



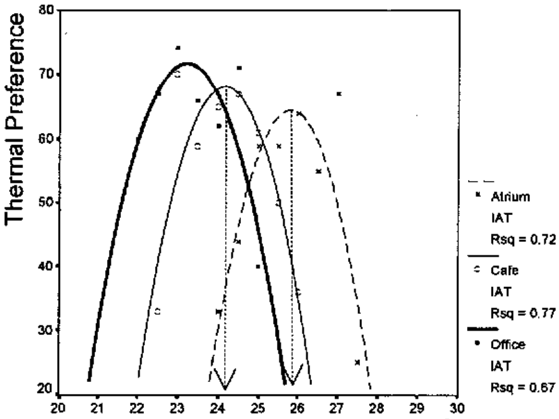
T_{Opt}= 23°C (Office) 24.2°C (Cafeteria) and 25.3°C (Atrium)

T_{Opt} = 24.9°C (Cafeteria) and 26.2°C (Atrium)

Figure 6.3. Thermal Comfort scale at half-degree bin intervals

With ET*, the curve for Offices is not significant at $p<0.05$. The R^2 for Atrium is 0.70, at $p<0.05$ and an F value of 6.91 (df=2). Cafeteria shows an R^2 of 0.82 at $p<0.05$ and an F value of 9.44 (df=2).

Response to the Thermal Preference scale shows significance for two curves on the IAT plot (see Figure 6.3). For the Cafeteria, R^2=0.77 with an F value=8.17 (df=2). For the Atrium, R^2=0.72 with an F value=6.51 (df=2). Both curves are significant at $p<0.05$.



T_{Opt} = 24.2°C (Cafeteria) and 25.8°C (Atrium)

Figure 6.4. Thermal Preference scale at half-degree bin intervals

Table 6.9 summarises the T_N and T_{Opt} values extracted from plots with the best fits and highest reliability. These differences amount to 2K difference overall, with values for Office typically the lowest and those for the Atrium the highest.

	Offices	**Cafeteria**	**Atrium**
T_N	24.5°C IAT 25.1° ET*	26.3°C IAT 26.5° ET*	No significance
T_{Opt}	23.0°C IAT	24.2°C IAT 24.9° ET*	25.3°C IAT 26.2° ET

Table 6.9. Summary of T_N and T_{Opt} from 'best fit' regressions

It is noteworthy that the T_N and T_{Opt} found here for the offices are in close agreement with those found in Survey 1 (see Section 5.1.3.2, Figures 5.1 and 5.2). The T_N found of offices here is also comparable with that found in past studies of AC office buildings in hot humid conditions (de Dear et al., 1991c; Ismail and Barber, 2001).

A final regression is carried out for the combined population sample from all three spaces. It is speculated that if a regression of significance emerges here, the responses in Table 6.9 may simply reflect differences due to population rather than location. If, on the other hand, no regression of significance is found for the combined population, it would suggest the response was specific to zone. This 'combined population' regression is carried out with IAT, which has proven, by far, to be the most reliable of the 3 indices.

Of the two scales tested with data from the combined population sample, only Thermal Sensation is significant at $p<0.05$ (see Figure 6.5). This suggests that in the case with Thermal Comfort, location, not population, is the likely cause of the outcomes summarised in table 6.9.

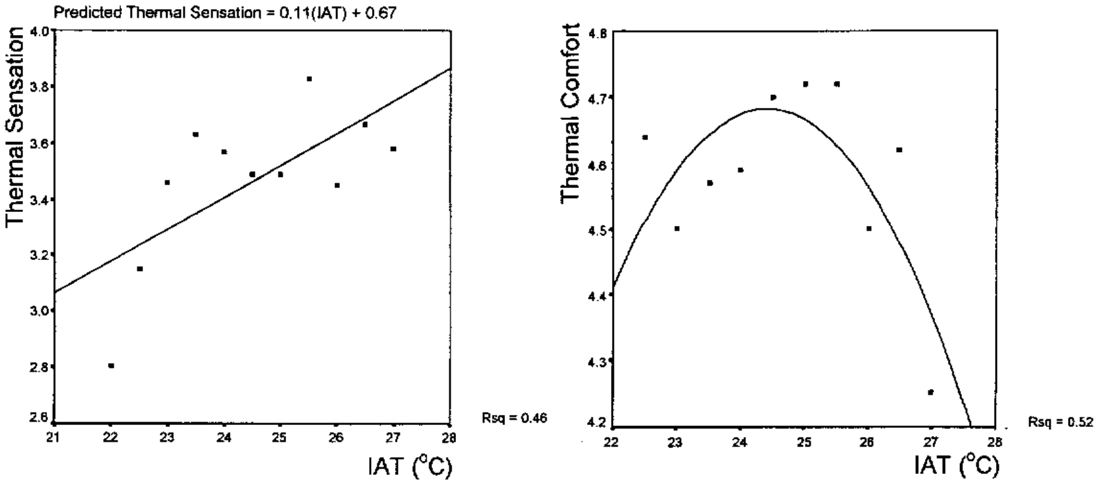


Figure 6.5. Thermal Sensation and Thermal Comfort scales for combined population

These findings suggest that occupant expectations, based on the criterion of Activity, affect the perception of thermal comfort, more so than that of thermal sensation.

In/Out Temperature

The final set of regressions seeks to examine the effect of outdoor conditions. Figure 6.6 shows response on the Thermal Sensation scale in relation to the difference between indoor and outdoor temperatures (Out DBT – IAT = In/Out Temperature). The Atrium shows the strongest fit here, with an $R^2=0.85$ at $p<0.005$ and an F value=16.64 (df=2). The Office has an $R^2=0.65$ at $p<0.05$ and an F value=7.51 (df=2). The Cafeteria regression is not significant at $p<0.05$. There are also no outcomes of significance with any of the other scales or indices (see Appendix C6: Regressions for Data from Survey 4).

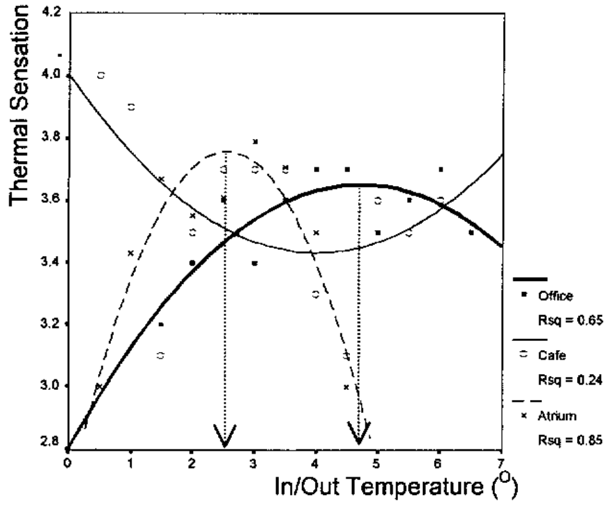


Figure 6.6. Thermal Sensation scale and In/Out Temperature

Figure 6.6 suggests that perception of thermal sensation in the Atrium is most affected by outdoor conditions. This may be due to two reasons:

- *Exposure to outdoors.* Over 75% of subjects here had experienced outdoor temperatures less than ½ hour earlier (see Table 6.6). It should be noted, however, that this does not explain why there is significant regression for Office but not Cafeteria. None of the subjects from the offices had recent exposure to the outdoors (i.e. less than 1/2 hour prior to interview); the figure for the Cafeteria, on the other hand, was 45%. On the basis of exposure to outdoors, the Cafeteria would be a stronger candidate for a significant outcome.
- *Visual connectivity with outdoors.* Of the three spaces, the Atrium had the highest WWR of nearly 100%, the Offices was 40% whilst the Cafeteria had no accessible windows. This is consistent with the outcome found here in which Atrium has the strongest regression, the Offices second and the Cafeteria none.

If WWR, and implicitly the view out, were affecting occupant perception, it would suggest that subjects rely on visual information about conditions outside, as opposed to actual exposure to them.

6.1.3.3. Comparison of Means

The analysis of Survey 4 concludes with a zonal comparison of subject comfort and the IAT at which it occurs. The objective of this analysis is to determine if the differences between mean subject response and IAT are significant for the three zones.

The first stage of this analysis involves a review of comfort response and IATs. Table 6.10 summarises the responses that approximate comfort, the proportion of votes received for this range of response, and the mean IAT at which these responses occur.

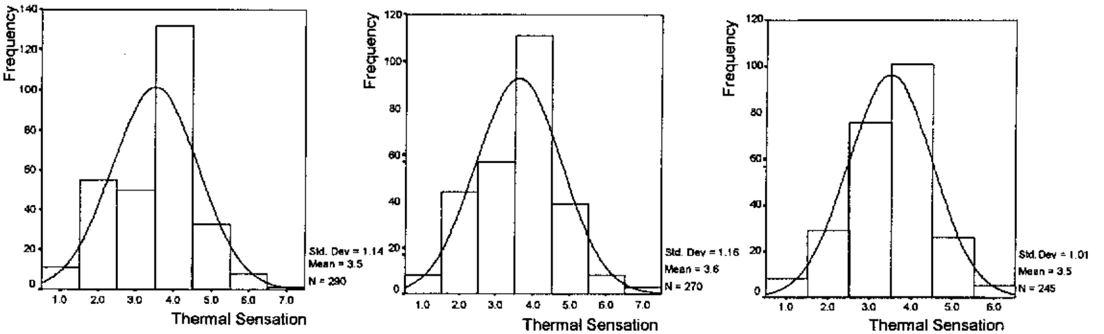
Range of responses approximating subject comfort	Zone	Number of votes	Mean IAT (°C) at which comfort occurs
Thermal Sensation Scale *'Slightly Cool' and 'Neutral'*	Office	177 (72)	23.2
	Cafeteria	171 (63)	24.5
	Atrium	182 (63)	25.4
Thermal Comfort Scale *'Slightly Comfortable' to 'Very Comfortable'*	Office	205 (84)	23.3
	Cafeteria	238 (88)	24.6
	Atrium	257 (87)	25.3

Figure in parenthesis is percentage of total sample size.

Table 6.10. Summary of comfort votes and mean IAT

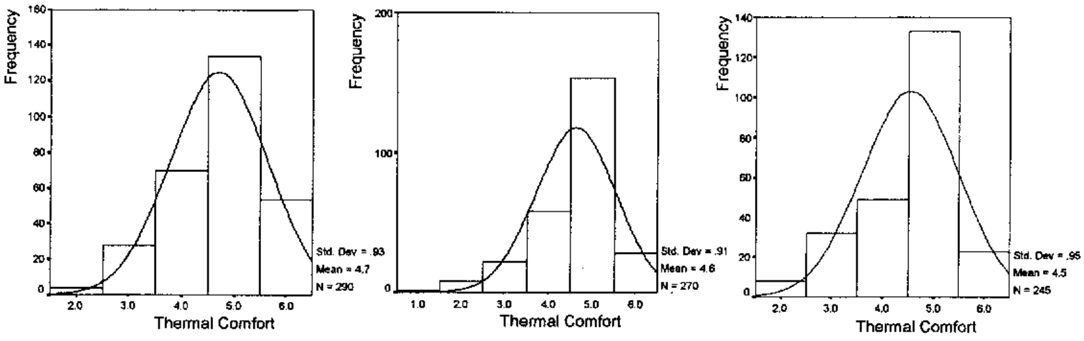
It is noteworthy that the percentage of subjects in each space stating they are comfortable is almost identical for the Thermal Comfort scale (84%-88%). The mean IAT at which it occurs varies across the three spaces by a margin of 2K (23.3°C – 25.3°C), lowest in the Offices and highest in the Atrium. These responses and temperatures, their distribution and range are again compared in a series of plots shown in Figures 6.7 to 6.9.

Figure 6.7 summarises the distribution of occupant response to the Thermal Sensation scale. Figure 6.8 summarises the distribution of occupant response to the Thermal Comfort scale.



Offices **Cafeteria** **Atrium**

Figure 6.7. Response to the Thermal Sensation scale in Offices, Cafeteria and Atrium



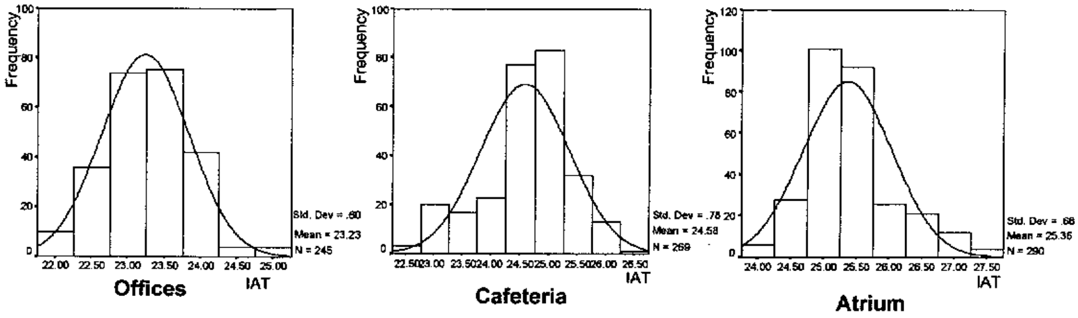
Offices **Cafeteria** **Atrium**

Figures 6.8. Response to the Thermal Comfort scale in Offices, Cafeteria and Atrium

The mean Thermal Sensation response is 3.5 for Offices and Atrium, and 3.6 for Cafeteria. The difference in means across the three spaces was tested using the Kruskal-Wallis test. It yielded χ^2 (2, N=805)=1.469 at p>0.05, suggesting that response was not significantly different (at p<0.05).

The mean Thermal Comfort response is 4.7, 4.6 and 4.5 for Offices, Cafeteria and Atrium respectively. The difference in means, with the Kruskal-Wallis test, yielded results that were not statistical significant (at p<0.05).

A comparison of mean IAT, howver, suggests that the three spaces are significantly different in terms of the thermal condition (see Figure 6.9). The mean temperatures are 23.2°C in the Offices, 24.6°C in the Cafeteria and 25.4°C in the Atrium. A One-Way ANOVA test showed that the difference between these means is highly significant; it yielded F(2, 803)=635.2 at p<0.001.



Figures 6.9. IAT recorded in Offices, Cafeteria and Atrium

These results suggests that whilst occupant response across the three spaces is not significantly different, the thermal condition is different (at p<0.001). In other words occupants in three distinct thermal environments were experiencing similar levels of comfort.

6.2. Energy Impact

6.2.1. Overview

Analysis of Survey 4 data suggests that the three activity zones can be designed with temperature differences amounting to 2K, beginning with the Work zone at 23°C+, followed by Support at 24°C+ and Transit at 25°C+. This present section examines the energy implication of these differences. It does so by re-setting RevH's thermostats while simultaneously monitoring the energy consumed by the building and its chillers.

The exercise lasted three months from May to July 2001 (see Table 6.11), during which daily energy readings were taken. Temperature readings and adjustments were confined to the month of June 2001.

This period of May to July was selected, as it was the first 3-month block available after the analysis of Survey 4 data concluded in February 2001. The intervening period from March to April was deemed inappropriate as it represented a peak period for RevH[1] due to a surge of activity and usage of the building's systems and premises.

Period	Activity	Objective
May 2001	Monitor energy consumption.	Benchmark daily and weekly energy consumption index.
June 2001	Monitor energy consumption. Re-set thermostats for entire building. Adjustments limited to 0.5K (Work) to 1.0K (Support and Transit) per week.	Create three thermal zones.
July 2001	Monitor energy consumption.	Gauge impact of temperature adjustments.

Table 6.11. Overview of energy impact

The temperature adjustments were spread out over a month for two reasons. First, it was deemed necessary that subjects were not exposed to sudden changes in ambient condition. Temperature adjustments were kept to a conservative 0.5K/week in the offices, where changes to ambient temperatures were most likely

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[1] April is the deadline for Singapore tax returns; processing these returns is a key activity of the government department that is the owner-occupant of RevH.

to be noticed. Second, the building's automation system, by which temperatures were controlled, had proven unreliable in Survey 4. It was noted then that any adjustment to the system did not translate to the same on the ground. Every re-setting therefore had to be confirmed with actual readings across the entire building, which slowed the process.

To evaluate the impact of the adjustments, the energy figure for July is compared with that of May. The difference between July and May 2001 is also compared with the same period from the preceding years (see Appendix C6: RevH Energy Figure for the Years 1999 and 2000).

6.2.2. Results and Analysis

Table 6.12 shows a summary of all adjustments made, along with temperatures logged in May and July 2001. The initial thermostat setting for the entire building was a uniform 23.5°C. Actual indoor conditions, however, varied within and between spaces. The most variable were the Atrium and Cafeteria. The high-end temperatures shown for these spaces were short lived, resulting from air seepage and/or occupancy surge[2]. It meant that upward temperature adjustments here had to be conservative.

Another constraint arose from the way the building was designed. Certain Support and Transit spaces - Photocopy Room, Staff Pantry, Store and Lift Lobby - were under the same thermal zone as the Offices. These spaces could not, therefore, be set to temperatures that were different to the Work zone.

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[2] The *Atrium* suffered from air seepage through its entrance doors. This was particularly so during peak period (for instance, lunch hour), when large numbers of people entered or left the building. The *Cafeteria*, meanwhile, experienced a surge of visitors at lunch during which IAT briefly rose to levels above 24°C.

Zone and Prescribed IAT		Original Thermostat Settings (°C)	Initial temperatures logged on-site (°C)	Overall adjustment (K)	Final Temperatures logged on-site (°C)
			Mean (Range) as at May 2001	*June 2001*	*Mean (Range) as at July 2001*
WORK 23°C+	**Offices***	23.5	22.2 (21.8-22.8)	+1.6	23.8 (23.5-24.0)
	Library		22.3 (22.0-22.8)	+1.2	23.5 (23.5)
SUPPORT 24°C+	**Cafeteria**		24.1 (22.5-25.0)	+0.2	24.3 (24.0-24.5)
	Recreation Centre		21.8 (21.0-22.5)	+2.7	24.5 (24.0-25.0)
	Day Care Centre		22.8 (22.5-23.0)	+1.2	24.0 (24.0)
TRANSIT 25°C+	**Atrium**		25.0 (24.0-26.5)	+1.0	26.0 (26.0)

* *This represents a grouping that includes Meeting Room, Photocopy Room, Staff Pantry, Store and Lift Lobby.*

Table 6.12. Adjustments to IAT at RevH

It is significant that the final temperatures arrived at in this exercise were slightly higher than those predicted in Survey 4. The absence of staff complaints, which were monitored closely for this period, suggested that these temperatures were tolerable.

Table 6.13 and 6.14 show the impact of the temperature adjustments on energy consumption. Table 6.13 is a summary of chiller consumption for the months of May and July. The daily chiller consumption index drops by 6.4%, whilst the weekly index drops by some 7.1%.

	Daily* Chiller Consumption Index	Weekly** Chiller Consumption Index
May 2001	19480 kWh/day	124,016 kWh/week
July 2001	18229 kWh/day	115,227kWh/week
Difference July/May readings	-6.4 %	-7.1%

* *This represents the average weekday figure, excluding weekends (Saturdays and Sundays), public holidays and the 1st weekday after a Sunday or public holiday. The latter typically included energy figures for the weekend/holiday that preceded it.*

** *This represents the average weekly figure excluding weeks with public holidays.*

Table 6.13. RevH chiller consumption before and after temperature adjustments

The overall energy consumption drops by 4.6% (see Table 6.14). This figure is compared with May/July figures for preceding years where it was found that consumption, across the two months, typically dropped between 1.7% and 2.9% for period when no adjustments were made to the building's systems/operations. This suggests that the net impact of adjustments made in 2001 lies somewhere between 1.7% to 2.9%, i.e. the 2001 July/May difference minus the 1999 and 2000 differences respectively.

	May Consumption (kWh)	**July Consumption (kWh)**	**Difference July/May**
1999	1,011,820	984,820	-2.9%
2000	1,381,984	1,358,324	-1.7%
2001	1,527,800	1,457,200	-4.6%

Table 6.14. May/July difference in overall RevH consumption for years 1999, 2000 and 2001

6.3.2. Energy Impact

- Temperature resetting in RevH, which resulted in building-wide non-uniformity of up to 2.5K, yielded a drop in chiller consumption of up to 7.1% and in overall consumption of up to 2.9%.

6.3.3. Background and Building Variables

- In the Offices, no background and building variables appear to affect response to any of the scales.
- In the Cafeteria, only the question of whether the subject is a visitor or staff affects response to the McIntyre/Thermal Preference scale.
- In the Atrium, in addition to divergence of Staff and Visitor response, the question of Gender, Age, Race and Time of Day appear to have a bearing on subject response to some scales.

Chapter 7. Discussion

7.0. Preamble

In Chapter 2, it was proposed that this present study would focus on specific questions arising from the literature. These are revisited here in the following order:

- ***The Office Building in Hot Humid Conditions*** (see Section 7.1)
- ***Indoor Variability*** (see Section 7.2)
- ***Comfort*** (see Section 7.3)

Each section begins with a synopsis of its structure and focus, with a reference to the findings that form the basis of its discussions. The chapter ends with a summary of thesis findings and discussions (see Section 7.4).

7.1. The Office Building in Hot Humid Conditions

Chapter 4 yielded findings from on-site surveys that had set out to establish how buildings are designed with regard to the climate (see Section 4.4). These findings, in addition to several from Chapter 5, pertaining to occupant preference for modes (see Section 5.4), are reviewed here, specifically against principles of the Bioclimatic Model for tropical high-rise (Yeang, 1994).

This section has the following headings:

- *Architectural Response to Climate* (see Section 7.1.1) looks at design in terms of form, orientation and envelope
- *Indoor Environment* (see Section 7.1.2) looks at conditions found inside the buildings studied
- *Energy Consumption* (see Section 7.1.3) compares Conventional and Bioclimatic buildings with regard to energy indices
- *Workplace Layout* (see Section 7.1.4) looks at how the design of the workplace affects climate and comfort-related objectives

These are followed by a summary of observations that suggest possible impediments to the adoption of Bioclimatic design principles (see Section 7.1.5).

7.1.1. Architectural Response to Climate

Response to climate is said to occur at several stages of the design process (Hyde, 2000; Rivard, Bedard, Fazio, & Ha, 1995). At the conceptual level it relates to the form, shape and orientation of the building. At the level of detail design it involves decisions about the envelope, i.e. the deployment of external sunshades, choice of materials and WWR.

In Section 4.1.3 it became evident that of the twenty buildings reviewed, none adopted the Bioclimatic approach to shape and orientation. All were essentially Modern or International-styled buildings with crisp geometry and extensive curtain-wall in which the envelope surface was smooth and uninterrupted. Only one building out of the twenty had window recesses and external sunshades. Service cores were frequently at the centre of the building plan. Of the side-placed cores, none appear as if they were intended to act as solar buffers since few faced the hotter elevations. None of the buildings had vertically distributed transitional spaces or landscaping to cool the envelope.

In terms of orientation, most buildings seem to respond to the street grid, frequently in NE-SW axis. This deference to context was carried through to the towers in cases where the building had a tower-podium configuration, where the tower could, in theory, have had an orientation different from that of its podium. For the two buildings that were not constricted by an urban grid, situated in stand-alone sites with maximum freedom, no climatic logic was evident either.

These observations, suggesting an indifference to climate, are consistent with an earlier survey of Southeast Asian cities, most with hot humid conditions like Singapore. In the context of this, and the present Singapore study, there is little or no deployment of sunshades and service cores for solar shading (see Table 7.1).

Study	No. of Buildings/Location	% WWR Mean (Range)	External Shading	Use of Core for Shading
Harrison, Loe and Read 1998[1] *Southeast Asia*	*"Generic"* Southeast Asian Office Building (based on a survey of 15)	*(20-100)	X	X
PRESENT STUDY **Kishnani, 2001** *Singapore*	10 Conventional buildings	43 (14-68)	X *(except for one building)*	X
PRESENT STUDY **Kishnani, 2001** *Malaysia*	2 Bioclimatic buildings	80 (80)	✓	✓ *only E facade*

* There was no mean WWR given in this particular reference.

Table 7.1. Overview of climatic response

Yeang's Bioclimatic buildings in Malaysia, MES and UMNO, reverse this trend with an extensive use of solar control devices, transitional spaces and external landscaping. Their shading strategies seem to allow them the luxury of a higher WWR with greater envelope permeability to daylight and natural ventilation. A closer examination suggests, however, that the principles of Bioclimatic Model have not been rigorously applied.

MES is situated in a stand-alone site where, instead of the optimal N-S facing rectilinear slab, the building adopts a circular plan. Whilst the E elevation is buffered from the morning sun by the service core, the W elevation on certain levels is exposed, often without external shades or transitional spaces. These passive elements, in general, are arranged in a spiral pattern in a manner that appears to have little to do with solar geometry.

With UMNO, the site is narrow, flanked by roads and abutting existing developments, therefore offering much less freedom than the MES site. UMNO has its service core as a buffer to the morning sun, ostensibly also to act as a *party wall* to future developments (van Schaik, 1998). An examination of the rest of the facades shows that this building suffers from conspicuous absence of sunshades on the W-facing elevation. The vertical distribution of transitional spaces here, as in

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[1] MES was one of the 15 buildings surveyed by Harrison et al. (1998).

MES, is inconsistent with solar load. Of the 16 office floors, only 8 have transitional spaces in W-facing orientation.

In both buildings, the failure to address a critical W façade, the periodic absence of sunshades, coupled with a high WWR and single-layer tinted glazing, creates high envelope temperatures, internal hot spots and glare (see Appendices A8 and A9). Thermal conditions are particularly varied and extreme in MES; sunlight penetration is a significant problem in UMNO.

With Conventional buildings from Singapore, further scrutiny of climate response was carried out via OTTV records. A review of 27 buildings and their 125 facades shows, first, that most building façades have a wide range of permeability. Facade thermal transmittance values range from 0 to 69.5 W/m^2 (see Section 4.1.3.2); $WWR_{Façade}$ ranges from 0 to 97.7%. The question that follows is whether climatic logic had been applied in deciding which façade was more permeable and which was less. This ideal relationship between permeability and orientation was presented at the start of Chapter 4 in the form of the Solar Response Spindle (see Section 3.4.1, Figure 3.3).

When mean $OTTV_{Façade}$, $WWR_{Façade}$, TT_F and TT_W were plotted for each of the eight key orientations, it emerged that none of the plots matched the shape of the spindle. This suggests that climate, in terms of solar load, is not a criterion in deciding thermal permeability of the facade. The sole exception to this is the case of $WWR_{Façade}$ on the E and W elevations, where there is a reduction in window size. The $WWR_{Façade}$ for the remaining six orientations was largely undifferentiated in relation to solar load. It was also found that TT_F had no correlation with TT_W, suggesting that there is no relationship between the thermal performance of windows and walls on the same facade.

On the whole, the analysis suggests that climate, in terms of solar load, does not feature significantly at the conceptual or detail design stage. There is some caution with regard to window size, but only for the E and W facades.

7.1.2. Indoor Environment

Of the ten Singapore cases logged for indoor conditions, all were found to be largely AC-reliant. The exceptions to this rule were a single NV entrance foyer and several mechanically ventilated toilets. In general, air-conditioned spaces were found to be on the cool side (see Section 4.2.3) often with air temperatures under the lower statutory limit of 23°C.

In terms of the visual environment, secondary spaces such as Toilets and Lift Lobbies were predominantly active-run, with little access to daylight. This is partly due to the fact that many of the service cores are centrally placed, hence depriving these spaces of access to natural light. Provisions for daylight in side-placed cores were, however, minimal. Cafeterias and Atria had high levels of daylight, but were nevertheless operated with some electrical light. In the Workplace, windows on the perimeter, often large, suggest some intent vis-a-vis daylight. This attempt to admit daylight was, however, negated by occupant behaviour vis-à-vis the blinds and placement of furniture and partitions (see Section 7.1.4). Most offices were heavily reliant on electrical lighting, even in perimeter zones.

The Bioclimatic buildings were designed to be substantially passive-run, particularly in secondary spaces like Toilets and Lift Lobbies. In the case of UMNO, a system of walls and openings was designed for all office floors thereby offering the option for reliance on NV for comfort cooling (Jones & Yeang, 1999). In both buildings, however, the workplace was operated in the active-mode. All-day air conditioning was the norm for all work-related spaces.

These observations suggest that whilst the two Bioclimatic examples differ from the Conventional buildings in terms of *design intent*, there is less difference in terms of *usage* (see Tables 7.2 and 7.3), i.e. the four buildings are less divergent in the way that occupants chose to operate them. This convergence of usage appears to be driven by preference. Occupant preference for air-conditioning, for instance, appears unaffected by the availability of naturally ventilated spaces and NV systems.

Table 7.2 summarises this convergence for the thermal modes. The design of Bioclimatic buildings is different from Conventional buildings in 4 of the 5 spaces logged. In terms of usage, this gap narrows to 2 spaces: Foyer/Atrium and Toilets.

Space	Bioclimatic Buildings		Conventional Buildings
	Design	*Usage*	*Design & Usage*
Workspace	◒/●	●	●
Foyer/Atrium	○/●	○/●	●
Cafeteria	●	●	●
Lift Lobby	○	●	●
Toilets	●/○	●/○	●

● Active-reliant ○ Passive-reliant ◒ Mixed- or multi-mode

●/○ Observations of UMNO and MES respectively

Table 7.2. Design intent vs. usage of thermal modes

Table 7.3 summarises the convergence in the case of visual modes. The Bioclimatic buildings were designed to be different in 3 spaces. In actual usage, this narrows to one: Toilets.

Space	Bioclimatic Buildings		Conventional Buildings	
	Design	*Usage*	*Design & Usage*	
Workspace	◒	●	◒	●
Foyer/Atrium	◒	◒	◒	
Cafeteria	○	◒	◒	
Lift Lobby	○	◒	●	
Toilets	●/○	●/○	●	

● Active-reliant ○ Passive-reliant ◒ Mixed- or multi-mode

●/○ Observations of UMNO and MES respectively

Table 7.3. Design intent vs. usage of visual modes

In MES and UMNO, daylight is abundant in all spaces due to the high WWR (80%), nearly double the average for Conventional buildings (43%). This often results in sunlight penetration in a substantial portion of the office spaces, typically in the afternoon. Due to the severity of the problem, natural light is negated through occupant deployment of blinds or tints, particularly in the workplace. In other spaces, it continues to be used in conjunction with electrical light. This is consistent with findings in Survey 2 (see Appendix B7: Survey 2 Data – Choice of Modes) where it was found that subjects preferred mixed-modes for visual conditions. In the case of thermal modes, user preference is clearly biased towards active-mode reliance, particularly in the workplace. This partly explains why the NV option is never used in UMNO.

In comparing workspace conditions logged in the present study with those from past studies in Southeast Asia (see Table 7.4), it is noteworthy that no examples of natural ventilation are cited for Singapore and Malaysia, unlike studies in Bangkok and Jakarta. It is unclear if the Ismail and Barber (2001) study in Malaysia left out NV buildings by choice or none were found to exist. In the present study, for which the buildings were randomly selected, no examples of passive-run offices were found suggesting that the passive-mode is less prevalent in Singapore.

Study	**Location**	**Number & Mode of Buildings**	**T_a (°C) Mean (Range)**	**RH (%) Mean (Range)**
Busch **1990**	Bangkok, Thailand	4 buildings 2AC, 2NV	AC: 23.7 (19.5 – 31.3) NV: 30.8 (23.5 – 34.2)	-
de Dear, Leow & Foo **1991c**	Singapore	12 buildings All AC	AC: 22.9 (18.3 – 27.8)	AC: 55.5 (35.6 – 74.1)
Karyono **1995b**	Jakarta, Indonesia	7 buildings 5 AC, 1NV, 1AC+NV	AC: (23.0 – 31.0) NV: 30.3 (28.0 – 32.0) AC+NV: 27.0 (24.0 – 31.0)	AC: (52.0 – 75) NV: 72.2 (69 – 79) AC+NV: 70.5 (65.0 – 80.0)
Jikhajornwanich ***et al.* 1998**	Bangkok, Thailand	5 buildings 3 AC, 2NV	AC: 25.0 (23.1 – 27.3) NV: 28.5 (27.3 – 30.0)	AC: 49.0 (38.1 – 59.2) NV: 55.6 (49.8 – 62.9)
Ismail & Barber **2001**	Penang, Malaysia	11 buildings All AC	AC: 23.1 (20.7 – 27.4)	AC: 53.5 (43.6 – 77.6)
PRESENT STUDY **Kishnani** **2001**	Singapore	10 buildings All AC	AC: 22.6 (19.6 – 24.3)	AC: 61.3 (53.0 – 67.0)
PRESENT STUDY **Kishnani** **2001**	Kuala Lumpur and Penang, Malaysia	2 buildings All AC	AC: 24.1 (21.3 – 28.3)	AC: 62.0 (51.0 – 72.0)

Table 7.4. Workplace indoor air temperatures from past and present studies in Southeast Asia.

It is significant that the mean workspace indoor air temperature is the lowest in Singapore at 22.6°C and also operates within the narrowest bandwidth of 2.4K (maximum temperature recorded minus the minimum). The mean found here is similar to the de Dear et al. (1991c) figure of 22.9°C. The bandwidth in that Singapore survey, however, was 9.5K.

The difference in bandwidth between the two studies suggests that AC systems have delivered increased stability and greater uniformity over the passing decade. The low mean temperatures found in the Singapore buildings in the present study, compared with those from other studies in Southeast Asia, suggest a national bias for cooler workplace conditions.

A comparison of workplace illuminance levels from the present study with those from past studies in Singapore shows that the bandwidth of visual conditions has narrowed since the 1980s (see Table 7.5). The lowest illuminance level recorded in earlier studies was 80 Lux (Woods, 1987). In the present study, excluding the Bioclimatic examples, this figure is 130 Lux. The highest level recorded has dropped over the years from 870 (Woods, 1987; Low, 1988) to 670 Lux.

Survey	**Location/ Number of Buildings**	**Illuminance levels (Lux) *Mean (Range)***
Woods 1987	Singapore*	385 (80 - 870)
Low **1988**	Singapore/ 6	**(164 – 870)
Woods 1994	Singapore/ 9	**(259 – 574)
Lim **1999**	Singapore / 14	**(296 – 675)
PRESENT STUDY Kishnani 2001	Singapore / 10 (Conventional)	480 (175 – 670)
PRESENT STUDY Kishnani 2001	Malaysia / 2 (Bioclimatic)	452 (130 – 700)

** The number of buildings was not specified in this study.*
*** The mean illuminance levels were not specified in these studies.*

Table 7.5. Workplace illuminance levels
from past and present studies in Singapore

It is possible that this narrowing of illuminance bandwidths is due to the introduction of statutory guidelines in 1979 that specified lighting levels at the workplace should be between 300 - 700 Lux, with a recommended value of 500 Lux (PWD, 1983). The earlier surveys by Woods (1987) and Low (1988) are likely to have included buildings that were designed prior to the introduction of this requirement, thereby showing up deviations from the code. All of the 10 buildings in the present Singapore survey were completed in the 1990s, which may account for the mean illuminance of 480 Lux.

It is noteworthy that the two Bioclimatic buildings, despite significantly higher WWR (see Table 7.1), actually operate at the same level of illuminance as the Conventional buildings. Active logging of MES and UMNO suggest that illuminance levels across the day do not vary much (see Appendix A8 and A9). Occupant interventions, in the form of tints and blinds, have dampened workplace illuminance, bringing it down to levels that match those found in Conventional buildings. In the passive mode, however, illuminance levels in the Bioclimatic buildings reached an excess of 10,000 Lux for UMNO and 5,600 Lux for MES.

7.1.3. Energy Consumption

Of the four buildings surveyed, the two Bioclimatic buildings consume an equivalent or greater amount of energy than the two Conventional buildings (see Figure 7.1).

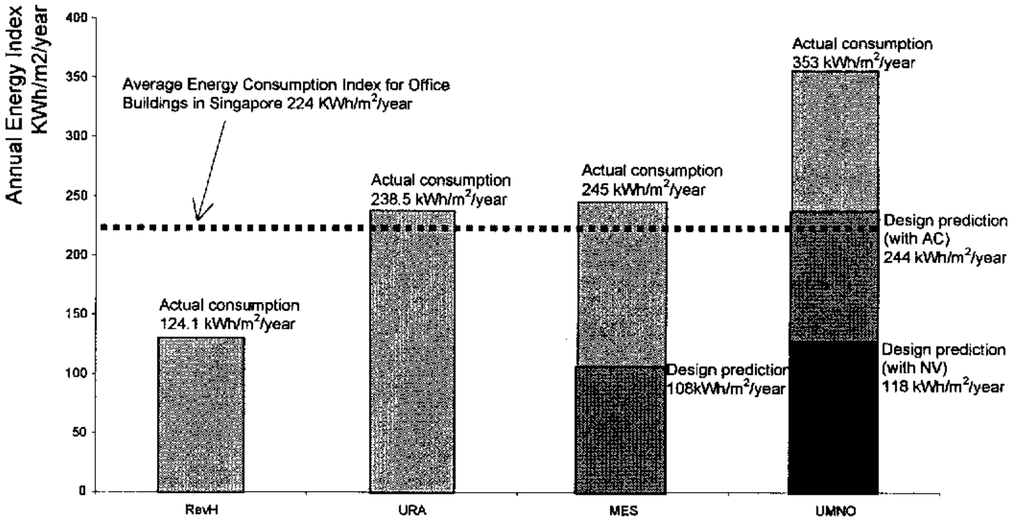

Figure 7.1. Annual energy index for the 4 buildings for the Year 1999

It is possible that a Bioclimatic building that is designed to rely on NV may consume more energy than projected when it is operated as an AC building (as was the case with UMNO). Air tightness might not have been a design consideration in such a building. This would have the effect of reducing the efficacy of its reliance on AC. It is also noteworthy that neither of the Bioclimatic buildings applies the principles of solar geometry with consistency and rigour. This probably exacerbates the heat load with which their AC systems must reckon.

It should be said, however, that a building's energy consumption is a composite index that embodies the efficacy of its electro-mechanical systems and their usage. In the absence of detailed information on these systems, the difference between the four buildings must be viewed with caution.

The more critical comparison is that of the *predicted consumption* of the building and its *actual consumption* after completion. It points to how well a building performs in relation to what was predicted by its designers and engineers. It suggests interventions by the occupant who may have negated energy saving features or failed to use others as the designers intended. This comparison is possible only for the Bioclimatic buildings where, in both cases, published figures are available from the design stage. For MES, consumption had been expected to average at 107.8 kWh/m^2/year (Yeang, 1992); for UMNO, it was expected to be 244 kWh/m^2/year with AC and 118 kWh/m^2/year with NV (Yeang, 1998a). In 1999, MES consumed 245 kWh/m^2/year whilst UMNO consumed an estimated 353 kWh/m^2/year.

It is likely that this gap between design prediction and usage is due, in part, to occupant behaviour vis-a-vis passive features and modes. In both UMNO and MES, for instance, reliance on natural light was a key design consideration. In actual usage there is virtually no reliance on daylight; occupants generally opt for electrical or mixed light sources instead. These lights are often switched on, even in secondary spaces like the toilets where daylight is available in abundance. In UMNO, the workspace is operated exclusively with AC even though provisions were made for comfort cooling via NV.

The question of light alone does not explain the gap between design prediction and actual usage, which in the case of UMNO amounts to a 70% increase. In all probability the Bioclimatic buildings are poor performers because of the AC systems have to cope with poor air tightness and high solar loads.

7.1.4. Workplace Layout

In the ten Singapore buildings studied, several consistencies emerge in terms of the interior layout. High partitions are commonly found around the plan periphery where they reach heights of up to 1.7m or extend from floor to ceiling. Low partitions, 1.2m height and less, are common at the plan centre (see Appendix A3: Summary of 10 buildings surveyed for indoor conditions). This pattern appears to relate with staff seniority and activity; senior staff and meeting rooms are typically situated in the outer zone, whilst junior staff and clerical activities, for instance, photocopying and filing, are situated in the inner zone (see Figure 7.2).

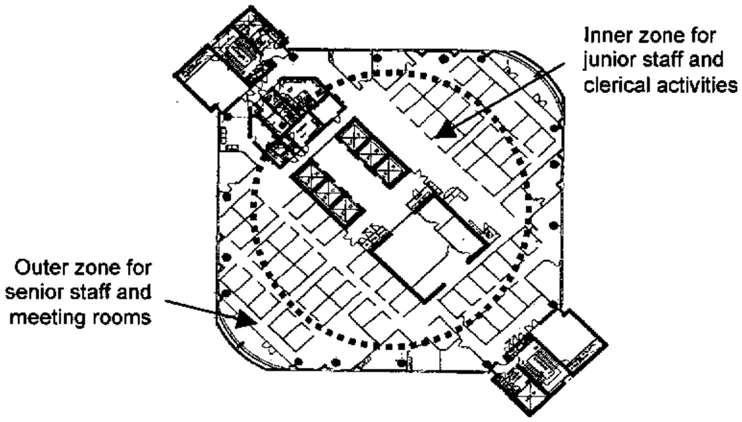

Figure 7.2. Plan from RevH illustrating internal layout criterion

The deployment of higher partitions at the plan periphery poses an obstacle to reliance on passive modes, particularly daylight. Natural light levels, highest near the envelope, drop significantly towards the plan centre partly because of shadows cast by the higher partitions. Occupants seated near the envelope have 'ownership' of windows, and often choose to keep the blinds closed all day due to glare and/or thermal discomfort.

With NV, the distribution of air speed between centre and perimeter logged in passive mode (see Section 4.2.3.4) suggests also that furniture and partition placement is likely to impede passive-reliance. This is clearly illustrated with UMNO. Figure 7.3 compares the airflow pattern that occurs on an unoccupied floor, without any furniture or partitions, with the layout of an occupied floor. It is evident that the question of NV is fundamentally at odds with the way offices space are organised. The only space on this floor that might conceivably have functioned with NV is the lift lobby.

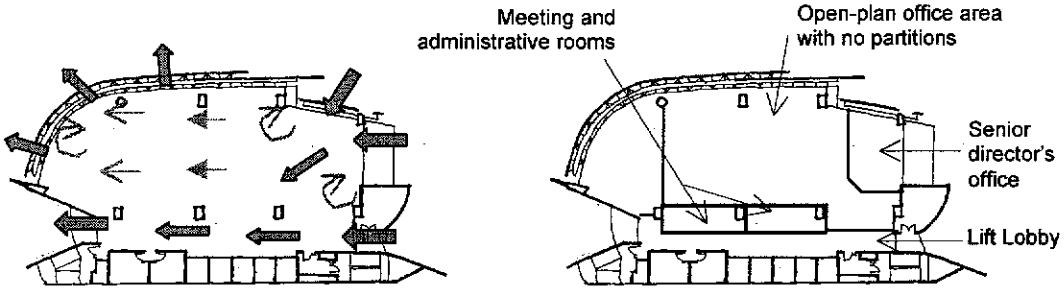

Figure 7.3. UMNO airflow pattern through an unoccupied floor
and the partitioned layout of an occupied floor.

Internal partitions, observed in all buildings, facilitate visual and acoustical privacy and enforce security. The prerequisites for passive-reliance seem to intersect, and conflict, with these needs.

A detailed exploration of the workplace culture is beyond the framework of this present study. Observations of the Singapore buildings visited, however, suggest that within Duffy's (1997) taxonomy of office types, the Singapore workplace is a hybrid of the Hive and Cell (see Figure 7.4). Furniture and partition placement appears largely to be driven by hierarchy and status; individual allocation of space predominates over shared spaces; occupants *'own'* their workstation full-time. Whilst reliance on IT is evident, computers are generally desk-bound PCs that are linked to mainframe systems, as opposed to laptops that are mobile.

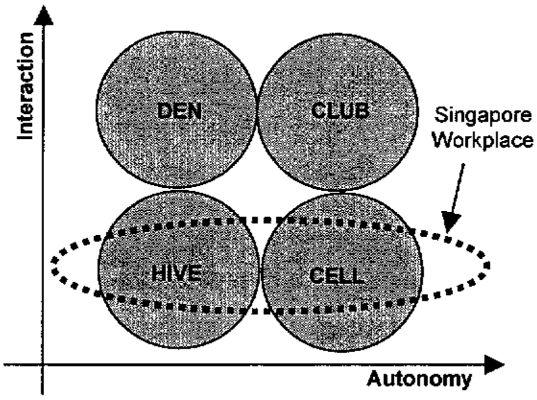

Figure 7.4. The Singapore office space according to Duffy's taxonomy

In the Hive and Cell office, occupants are generally bound to their workplace and therefore immobile for a significant portion of the day. It is likely that the occupant's inability to move away from zones of discomfort creates a preference for stable and uniform conditions.

The importance of organisational and national culture in the design of workplace cannot be underestimated. Van Meel (2000) argued that even in Europe, there are different national and organisation cultures, hence, approaches to office design. It is likely that this is also true for the Asian workplace, although no studies found address this directly.

The organisational culture found in Singapore suggests that ideas of the *New Office* (Duffy, 1997) and *Fresh Air Architecture* (Hartkopf et al., 1993; Shepard et al., 1995) advocated for office buildings in cooler climates in the West, must be critically evaluated in the East. This is particularly so where conditions are hot and humid and where internal layouts, reflecting organisational or national values, do not facilitate the unimpeded movement of air and light.

7.1.5. The Office Building in Hot Humid Conditions: *Impediments to Bioclimatic Design*

Findings from the present study suggest there are several obstacles to the integration of climate with the design of office buildings in Singapore:

- *Occupant preference* for active modes
- *Internal layouts* that obstruct light and air distribution
- *Architect's bias* towards aesthetics

Occupant Preference

Data on user-preference shows that given a choice, occupants of office buildings surveyed opt for active modes at the workplace (see Section 5.2.2.2). This is especially so for the thermal environment in which AC was preferred by 98% of all surveyed (see Appendix B7: Survey 2 Data – Choice of Modes). In terms of the visual condition, workplace preference lies with electrical light with some natural light - a predominantly active-mode. The prevalence of active modes in the buildings logged (see Chapter 4) suggests that user preference and indoor conditions reflect each other, perhaps even reinforce the other.

In Singapore, there are no known recent surveys that simply ask people what they prefer in terms of comfort conditions at the workplace. This premise of occupant preference is also not sufficiently explored in the arguments for the Bioclimatic Model. Two observations in Bioclimatic buildings challenge assumptions about user-preference. First, occupants do not deploy NV in the UMNO workplace; second, transitional spaces in both buildings are almost never used (except by smokers). The issue of NV reinforces feedback in Survey 2, in which the strong preference for AC in the workplace was expressed. Transitional spaces were not used because, said the occupants, they were unacceptable as extensions to the workspace.

In a sense, survey findings and observations highlight the role of the occupant. They challenge the passive paradigm and physiology-based premise of comfort and its application to hot humid conditions.

Coldicutt, Williamson and Penny (1991) argued that in designing for comfort, it is important not to be biased by *"any existing unbalanced body of thermal response knowledge, some of which implicitly emphasises climatic attributes at the expense of built and human environmental attributes"* (p. 90). The fact that the occupants of MES and UMNO do not opt for passive modes, or use transitional spaces, suggests that the designers of these buildings misjudge what workplace occupants want in terms of comfort or what they are prepared to tolerate.

Internal Layout

The second impediment to the use of passive modes is the impact of organisational culture on the layout of offices. The new IT-driven workplace, heralded by Duffy (1997), appears not to be prevalent in Singapore as yet. Designers who advocate passive reliance do not seem to take into account the fact that these spaces will ultimately be divided by way of partitions and furniture systems.

In the literature on UMNO, for instance, it has never been suggested how the NV option would be reconciled with the presence of internal partitions. Yeang has argued that in providing the NV option to its tenants, he has offered them a choice of modes for different times of the day (Khosla, 2000c). The question that emerges is, 'how meaningful is this choice in the context of leased office space such as in UMNO?' The present study has shown that the open-plan office, which allows breezes to waft through and daylight to penetrate its depths, is an unlikely scenario in an owner-occupied setting, much less in a commercial context where tenant preference often takes precedence over design intent.

Aesthetic Bias

The third obstacle is the issue of architectural aesthetics. The observation supporting this is the prevalence of Modern and International Styles in the case of the twenty Singapore buildings, almost all of which appear to be climate rejecting. This stylistic bias incorporates planar geometry, extensive curtain-walling, and seems at odds with the 'clutter' of the external sunshades, transitional spaces and vertical landscaping implicit in the Bioclimatic Model.

Lam, Chan and Li (2000), who studied office buildings in Hong Kong that were built over a 50-year period, found that envelope design was primarily an issue of style.

By the 1990's the curtain-wall aesthetic of the International style had become so prevalent that it resulted in higher OTTV due to the increased use of glass and presence of windows.

Style, as a perceptual construct, has also been argued by Wilson (1990) who showed that as a group, architects are taught from the start of their training to regard a building in terms of style, sometimes *"to the exclusion of function or the likely experience of their users."* (p. 449).

Past studies have commented on the role of style in Yeang's approach. It has been suggested that his Bioclimatic buildings grew out of the Regionalist sentiment and continued to exhibit a conflict between style and performance (Jahnkassim, 1998; Kishnani, 1999). Ahmed (2000), for instance, showed that MES did not go far enough in its strategy of service core placement. Had the core been West-facing, instead of East-facing, the building would have had energy savings amounting to 7.8%. In this present study, it was noted that the spiral arrangement of MES' passive solar features is not consistent with the sun's path. It is difficult to explain the absence of sunshades on MES' and UMNO's W facades. Had the sun's path been the design reference, sunshades and transitional spaces of MES would all have been W-facing, rather than the floor-to-floor variability that one encounters. It is likely that these represent aesthetic choices, rather than climatic ones.

It should be said, however, that the shortcomings of these buildings do not represent a failure of the Bioclimatic Model as such. The present study shows that passive precepts and features, where applied in a manner consistent with the climate, reduce envelope surface and indoor temperatures (see Section 4.3.3.1). There is in these buildings a failure to apply these same principles consistently. There is also reluctance on the part of the occupants to use these buildings in a passive mode, as the designer had hoped.

7.2 Indoor Variability

Findings from Chapter 4 on passive and active logging (see Section 4.4.3) are discussed here, along with those from Chapter 5 that pertain to occupant perception of the variable environment (see Section 5.4).

This section on indoor variability has the following headings:

- *Envelope Performance* (see Section 7.2.1) looks at the role of the building skin in the making of indoor variability
- *Perimeter vs. Centre* (see Section 7.2.2) delineates the plan according to ambient conditions, with distance from the envelope
- *Perception of Variability* (see Section 7.2.3) asks the questions of where and how variability is perceived by building occupants

These are followed by a review of the question of the stable, uniform environment (see Section 7.2.4).

7.2.1. Envelope Performance

The discussion of indoor variability begins with a review of a key component in the building-climate interface: the envelope. In its role as environmental filter, it should be a selective barrier, admitting natural light and, in a hot climate, minimising heat flow into the building.

Envelope permeability is critical to the question of indoor variability; higher permeability implies higher indoor variability, largely because indoor conditions are freer to fluctuate with diurnal, weather-related and seasonal changes. It has been found in the present study that in this dynamic interplay, passive features and envelope attributes play an important role.

Before discussing indoor variability per se, it is instructive to review findings on passive features and attributes. Table 7.6 summarises several texts in the literature that have advocated the importance of the same four passive features and strategies monitored in the present study: orientation, solar shades, material attributes and transitional spaces.

The consensus of past and present studies is that passive features and attributes make a significant impact in the hot climates. Highlighted in the table are principal performance measures for each study, along with specific areas of emphases.

<table>
<tr><th>Study</th><th>Orientation</th><th>Solar Shades</th><th>Material Attributes</th><th>Transitional Spaces</th><th>Measure of Performance</th></tr>
<tr><td>Olgyay (1963)</td><td>✓</td><td>✓
Colour is important: lighter shades give better solar protection than darker shades.</td><td>✓
Glass has significantly higher heat transmission levels than other materials.
This makes windows more critical, than either walls or roofs, in terms of solar load.</td><td>Not Reviewed</td><td>Heat transmission Btu/ft^2 (W/m^2)</td></tr>
<tr><td>Givoni (1969)</td><td>✓</td><td>✓
Iterates importance of colour. Argues that with efficient shading, it is possible to eliminate more than 90% of the heating effects of solar radiation.</td><td>✓
Colour is important to heat transmission; darker colors result in higher indoor surface temperatures.</td><td>Not Reviewed</td><td>External and internal surface temperatures, plus indoor air temperature.</td></tr>
<tr><td>Daniels (1997)</td><td>✓</td><td>✓
Comparison of room air temperatures using different types of shades. Difference between worst and best case sunshade equals 10K.</td><td>✓</td><td>✓</td><td>Indoor air temperature.</td></tr>
<tr><td>Rao (1999)</td><td>Not Reviewed</td><td>Not Reviewed</td><td>✓
Compares four glass types of different colour and shading coefficients.</td><td>Not Reviewed</td><td>Internal surface temperature and energy consumption.</td></tr>
<tr><td rowspan="2">PRESENT STUDY Kishnani (2001)</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td colspan="5">Internal envelope temperature and indoor air and mean radiant temperatures logged at varying distance from the envelope. Each feature and attribute found to be significant in terms of its impact on surface and internal conditions. The best case combination of envelope features/attributes compared with worst case results in conditions that are 17.4K difference in envelope temperatures (MES) and up to 7.5K difference in indoor temperatures (UMNO). Poor passive design results in internal hotspots next to facades with high surface temperatures.</td></tr>
</table>

Table 7.6. Past and present studies on passive envelope features and attributes

It is noteworthy that EST, particularly of the inside face of window glazing, is an oft-used means of gauging envelope transmittance. In the present study, it was found that windows, more than walls, are sensitive to the variability of the climate, reaching surface temperatures far higher than outdoor air temperatures (see Section 4.3.2). It was also shown that the amplitude of EST_{Glass} can be traced directly to incident solar radiation on the glass surface, and that it affects indoor air temperature, particularly in the perimeter zone. The presence of passive features and strategies play a key role in the outcome of EST.

EST_{Glass} results from present and past studies are summarised in Table 7.7.

Study	Context and Approach	EST_{Glass} Range	Other parameters and outcomes
Rao (1999)	Laboratory - based study and energy simulations for 4 glass types in Singapore climate.	35°C- 47°C The worst performer was a glazing with solar film. Best performer was a double-glazed low-emissivity system.	External surface temperatures rise as high as 55°C. Energy difference of 20% for cooling spaces with worst- and best-case glass options.
Lyons, Arasteh and Huizenga (2000)	Computation of surface temperatures for 10 glass types in summer and winter conditions.	23.9°C – 37.3°C (for summer conditions in which outdoor conditions were assumed to be in excess of 30°C) Worst performer was single glazed panel with bronze tint. Best performer was single glazed clear.	Direct insolation at 45° incidence: 168 – 641 W/m^2 Worst performer was single-layer clear glass. Best performer was a high performance window with low U value and solar heat gain coefficient.
PRESENT STUDY Kishnani (2001) *Singapore*	Logging of indoor envelope surface and indoor temperatures for three Conventional office buildings in Singapore.	26.2°C – 40°C	Highest indoor temperatures recorded in passive mode in perimeter zone: IAT: 29.4°C MRT: 29.0°C*
PRESENT STUDY Kishnani (2001) *Malaysia*	Logging of surface and indoor temperatures for two Bioclimatic office buildings in Malaysia.	31.2°C – 50.0°C	Highest indoor temperatures recorded in passive mode up to 4 m from envelope: IAT: 38.5°C MRT: 41.2°C

** MRT loggers were situated from 4m mark onwards. The first IAT logger was 1m from the envelope. This might explain why IAT, in this instance, is higher than MRT.*

Table 7.7. Past and present studies involving envelope surface temperatures

The bandwidth of EST in the Lyon et al (2000) study is similar to that of Singapore buildings from the present study. The Rao (1999) study is closer to the bandwidth of the Bioclimatic buildings. These collectively suggest EST_{Glass} is useful as a gauge of envelope performance, one that offers an index for the combined effect of passive features, strategies and attributes. The overall EST range - 23.9°C to 50°C - represents best- and worst-case performance in hot conditions.

In the present study, for which the buildings exhibited temperatures both at the high and low end of the scale, it was found that with an optimal combination of passive features and attributes, EST_{Glass} stayed below 30°C. Table 7.8 summarises the highs and lows of the four buildings logged.

	Max. EST_{Glass} (°C)	Time of Day/Orientation	Shade/Exposure
Coolest Facades			
RevH	28.4	2:30PM/ NE	Shade = orientation + time of day/year
URA	26.2	2-4PM/N	Shade = orientation + time of day/year
MES	32.6	4-6PM/S	Shade = orientation + transitional space
UMNO	31.2	4:30-6PM/NE	Shade = orientation + time of day/year + transitional space
Warmest Facades			
RevH	40.0	11AM/NE	Exposure = orientation + time of day/year
URA	38.5	9:30AM/E	Exposure = orientation + time of day + external sunshades
MES	50.0	4:30PM/W	Exposure = orientation + time of day
UMNO	>41.3*	6PM/W	Exposure = orientation + time of day/year

** Upper limit of the temperature logger used in this particular instance.*

Table 7.8. EST_{Glass} in relation to passive features and strategies

The first observation here is that the Conventional buildings do better than the Bioclimatic on both counts of the coolest and warmest facades. The second observation is that passive features are most affected by poor orientation, as is the case with URA's E-facing wall, which reaches highs of 38.5°C in the early morning, despite the presence of setbacks and external sunshades. Where poor choice of orientation is combined with the absence of solar features, however, temperatures can reach 50°C, as with MES' W-facing facades.

Two cautionary notes on comparing ESTs across buildings:

- It was not possible to account for the role of AC on ESTs. Simultaneous passive and active logging of EST_{Glass} in UMNO showed that AC can cause envelope glass to be 1.6K cooler during the day (see Section 4.3.3.4). All readings shown here were taken in active mode. It is not possible to argue, however, that the cooling system of one building, perhaps more robust than another, did not affect EST to a greater degree.
- ESTs of each building will reflect the weather for the period that it was logged. These conditions will invariably differ with location and period of logging. A summary of outdoor DBT for each building is shown in Appendix A5 (Summary of Weather for Period of Logging).

7.2.2. Perimeter vs. Centre

In the design of AC systems, it is commonly suggested that the floor plan should be delineated into perimeter and centre zones, the former affected by its exposure to the building's skin load (Parlour, 1990). Chen, Kamimura and Watanabe (1999) further suggest that AC systems should compensate for conditions on the plan periphery:

> *Skin load is the main contributor to changes in the thermal environment of the perimeter zone, and if skin load can be measured, the air temperature of the perimeter zone could be equalised with that of the interior zone by imposing a heat load equivalent of the skin load on the perimeter zone's air conditioner.*
>
> Chen, Kamimura and Watanabe (1999, p. 80)

They propose using radiant temperature sensors as a means of gauging EST_{Glass}. By accounting for skin load, the cooling system might be designed to actively balance the difference between perimeter and centre, using variable airflow to create stable and uniform conditions. Hyde (2000) took this dual-zone idea a step further when he suggested that the outer zone should be designated as passive-run, the centre as active-run.

Table 7.9 summarises readings in the passive modes taken at regular intervals, up to 16 m from the envelope.

	Temperature Gradients (K) Drop in temperature from perimeter to inner zone		**Air Movement (m/s)** Maximum air speeds recorded		**Illuminance (Lux)** Drop in illuminance from perimeter to inner zone	**Relative Humidity (%)**
	IAT	**MRT**	**Perimeter**	**Centre**		
RevH	1.9	-	> 5.0	2.0	1800 - <100	Minimal differences of between plus/minus 1-2% across the floor plan
URA	0.6	0.6	Not available		Not available	
MES	3.3	3.8	3.0	0.5	5600 - <100	
UMNO	7.4	-	5.0	1.0	>10,000 - <100	

Table 7.9. Periphery vs. centre readings for 4 buildings (passive mode)

The first observation is that the perimeter zone, predictably, has more air movement and natural light. The second is that it also has higher temperatures, which are particularly pronounced in the Bioclimatic buildings.

Hyde's bimodal approach may, in theory, work for RevH, which has gentle temperature gradients and high perimeter air speeds. The steep gradients in MES and UMNO, however, are less likely to be offset by the air speeds recorded in their perimeter zones.

In Section 4.3.3.3 the active-mode data suggested that the electro-mechanical systems dampen these temperature gradients without actually eliminating them. The IAT gradient in URA, for instance, drops from 0.6K in passive state to 0.4K in the active. In RevH, the S half on the whole is 1.7K warmer than the N half, due to the latter being in perpetual shade for the time of year. The impact of the envelope on the perimeter is most evident in the case of MES where hotspots occur at the same locations where EST_{Glass} is at its highest. The perimeter temperatures in UMNO are even more pronounced, with a gradient of 7.4K. Even though no matching active readings were possible, it is unlikely that this difference between perimeter and centre could have been eliminated.

Given the connectivity of indoor conditions and envelope temperatures, the perimeter zone is not just one where higher temperatures and illuminance levels exist; it is also one where there is likely to be greater amplitude in the variability. The extent to which conditions fluctuate will depend on the envelope's permeability vis-à-vis passive features, strategies and WWR. The perimeter zone is therefore in a dynamic state, largely dependent on envelope design and climate (see Figure 7.5).

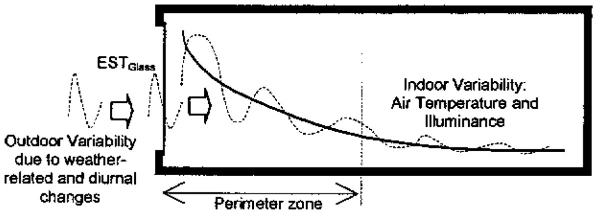

Figure 7.5. Ambient highs and amplitudes of change in the perimeter zone

7.2.3. Perception of Variability

Elder and Tibott (1981) found that thermal dissatisfaction related with variability, typically in the perimeter zones where occupants experienced changes in the ambient conditions as a result of their proximity to an envelope. In the present study, the most compelling evidence that indoor variability is perceived by, and matters to, the occupants of office buildings is the emergence of *Control/Consistency* as a comfort criterion in Section 5.2.3. This will be covered in greater depth in Section 7.3 in the discussions on comfort expectations.

In this section, response from Surveys 1, 3 and 4 is reviewed in the context of:

- *Response to variability* itself.
- Difference between response of those in the *perimeter* zone and those at the plan *centre.*
- Perception of, and behaviour towards, *environmental controls.*

Response to variability

Response to variability is inferred from the longitudinal study (Survey 4) in Chapter 6 in which three floors of RevH were monitored and surveyed. Table 7.10 summarises occupant feedback to the thermal acceptability, preference and comfort scales, alongside two indicators of thermal variability. These indicators are AM/PM difference and the IAT range plus bandwidth during the first week of the study, when no adjustments were made to the thermostats.

	Occupant Perception			**Thermal Variability for 1st Week**	
	Acceptable *(% vote)*	**No Change** *(% vote)*	**Comfort** *(mean vote)*	**AM/PM Maximum Temperature Difference** *(K)*	**Range (°C) and Bandwidth of Temperatures (K) across the week**
L3	94.4	70.8	4.6	0.5	22.0 – 24.5 (2.5)
L19	94.7	72.9	4.7	0.5	22.0 – 24.0 (2.0)
L23	81.7	60.0	4.4	1.5	21.0 – 24.2 (3.2)

Table 7.10. Thermal comfort and amplitude of indoor variability at 3 office floors in RevH (Survey 4)

L23 stands out amongst the three floors surveyed because it had the most variable temperatures[2]. The range of temperatures logged for the first week showed a bandwidth of 3.2K; the difference between morning and afternoon readings had a margin of up to1.5K.

L23 also has the worst score in terms of occupant response to the various scales. It received the lowest percentage of those who voted 'Acceptable' (81.7%) and 'No Change' (60%), plus the lowest mean comfort vote (4.4).

---

[2] It is not clear why this particular floor exhibits greater variability than the other two. The building's operators were not able to explain the anomaly. It could be due to a mechanical problem related with the performance of its AC air-handling unit.

The dissatisfaction with the thermal condition on L23 could, arguably, be due to more than variability alone. Environmental or occupant-related factors may have affected comfort levels as well. Table 7.11 suggests that differences in this regard were fairly minimal, not enough to explain the level of dissatisfaction in L23.

	Mean IAT (°C)	Mean (Range) Relative Humidity (%)	Air Speed Range (m/s)	Mean Clothing Insulation (Clo)	Mean Metabolic Rate (Met)
L3	23.2	59 (53-65)	Low to Negligible 0.25 – 0.05	0.53	1.36
L19	23.3	57 (45-67)		0.54	1.33
L23	22.9	55 (49-67)		0.52	1.46

Table 7.11. Thermal comfort variables at 3 offices floors in RevH (Survey 4)

It is suggested here that the discomfort on L23 is most likely due to its indoor variability.

On the question of which extraneous factors cause variability, subjects in Survey 1 stated that their perception varied with time of day (AM/PM) and weather (sunny vs. rainy). Data from the Chapter 4 support these claims with observations of diurnal and weather-related fluctuations in EST and IAT in all buildings (see Section 4.3.3.2).

Perimeter vs. Centre

While the difference between perimeter and centre conditions is evident, the data are silent on whether perception of comfort actually varies with location, i.e. if an occupant situated closer to the envelope is likely to respond differently than one further away. The difference between the response of the two groups to thermal scales was found not to be statistically significant. This may either have been a Type II statistical error, in that the rating scales do not pick up the degree of difference experienced by the occupants, or that the thermal gradients are masked by the AC system.

A difference between the groups' response emerges only on the question of light. Those near the envelope acknowledged that they experienced higher and more variable levels of light, and also expressed a wish for less variability.

Environmental Control

On the question of environment control, findings from Surveys 1 and 2 suggest that control options, where available, are rarely utilised. Critically, satisfaction with control appears not to relate to availability of control itself; it relates instead with thermal comfort and satisfaction with light (see Section 5.1.3.5). This suggests that in speaking of *control*, subjects may be really speaking of the *controlled* environment. If a building delivers acceptable conditions, occupants appear satisfied with environmental controls. This is notably different from arguments cited in the literature on the intrinsic value of environmental controls themselves (Pacuik, 1989).

It is conceivable that this interaction is partly a cultural issue. George (2000) suggested that in the broader socio-political context of Singapore, the individual surrenders control in exchange for comfort. This 'surrender', if applicable to design, would suggest that in creating control systems, a designer should ask if occupants of the building are prepared to participate in the day-to-day management of comfort. User interventions, such as MES' tints, seem to strive for conditions that are predictable, requiring little subsequent management. The design of NV in UMNO and task lights in RevH, however, both relied on frequent user involvement in management of indoor conditions. They may have failed partly because occupants prefer that the buildings do the job of providing general conditions of comfort.

7.2.4. Indoor Variability: *The Myth of the Stable, Uniform Environment*

At the height of the 1970s energy crisis, Wyon (1973) challenged the notion and necessity for an engineered solution for a stable, unchanging environment.

> *It is commonly assumed that room temperatures should be constant for a given activity, and a great deal of expense is incurred in attempting to achieve this. In fact, surprisingly large temperature swings are tolerable and for some activities, may even be desirable. The technical ability to control indoor temperatures has led, over a period of years to increasingly high indoor temperatures in the developed [cold] countries. This is expensive and consequently [will] lead to a number of undesirable effects, among them a marked reduction in the width of the subjectively tolerated comfort zone... In the hot countries, the trend is in the opposite direction and is even more expensive.*
>
> Wyon (1973, p. 39)

Findings from the present study concur with Wyon's argument on several counts. First, the need for a constant environment is an engineering assumption, and a costly one at that. In Section 6.2, it was shown that a modest 2K+ variation in temperature across RevH resulted in energy savings of up to 2.9%.

Second, familiarity with cooler temperatures and narrower bandwidths may create a subjective preference for the same. Data from the office buildings surveyed (see Tables 7.4 and 7.5) suggest that Singapore has one of the coolest workplaces in Southeast Asia, one that has, over the years, operated within increasingly narrower bandwidths of temperature and illuminance.

The questions asked by Wyon in 1973 are applicable today: *Is uniformity necessary? Does activity play a role in determining acceptance of variability?* The answers, it is suggested here, will depend on comfort expectations. These will be dealt with in Section 7.3.1.

7.3 Comfort

The discussion in this section draws on findings on occupant response to thermal and visual conditions, as summarised in Section 5.4 and Section 6.3.

This section on comfort has the following headings:

- *Comfort Expectations* (see Section 7.3.1) which discusses findings from Survey 2, as supported by past and present surveys.
- *Thermal Comfort* (see Section 7.3.2) focuses specifically on findings from Surveys 1, 2 and 4, looking at how findings here compare with thermal comfort studies in other climates and building types.
- *Visual Comfort* (see Section 7.3.3) focuses on findings from Surveys 1 and 2, looking at how response to the visual condition differs from, or relates with, response to the thermal.

These are followed by the question of how comfort can vary with mode and activity, seeking to define a framework for acceptability (see Section 7.3.4).

7.3.1. Comfort Expectations

De Dear (1993) suggested that the cognitive nature of expectations is critical to the adaptive model of thermal comfort. This question of expectations has been explored in the present study through the use of Multiple Sorting Procedure (Survey 2), data from which was subsequently analysed using three tools: Content Analysis, Multidimensional Scaling Analysis and Multiple Scalogram Analysis. The results from these analyses are summarised in Table 7.12 in terms of the comfort criteria that emerged.

	Content Analysis	**Multidimensional Scaling (MDS) Analysis**	**Multiple Scalogram Analysis (MSA)**
Thermal Comfort	• Activity • Duration/Frequency of Use • Consistency/Control • Health/Hygiene • Openness • Comfort • Image	• Activity • Consistency/Control • Health/Hygiene • Privacy	No emergent criteria
Visual Comfort		• Activity • Consistency/Control	Building (Acclimatisation)

Table 7.12. Results from Survey 2

In Sections 7.3.1.1 and 7.3.1.2, this list is divided into primary and secondary criteria, on the basis of the frequency with which they were cited by subjects and their outcome in more than one mode of analysis.

7.3.1.1. Primary Criteria

Activity

Activity is the most frequently cited criterion for comfort. Through MDS analysis it was found that it might be used to divide an office building into three broad zones: Work, Support and Transit. It was noted that these groupings are near identical to those which emerged from the criterion of *Duration/Frequency of Use,* suggesting that the two criteria might represent the same perceptual dimension.

The criterion of *Activity* supports the arguments of Wyon (1973) who coupled thermal comfort with *performance.* In the present study, subjects speak of comfort-modes as facilitating either *Concentration* or *Relaxation*, which parallels Wyon's theory of arousal in which the environment is seen to promote a state of mind that can influence performance.

It was also found in the present study that in the Work zone, the need for comfort is deemed more important and less open to compromise than in other zone. Ninety-eight percent of all surveyed opted for AC in the workspace in the first sort and chose not to move it in the second (see Appendix B7: Survey 2 Data – Choice of Modes). This may be due to the fact that in the Work zone, subjects are typically assigned to a particular workstation and often do not have the option to move away in the event of discomfort. AC is also seen to deliver higher levels of personal comfort (see *Comfort* criterion in Section 7.3.1.2).

In a related set of responses from Survey 1, subjects seemed more accepting of cooler sensations than warm ones (see Section 5.1.3.2). This may be because cooler conditions, within the temperature bandwidths logged, were easier to deal with via adaptive behaviour. This was affirmed by the fact that 'putting on a jacket' was cited as the most common adaptive response (see Section 5.1.2.3, Table 5.6). It is noteworthy that Wyon's (1973) suggested that cooler conditions are more likely to promote arousal that improves performance.

The criterion of Activity is also supported by findings from Surveys 3 and 4. In Survey 3, it was observed that the deployment of solar tints in MES concurred with activity zones identified in Survey 2; darker tints were used for windows in the Work zone, light or no tints in Support and Transit zones (see Section 5.3.2.7). In Survey 4 it was found that the three zones could each be operated at different indoor air temperatures without sacrificing thermal comfort. This was interpreted to mean that occupant response could vary, on the basis of location and activity.

It should be noted that literature on workplace performance differentiates between types of activity, for instance, administrative versus creative, each assumed to require different conditions (Stone & Irvine, 1994). The data from the present study, however, do not facilitate analysis on this, as most subjects surveyed were engaged in administrative work.

Consistency/Control

In Section 7.2, it was suggested that occupant perception of variability in the workspace can lead to dissatisfaction and discomfort. Findings from Survey 2 further suggest that in the Support and Transit zones, indoor variability becomes a matter of preference. These two sets of findings suggest that acceptance of the variable environment increases from work to support to transit zones. This shift from tolerance to preference might be because variability is associated with *Connectivity with Outdoors*. Changing light levels and natural breezes, whilst a distraction in the workspace, seem desirable in other zones because they promote a sense of *Relaxation*.

It is noteworthy that the criterion of *Consistency/Control* is cited predominantly in the context of visual modes, less so for thermal modes. This may be because natural light levels can change suddenly in the course of a day. Shifting cloud cover can rapidly alter conditions indoors and may, therefore, be perceived as a distraction.

7.3.1.2. Secondary Criteria

Health/Hygiene

The issue of workplace health in past studies is typically cited with regard to heating and cooling systems and their perceived role in sick building syndrome (Sensharma, Woods, & Goodwin, 1998). In the present study, however, health/hygiene is cited in the context of secondary spaces such as the toilets and gymnasium, expressed as a preference for NV. This appears to be a concern with the presence of odour and perspiration, with which AC is deemed to be less capable of dealing.

This finding appears to relate with concerns cited by Fry and Drew (1956) who noted that heat and humidity of the tropics promote decay and fungal growth. In their prescriptions for the hot humid climate, they advocate caution with regard to areas associated with food and wetness. Feedback from the present study supports this concern, in areas such as the pantry and cafeteria.

These findings challenge the assumption that NV in Southeast Asia is likely to be preferred in the workspace for the same European concerns over sick building syndrome (Jones & Yeang, 1999). Conversely, it supports the Bioclimatic principle of placing service spaces, such as toilets and pantry, in side-situated cores where they can be naturally ventilated.

It is noteworthy that the choice of visual modes is not cited as a health concern in the present study. In past studies, this has been the case particularly with regard to natural light (Phillips, 1975; Swarbrick, 1953). Many of these past studies, however, were set in therapeutic environments, such as hospitals, where health was likely to have been more of an issue (Keep et al., 1980; Ulrich, 1984).

Openness

The criterion of *Openness* is commonly cited for visual modes along with *Connectivity with Outdoors*, suggesting that it concerns envelope permeability, i.e. the degree to which light is permitted into the building and view is permitted out.

Comfort

This criterion is cited almost exclusively in the context of AC suggesting that this mode represents a *higher degree* or *better type* of comfort than passive or mixed-mode alternatives. In Survey 2, subjects were asked to address this specific question of type versus degree. Data from this question are inconclusive (see Section 5.2.2.2, Table 5.11); the frequency with which *Type* is cited is no different from *Degree*, with both thermal and visual mode options.

It is suggested here that this may represent an inherent duality in the nature of comfort. In an active-run environment, the ambient condition may be viewed as a question of degree. A change in, say, air temperature affects occupant sensation and comfort proportionately. Between modes, however, the difference may be a question of type, for which separate bandwidths of acceptability apply. This would be consistent with findings from other studies carried out in hot climates where it was found that occupants in NV settings can be as comfortable as those in AC settings (Nicol, 2000).

Past and present studies may, in fact, suggest that the adaptive model is an inter-modal exploration of comfort, whilst the heat-balance model addresses the mechanics of intra-modal perception.

Image

Even though *Image* emerged low in the frequency-rankings of the sorts (see Section 5.2.3.1) and could not be supported by MDS analyses, it is a noteworthy criterion because it suggests that comfort is, at least partly, a cultural issue. In the present study, this emerged primarily as a matter of corporate culture. Active modes, AC and EL, were preferred because they projected a favorable image of the organisation.

Supporting this idea of corporate influence is the observation of attire in Survey 3. In MES, ties were worn by male occupants, whilst jackets were worn by women in this and several other buildings. The women who wore a jacket were typically in managerial positions. This relates with past studies and observations on attire at the workplace (Brager & de Dear, 2001) and underscores the point that comfort is partly, at least, a lifestyle choice, as opposed to an exclusively physiological response.

Privacy

The criterion of Privacy is distinguished from others cited here in that it did not emerge first through content analysis. Its inclusion in MDS analysis related to an earlier study that had relied on MSP, in which it emerged as a key construct (Kraemer, 1995).

In environmental psychology, privacy is defined as *"an interpersonal boundary by which people regulate interactions with others"* (Bell, Greene, Fisher and Baum, 1996, p. 276). It is typically discussed in the context of visual and acoustical conditions (Bell et al. 1996), as an extension to arguments about Personal Space (Veitch and Arkkelin, 1995). Bell et al. speak of *"privacy gradients"* (p. 459) in the context of the home, suggesting that visitor access will depend on how well s/he is known to its occupant. In the present study, *Privacy* emerges as a gradient in MDS thermal plots, but not for visual plots.

The MDS plot shows gradations from public to private, beginning with the atrium and lift lobby at one end of the plot (see Section 5.2.3.3, Figure 5.9). This is followed by a series of spaces with limited visitor access: auditorium, cafeteria and meeting room. Beyond the *limit of visitor access* are the staff spaces, starting with shared facilities such as the gymnasium, library, photocopy room and toilets, and ending with the most private of staff areas, the day-care centre[3]. This implies that an office building can be divided into public and private domains, the latter typically associated with transit spaces.

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[3] Day care centres in Singapore office buildings are typically for children of staff who work in the building, particularly in the case of owner-occupied, government buildings such as RevH and MND. It is arguably the most private of staff areas as it is accessible only to staff who have placed their children in the centre's care.

It is noteworthy that in this context, an individual's workstation is midway in the plot, just past the limit of visitor access. This suggests that a workplace may be viewed as only partly private, perhaps a culture-driven view of privacy at the workplace.

Acclimatisation

Acclimatisation is often cited in the context of thermal comfort at the 'macro' level of climate, whereby one becomes acclimatised after a period of exposure to a particular set of conditions (Oseland and Humphreys, 1994). It is notable, therefore, that in the context of the present study, it emerges as a factor at the 'micro' level, in which the 'building' acts as a variable affecting response of its population. This was found to be the case with visual comfort, but not with thermal.

In the MSA plot for visual sorts (see Section 5.2.3.3), subjects from MND are partitioned from those from other buildings. Within the latter grouping, subjects from MES emerge as a subset. These groupings suggest that expectations of visual comfort are affected by the building, or more specifically, by the conditions found in the building. If so, this might explain why, with the combined population of the five buildings, there is no correlation of response to visual scales with illuminance levels recorded (see Appendix B3: Regressions for Data from Survey 1).

7.3.2. Thermal Comfort

Findings from Surveys 1 and 4 are discussed under three headings:

- *Context and Comfort* (see Section 7.3.2.1) compares present study with findings from past studies in Southeast Asia, plus other climate and building settings.
- *Activity Criterion* (see Section 7.3.2.2) here asks if the Survey 4 findings represent a clear affirmation of this comfort criterion.
- *Bioclimatic Performance* (see Section 7.3.2.3) gauges the success of the Bioclimatic building in terms of comfort response, as per findings from Survey 1.

7.3.2.1. Context and Comfort

Thermal comfort has been studied in terms of occupant response to varying contexts and settings (Oseland and Humphreys, 1994; Nicol, 2000). Typically, two measures of response are extracted from the analysis of response to various rating scales: Neutral Temperature (T_N) and Acceptability. The former has been defined in Chapter 2 as the temperature at which occupants are most likely to respond 'Neutral' on the ASHRAE scale (see Section 2.3.1). The latter is less clearly defined and is often inferred from a range of scales and analyses. It may, for instance, be expressed as a temperature or a range of temperatures at which subjects express a preference for 'No Change' on the McIntyre scale (Busch, 1990; Ismail & Barber, 2001).

Neutrality and acceptability, as parameters of thermal response, can offer insights into the nature of comfort when they are compared across settings and with each other. This may be about how response is influenced by the setting or in terms of the relationship between the perception of sensation and comfort.

In the present study, two rating scales yielded results of statistical significance: Thermal Sensation (ASHRAE) and Thermal Comfort. From these, T_N and T_{Opt} were extracted as indicators of thermal neutrality and acceptability respectively (see Section 5.1.3.2). The results from Surveys 1 and 4 are summarised in Table 7.13. This table also presents findings from past studies carried out in the hot humid context of Southeast Asia which cover a range of settings: building type (workplace versus residential), operational mode (AC versus NV) and study condition (climate chamber versus fieldwork).

Study Author, Year and *Country*	Method	Setting	Number/ Ethnicity of Subjects	Thermal Rating Scales	Outcome(°C)
Ellis **1953** ***Singapore***	Field Study	NV Homes, Offices and University premises	175/ Chinese, Malay, Indian, Ceylonese, Eurasian, Caucasian	Bedford Scale	22.0 – 25.5 ET^* (24.5 – 27.8 T_a)
Webb **1959** ***Singapore***	Field Study	NV Homes and Offices	20/ Chinese, Malay, Indian, Eurasian, Caucasian	Bedford Scale	26.2 ET^*
Busch **1990** ***Bangkok, Thailand***	Field Study	2 AC and 2 NV Office Buildings	1146/ Thai	ASHRAE & McIntyre Scales	Neutral Temperature: 24.7 ET^* (AC) 27.4 ET^* (NV) 25.0 ET^* (Combined Sample) Acceptability: 22.0-28.0 ET^* (AC) N/A-31.0 ET^* (NV) 22.0-30.5 ET^* (Combined Sample)
De Dear, Leow and Ameen **1990a** ***Singapore***	Climate Chamber		32/ Singaporean	ASHRAE & McIntyre Scales	Neutral Temperature: 25.4 T_a
De Dear, Leow and Ameen **1990b** ***Singapore***	Climate Chamber		98/ Singaporean	ASHRAE, 4-point Comfort Scale and 2-point Acceptability Scales	Neutral Temperature (Upper limit): 27.6 T_a (with 70% RH) 27.9 T_a (with 35% RH)
De Dear, Leow and Foo **1991c** ***Singapore***	Field Study	12 AC Office Buildings and 4 NV Residential Blocks	818/ Singaporean	ASHRAE & McIntyre Scales	*Office Buildings* Neutral Temperature: 24.2 T_a (AC) *Residential Blocks* Neutral Temperature: 28.5 T_a (NV)
Karyono **1995b** ***Jakarta, Indonesia***	Field Study	5 AC, 1 NV and 1 AC+NV Office Buildings	596/ Indonesian	ASHRAE Scale	Neutral Temperature: 26.4T_a 26.7T_o 25.3T_{eq} } Combined Sample
Jitkhajornwanich, Pitts and Malama **1998** ***Bangkok, Thailand***	Field Study	Transitional Spaces: Indoor AC and Outdoor NV	593/ Thai	ASHRAE, McIntyre and Expectation Scales	Neutral Temperature: 27.1T_a Acceptability: 25.5 – 31.5 T_a } Combined Sample
Ismail and Barber **2001** ***Penang, Malaysia***	Field Study	11 AC Office Buildings	501/ Malay, Chinese, Indian, Eurasian	ASHRAE & McIntyre Scales	Neutral Temperature: 24.6 T_a (AC) Acceptability: 20.3 – 28.9 T_a
PRESENT STUDY **Kishnani** **2001 (Survey 1)** ***Singapore and Kuala Lumpur, Malaysia***	Field Study	5 AC Office Buildings (including 1 Bioclimatic building and 1 Training Institute with an office floor)	109/ Malay, Chinese, Indian	ASHRAE & 6-point Comfort Scale	Neutral Temperature: 24.3 T_a (AC) Acceptability (T_{Opt}): 23.2 T_a
PRESENT STUDY **Kishnani** **2001 (Survey 4)** ***Singapore***	Field Study	1 AC Office Building (with 3 Activity Zones)	1024**/ Malay, Chinese, Indian, Eurasian	ASHRAE, 6-point Comfort, McIntyre & 2-point Acceptability Scales	*Work* (AC) Neutral Temperature: 24.5 T_a, 25.1ET^* Acceptability(T_{Opt}): 23.0 T_a Indoor/Outdoor Link = 4.7K *Support* (AC) Neutral Temperature: 26.3 T_a, 26.5 ET^* Acceptability (T_{Opt}): 24.2 T_a 24.9 ET^* *Transit* (AC) Neutral Temperature: Undefined Acceptability (T_{Opt}): 25.3 T_a 26.2 ET^* Indoor/Outdoor Link = 2.5K

*** This figure includes subjects who were surveyed more than once.*

T_a – Air Temperature; T_o – Operative Temperature; T_{eq} – Equivalent Temperature; ET^* - Effective Temperature

Table 7.13. Thermal comfort studies in Southeast Asia

The Air Conditioned Workplace in Southeast Asia

In the present study, T_N at the AC workplace was found to be 24.3°C in Survey 1 and 24.5°C in Survey 4. This concurs with findings from two past studies involving AC office buildings. De Dear et al. (1991c) found T_N of 24.2°C in Singapore office buildings. Ismail and Barber (2001) found T_N of 24.6°C in the Malaysian office building. In the Busch (1990) study in Bangkok, T_N occurred at 24.7ET*, which is comparable with the finding of 25.1ET* in the present study.

Acceptability, in the present study, was found to occur at T_{Opt} of 23.0°C (T_a) in Survey 4. Survey 1 had a slightly higher value of 23.3°C. In Survey 1, it was also noted that temperatures above 25°C solicited a response of warm discomfort. This condition is assumed to represent the upper limit of acceptability. In the Busch (1990) and Ismail and Barber (2001) studies, acceptability had an upper limit of 28ET* and 28.9°C (T_a) respectively. This suggests that in Singapore, there may be a lower temperature threshold for warm discomfort.

Influence of Setting

In Table 7.13, several studies suggest that subject response can differ with setting. The Busch (1990) study, for instance, shows that the difference between AC and NV offices in Bangkok amounts to 2.7K in terms of T_N. The de Dear et al (1991c) study suggests that the difference office and residential settings in Singapore can amount to 4.3K, again in terms of T_N. Another study by de Dear et al (1991a) shows that T_N for a Singapore sample in climate chamber is 25.4°C, straddling the values found in homes and offices (28.5°C and 24.2°C respectively).

The present study adds to this list of settings the criterion of Activity; three zones within the context of a single building. In Survey 4 these were shown to have a difference of 2.3K in terms of T_{Opt} (across all zones) and 1.8K in terms of T_N (Work and Support). Whilst T_N also yielded a regression of significance with the combined population sample, T_{Opt} did not, suggesting that the perception of comfort was related to location, as per activity-zone. None of the other studies show a similar divergence of outcomes across AC spaces found within the same building.

Sensation and Comfort

In the present study the gap between T_N and T_{Opt} amounts to 1.1K in Survey 1 and 1.5K in Survey 4, comfort occurring at temperatures below neutrality. This is similar to findings by Chan, et al (1998) and Cena and de Dear (1999), who found a difference of 1K for summer conditions (see Table 7.14). This asymmetry between sensation and comfort is attributed to the fact that *"a population who commonly experience excessive heat would usually express a preference for cool sensation... equivalent to up to a degree in room temperature"* (Humphreys, personal communication, June 25, 2001).

Study **Author, Year and** ***Country***	**Climate**	**No. of Subjects/ Buildings**	**Thermal Rating Scales**	**Outcome (°C)**
Schiller **1990** ***San Francisco, USA***	Temperate	304/ 10 Buildings	ASHRAE & 6-point Comfort Scales	Neutral Temperature: 22.0 ET^* (winter) 22.6 ET^* (summer)
Chan, Burnett, de Dear and Ng **1995** ***Hong Kong, SAR, China***	Subtropical	2173/ 13 Buildings	ASHRAE & McIntyre Scales	Neutral Temperature: 21.5 T_o (winter) 23.5 T_o (summer) Acceptability (Preferred Temperature): 20.8 T_o (winter) 22.5 T_o (summer)
Cena and de Dear **1999** ***Kalgoorlie Australia***	Hot Arid	935/ 22 Buildings	ASHRAE & McIntyre Scales	Neutral Temperature: 20.3 T_o (winter) 23.3 T_o (summer) Acceptability (Preferred Temperature) 22.2 T_o (winter) 22.3 T_o (summer)
PRESENT STUDY **Kishnani** **2001** ***Singapore and Malaysia***	Hot Humid	Survey1: 109/ 5 Buildings Survey 2: 1024/ 1 Building	ASHRAE & McIntyre Scales ASHRAE, 6-point Comfort, McIntyre & 2-point Acceptability Scales	Survey 1: Neutral Temperature: 24.3 T_a Acceptability: 23.2 T_{Opt} Survey 2: Neutral Temperature: 24.5 T_a, 25.1 ET^* Acceptability: 23.3 T_{Opt}

T_a – Air Temperature; T_o – Operative Temperature; ET^* - Effective Temperature

Table 7.14. Thermal comfort studies at the workplace in different climates

In cooler conditions, for example, winter, the reverse was found to be the case. Cena and de Dear noted that acceptability was 1.9K higher than neutrality. In the Chan et al. study during a Hong Kong winter, however, the reversal is not confirmed; comfort takes place at temperatures below neutrality, with a gap of 0.7K.

On the whole, studies in Table 7.14 suggest that the relationship between sensation and comfort is not static; that it may vary with seasons and climates. Furthermore, the temperature bandwidth within which comfort occurs is not evenly distributed on either side of T_N. The difference between T_N and Acceptability in warm conditions suggests that people prefer sensations on the cool side of neutral, a fact supported by Surveys 1 and 4 of the present study.

On the difference between sensation and comfort, the present study has also noted that sensation is sensitive to small changes in temperature, whilst comfort is less so. This is inferred from the fact that data from Survey 4 yielded strong regressions for response to the thermal sensation scale at ¼ degree bins; the thermal comfort scale regressions yielded no regressions at the same interval but did so at ½ degree bins. This might be explained by the fact that comfort often involves adaptive response, such as consumption of drink or change to activity level. This would imply that whilst a change in air temperature is perceived in terms of thermal sensation, it might not equally affect thermal comfort.

7.3.2.2. Activity Criterion

Nicol and Humphreys (2001) suggest that acclimatisation and adaptive behaviour affect response, bringing subject response in line with mean indoor air temperature of the space in question. If this were argued in the context of findings from Survey 4, it would undermine the idea that differences between T_N and T_{Opt} across the three zones reflect expectations based on the criterion of activity. Table 7.15 summarises the differences in subject response, as well as three variables that reflect adaptive response and acclimatisation.

	Work *(Offices)*	**Support** *(Cafeteria)*	**Transit** *(Atrium)*
T_N *(T_a - °C)*	24.5	26.3	Undefined
T_{Opt} *(T_a - °C)*	23.0	24.6	25.3
Adaptive Response 1 - Clothing Insulation *Mean Clo*	0.54	0.55	0.56
Adaptive Response 2 - Metabolic Rate *Mean Met*	1.36	1.47	1.68
Acclimatisation - Percentage of population that has had contact with outdoors in preceding half hour	0	50	75

Table 7.15. Adaptive variables and exposure time for Survey 4

In testing the possible effects of adaptive response, the maximum and minimum mean values for Clo and Met rates were keyed into the Human Heat Balance calculator (de Dear, 2001). This was to determine the temperature difference that would result in the same thermal sensation in two subjects with different clothing and met rates. It was found that the combined effect of the differences in Clo and Met would require a 1K difference to produce the same thermal sensation. The study, however, has shown an identical response to a 1.8K difference in T_N (Work and Support) and a 2.3K difference in T_{Opt} (Work and Transit). This suggests that clothing insulation and activity levels alone do not explain the difference in occupant response across the three zones.

In terms of acclimatisation, it could be argued that only those who had been in the space for some time before being surveyed could have adjusted their comfort response to existing conditions. This could not have been the case in the cafeteria and atrium where subjects were mostly passing through or visiting for short periods. It is unlikely therefore that they had pegged their comfort to conditions to which they had been exposed for periods of less than ½ hour.

Furthermore, if acclimatisation to thermal condition existed, it would be possible to partition the MSA thermal plot according to population groups from the five buildings. This was, however, not the case (see Appendix B9: Survey 2 Analysis – MSA Thermal Plot). The combined population of the same 5 buildings in Survey 1 instead yielded strong regressions which suggests that the groups were not acclimatised to conditions found within any one building.

7.3.2.3. Bioclimatic Performance

In comparing the four Conventional buildings with Bioclimatic, it emerges that MES' mean thermal sensation response is highest at 4.2 (between Neutral and Slightly Warm), thermal comfort is lowest at 4.1 (just above Slightly Comfortable) and the percentage of occupant's feeling uncomfortable is the highest at 29.2%. The percentage experiencing warm sensations is also highest at 37.5%.

The findings from Survey 1 suggest that MES is thermally, least comfortable of the five buildings (see Table 7.16).

	Conventional				Bioclimatic
	RevH	**URA**	**MND**	**CSC**	**MES**
Indoor Air Temperature (°C)* *Mean (Range)*	22.5 (21.0-23.5)	23.3 (22.0-24.5)	23.8 (23.0-25.0)	22.9 (22.0-23.5)	24.7 (22.0-26.5)
Mean Thermal Sensation *(in general)*	2.8	3.5	3.9	3.5	4.2
Mean Thermal Comfort *(in general)*	-	4.8	4.8	4.4	4.1
Percentage of subjects expressing thermal discomfort (%) *(Slightly Uncomfortable to Very Uncomfortable)*	-	0.0	15.0	20.0	29.2
Percentage of subjects feeling slightly warm or worse on Thermal Sensation scale (%)	0.3	4.8	25.0	15.0	37.5
Percentage of subjects equating daylight with thermal comfort (%)	-	28.6	30.0	10.0	45.8

** Temperatures shown here are summaries of readings taken at the end of each survey.*

Table 7.16. Thermal conditions/comfort in Conventional and Bioclimatic buildings

Whilst these responses are consistent with higher air temperatures found in MES, it is noteworthy that the perceived link between presence of natural light and the sensation of warmth is highest in MES, with 45.8% saying the link exists. This is despite the fact that this particular building does not stand out in terms of illuminance levels (see Table 7.17). It is possible that occupants associate brighter days with hotter conditions indoors.

7.3.2.4. Methodological notes

ET* and SET* indices used in the present study yielded no significant results. This is not new to thermal comfort studies; Raw and Oseland (1993) pointed out that the estimation of Clo and Met, both of which factor into SET*, is difficult, at best. Oseland and Humphreys (1994) added that thermal radiation and air movement, which factor into ET* and SET*, are problematic to estimate in terms of their impact on the human body. They suggest that simpler indices, such as IAT, often relate better with occupant response. This has been the case in the present study.

With regard to the McIntyre and Acceptability scales, the absence of significant results cannot be easily explained. It may be that these scales, in particular

Acceptability, operate across temperature bandwidths wider than were experienced by subjects. In this regard, Survey 4 was constrained by RevH's manager who capped a limit on discomfort. High-end of temperatures, which resulted in complaints from staff or visitors, could not be sustained for more than one day at a time. It was therefore not possible to collate a sample of responses at temperatures at which sufficient numbers voted 'Unacceptable' on the Acceptability question.

7.3.3. Visual Comfort

Unlike the relationship between IAT and occupant response to thermal scales, Survey 1 does not show a link between illuminance levels and response to visual scales (see Appendix B3: Regressions for data from Survey 1). Findings from Survey 2 suggest that this may, in part, be due to acclimatisation, i.e. that occupant expectations are pegged to the visual condition they are most familiar with, in terms of the building that they work within.

Elder and Tibott (1981) in a two-stage post-occupancy evaluation of an office building found that satisfaction with light increased over time. Their first interview was conducted when the building was newly opened. Eight months later, during the second interview, they found that satisfaction had increased by 11%, to a high of 73%, even though no adjustments had been made in the interim period to the lighting system. This is consistent with the present study, in which satisfaction with light was consistently high. Ninety-seven percent of all surveyed stated they were satisfied with illuminance ranging from 130-720 Lux, across buildings that were between 1 to (almost) 30 years old (CSC and MND respectively).

Elder and Tibott also noted that whilst there was a strong preference for some daylight in the workplace (95%), the majority opted for a combination of daylight and electrical light (70%), as opposed to total reliance on either. Findings from the present study are consistent with this. In the sorting tasks of Survey 2, it was found that preference for mixed-mode ranked highly for workspace at 80% (see Appendix B7: Survey 2 Data – Choice of Modes). It should be noted that the conditions with which subjects were satisfied were predominantly EL with a small amount of daylight, often amounting to less than 100 Lux. This suggests that in speaking of a mix of the two light sources, subjects refer to a mode that is predominantly active.

Finally, it was noted thermal comfort relates with overall light intensity, i.e. the combined illuminance from electrical and natural sources. No correlation was found to exist between thermal comfort and the perceived level of natural light. The latter would have been the more logical outcome, on the assumption that higher levels of natural light might relate with increased sensations of warmth. It is possible, however, that the link between thermal comfort and overall light intensity is a qualitative issue, not covered by the data here. In the present study, no information on the qualitative attributes of lighting, such as colour and warmth, were collated.

On the question of how well the Bioclimatic building performs vis-à-vis visual comfort, the summary of visual conditions and occupant response (see Table 7.17) suggests that it does not stand out against the Conventional buildings on any score.

	Conventional				**Bioclimatic**
	RevH	**URA**	**MND**	**CSC**	**MES**
Illuminance level (Lux) *(Mean/Range)*	358 (240-600)	574 (300-750)	451 (250-720)	320 (235-523)	367 (130-540)
Overall Perception of Light *(Mean)*	3.9	4.0	3.9	4.0	3.9
Perception of Natural Light *(Mean)*	2.3	2.9	2.4	2.7	2.4
Preference for Natural Light *(% voting for No Change)*	25	81	50	65	50
Overall Satisfaction with Light *(Mean)*	-	4.7	4.8	5.2	5.0

Table 7.17. Illuminance and occupant response in Survey 1

On most rating scales, in fact, no one building stands out despite clear differences in illuminance levels. The sole exception to this is Preference for Natural Light, for which RevH scores a low 25% wanting 'No Change' and URA scores 81% voting the same. The overall consistency of response, particularly with regard to Satisfaction with Light, might be reflective of acclimatisation mentioned earlier.

7.3.4. Comfort: *Defining Acceptability through Design*

The present study has found that the perception of comfort is activity-based. This is contrary to the current design approach to active modes, which strives for uniformity and consistency across all spaces within a building. The present study has further found that perception of sensation, comfort and variability may vary in relation to each other and in terms of the bandwidths of conditions deemed acceptable in each activity-zone. Figure 7.6 summarises present findings in support of the adaptive model. It is a representation of orthodox thermal comfort theory against an activity-based comfort structure for an office building.

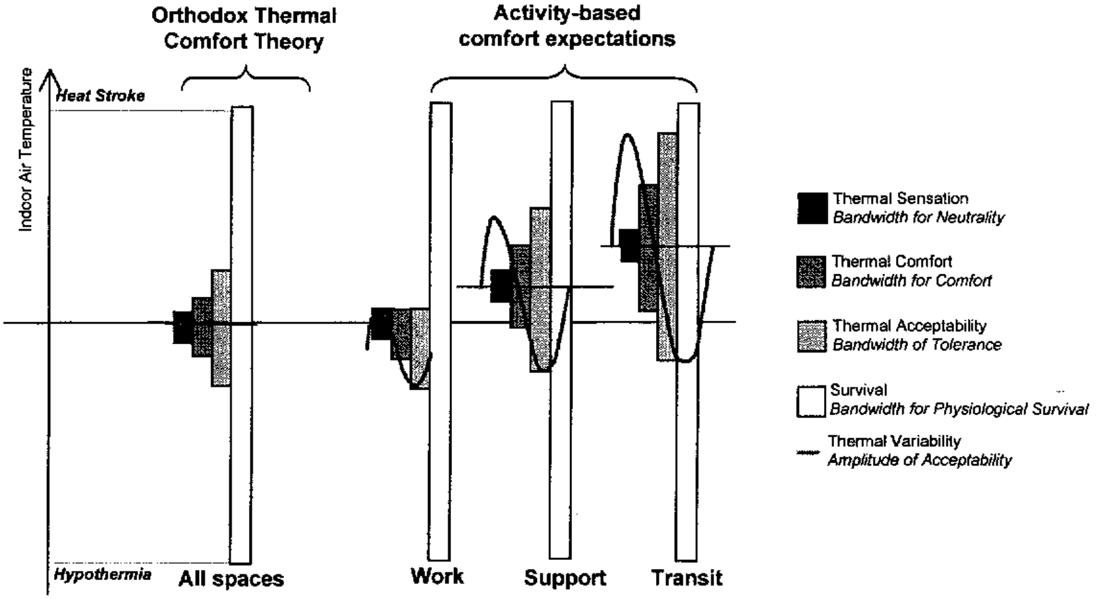
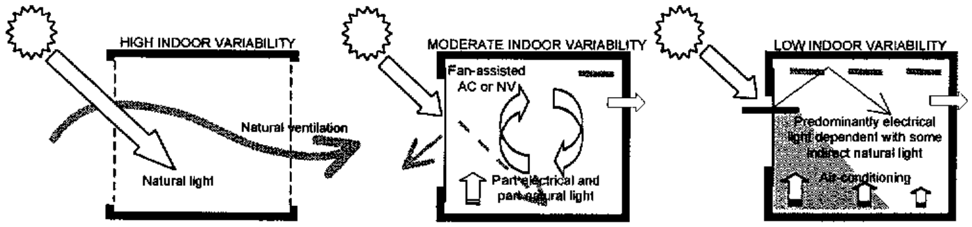


Figure 7.6. Thermal comfort expectations in Singapore office buildings

It suggests that acceptance for thermal variability increases from Work to Support to Transit zones. In orthodox comfort theory, the three descriptors of thermal response - sensation, comfort and acceptability - are assumed to be narrow, symmetrical and centred around the perception of thermal sensation. The present study suggests that this relationship widens in the Support and Transit zones, where higher air temperatures are deemed acceptable along with drifts within wider bandwidths. In the Work zone, however, the relationship is confirmed to be narrow and biased towards cooler sensations. From this relationship between the parameters of comfort (variability, perception, comfort and acceptability), a matrix emerges that translates findings from the present study into prescriptive guidelines.

Table 7.18 summarises these prescriptions, based on results from the sorts summarised in Appendix B7 (Survey 2 Data – Choice of Modes). Mode options are presented here for activity zone. In each cell of the matrix, a recommendation is made, based on occupant response to thermal and visual sorts. Implicit in the assignment of mode to zone is acceptance of indoor variability, plus the comfort criteria summarised in Section 7.3.1.



	PASSIVE	MIXED	ACTIVE
WORK	**Thermal: Unacceptable** Except store, which is acceptable in either passive or mixed-mode. **Visual: Unacceptable**	**Thermal: Unacceptable** Except photocopy room. **Visual: Acceptable** Mixed-mode is acceptable in some work-related spaces such as library.	**Thermal: Preferred** Air-conditioning set point at 23.0 - 23.5°C. Indoor variability should be kept down to plus/minus 1K. Perimeter zone needs to be kept cool and shaded, with EST_{Glass} below 30°C. **Visual: Preferred.** Optimal illuminance level appears to be 500 Lux, ideally in combination with some indirect natural light making up the ambient condition.
SUPPORT	**Thermal: Unacceptable** Except toilet, which is acceptable in the passive or mixed-modes. **Visual: Preferred** Natural light is preferred in some spaces, such as staff pantry and lounge, cafeteria and gymnasium, where it is seen to promote a sense of relaxation.	**Thermal: Acceptable** Fan-assisted ventilation preferred in some areas for reasons of health and hygiene (pantry, gymnasium and cafeteria). In other spaces, for instance, day care centre and staff lounge, the option exists for fan-assisted AC, with higher set points. **Visual: Acceptable**	**Thermal: Preferred** **Visual: Acceptable**
TRANSIT	**Thermal: Acceptable** Indoor acceptability of natural ventilation is pegged to outdoor conditions; optimal condition involves indoor air temperatures that are 2-3K lower than the prevalent outdoor condition. **Visual: Preferred** Natural light is preferred for its connectivity with outdoors.	**Thermal: Acceptable** **Visual: Acceptable**	**Thermal: Preferred** Except in the context of the fire-escape stairs. **Visual: Acceptable**

Table 7.18. Relationship of modes to activity zones

7.4. Summary of Key Findings and Discussions

Before reviewing the present study for its implications on design and theory, the discussions from this chapter are summarised as follows:

Office Building in Hot Humid Conditions

- The principles of the Bioclimatic Model are not applied to the Singapore office building in which passive envelope response to climate is typically minimal and indoor conditions are primarily active-reliant.
- The two Malaysian Bioclimatic buildings delivered less comfort and higher energy consumption than Conventional buildings in Singapore.
- Design features proposed under the Bioclimatic Model, such as the NV option and transitional spaces, where available, were not used by building occupants.
- The Singapore Workplace appears to be one of the coolest amongst Southeast Asian cities, probably due to occupant comfort expectations.
- The question of comfort, and the role that climate plays, appears to be partly a cultural issue. The choice of passive and active modes seem to be lifestyle choices, sometimes associated with the image they project. Workplace attire appears to be driven by organisational factors, such as status and rank. Finally, office buildings and office interiors appear to be designed in response to aesthetic preference and organisational hierarchy (respectively).

Indoor Variability

- The uniform and stable indoor environment appears not to exist. Buildings exhibit a degree of indoor variability, even when operating under active modes.
- Buildings designed to be climate-responsive, i.e. with greater reliance on passive features, attributes and modes, have higher levels of indoor variability than climate-rejecting ones, i.e. those with greater reliance on active systems.
- The degree of indoor variability depends largely on the envelope, its passive features and WWR. These determine indoor-outdoor connectivity and most visibly affect conditions in the zone adjacent to the building envelope. The impact of the envelope diminishes with depth into the building.
- A building's occupants are aware of and respond to these climate-driven variations, even in active-run spaces. In the workspace, there is strong

preference for stable and consistent conditions, typically via active modes. There is little or no acceptance of passive reliance in this zone.

- Satisfaction with environmental control appears to be contingent on the level of comfort experienced. Environmental controls, where available, were not used. The most common form of adaptive behaviour, vis-à-vis thermal comfort, occurs at the level of the individual, primarily in terms of clothing adjustment and consumption of drinks.
- EST_{Glass} is an index of thermal variability within a building.

Comfort

- Comfort expectations are predicated on two key criteria: *Activity* and *Variability*. The office building, vis-a-vis comfort expectations, can be divided into three zones: *Work*, *Support* and *Transit*. Each corresponds approximately with a preferred mode option which, in turn, relates with degree of indoor variability.
- The perception of visual comfort appears to be due in part to acclimatisation to conditions found within a particular setting.
- There is a difference between perception of thermal sensation and thermal comfort. In warm conditions, T_N is higher than T_{Opt} by 1K+. Perception of sensation also appears to be sensitive to small changes in temperature, more so than the perception of comfort.

Chapter 8. Implications and Conclusion

8.0. Preamble

The present chapter begins with an overview of findings and discussions from preceding chapters (see Section 8.1) and proceeds to extrapolate from present findings, a comfort-based model for the design of office buildings in the hot humid climate (see Section 8.2). It then re-examines statutory codes that steer the design and operation of these buildings (see Section 8.3) and the theory of thermal comfort (see Section 8.4), on which design standards and engineering norms are predicated. Directions for future research are considered (see Section 8.5) before the thesis is concluded with a review of what its findings and the new model signify from a theoretical and practical standpoint (see Section 8.6).

8.1. Theory and Application: *The Bioclimatic Paradox*

In general, the present study supports the precepts of the Bioclimatic Model as argued by Yeang (1994), specifically the use of solar control features and strategies. Yeang has suggested that their application should significantly improve a building's performance, both in terms of reduced reliance on electro-mechanical systems, hence energy, and improved occupant comfort. Yet, of the two Bioclimatic buildings evaluated in the present study, neither performs better than the Conventional buildings on either count. Indeed, UMNO performs significantly worse in terms of its own predicted energy use. This represents further evidence of the gap between theory and application, first mentioned in Chapter 1.

The question asked then is 'why does the Bioclimatic building not deliver on the promises of the Bioclimatic Model?' The answer to this is crucial to any formulation of an improved model for the Office Building. There appear to be two reasons for this. First, it appears that passive features and strategies in Yeang's buildings are not consistently deployed in relation to climate. Second, the notion of delivering comfort seems to be technique-driven. Solutions, such as the wind-wing wall, are technically innovative but fail to address comfort from the occupant's perspective.

These two arguments are elaborated in the text that follows, which looks at the Bioclimatic and Conventional building in terms of the Aesthetic Imperative and Premise of Comfort.

The Aesthetic Imperative

It has been suggested that architects are preoccupied with the outward appearance of their buildings, as represented by the building shell (Banham, 1984) sometimes at the expense of response to climate (Watson. 1984). Whilst the conflict between appearance and climatic response might be expected with the Conventional building, it is surprising to note that in the two Bioclimatic buildings, there is evidence of the same. These compromises are most visible in the deployment of external shades and transitional spaces (MES and UMNO), placement of service core (MES), overall form and orientation (MES). The design of active systems, AC and EL, appears not to be integrated with the passive systems, neither accounting for envelope permeability nor strategising environmental controls such that they reflect workplace needs. The present study cannot critique the design process of these buildings as no review was carried out of how decisions were made for either. Yeang (personal communication, September 13, 2001) has suggested that the compromises on performance were partly due to *"cost"* and *"expediency"*, a combination of client demands and design oversights. However, others who have studied his work suggest that Yeang's Bioclimatic approach, as exemplified by these buildings, is also rooted in the regionalist search for identity (Jahnkassim, 1998; Powell, 1999). In this regard, it sometimes becomes a question of what the building is seen to be doing, vis-à-vis the climate, as opposed to what it actually does.

The conflict between what a building does and how it looks is most evident in the office buildings surveyed in Singapore. These showed a stylistic consistency, a bias towards Modern and International Styles, plus an absence of climate-based choice of form and orientation. The consistency of style and climate-exclusion supports the argument that architects are more inclined to design on the basis of visual appearance than on climatic performance.

The OTTV study further affirmed the absence of climate-response in envelope design, suggesting that the responsibility for occupant comfort may consciously (or otherwise) be abdicated to electro-mechanical systems designed by engineers, as opposed to shared with the building shell designed by the architect.

The Premise for Comfort

The present study suggests that the under-performance of the Bioclimatic building may be due, in part at least, to flawed assumptions about the nature of comfort. It does poorly partly because of its optimism, particularly with regard to occupant preference for natural light and contact with outdoor conditions. On both counts, the threshold of occupant acceptance was clearly misjudged.

In the case of UMNO, for instance, several assumptions appear to have been made with regard to NV. First, that NV represented an equivalent comfort type as AC. Enhanced air movement was expected to offset higher indoor air temperatures and humidity levels; occupants were expected to willingly switch from one mode to another at their workspace. Second, that NV would be a palatable option because of occupant familiarity (at home or with indigenous buildings) and health concerns relating AC to sick building syndrome. These were assumptions about comfort that were based on cultural models and lifestyle choices. The literature, however, suggests that comfort response in the office is not the same as in the home (de Dear et al. 1991c). The present study has shown that health concerns are confined to a preference for NV in secondary areas, such as the toilet and pantry, not a dislike for AC in the workspace.

With regard to visual comfort and reliance on natural light, there are two perspectives in the literature. Many argue that daylight is better than electrical light for reasons of occupant preference (Ruck, 1995), health (Baker, 2001) pleasure (Phillips, 1975) and energy savings (Ullah, 1996). Texts on the architecture for the hot humid climate, however, are more cautious, referring instead to architecture of shade and shadow (Fry & Drew, 1956; Powell, 1997). The Bioclimatic buildings seem to opt for the former perspective, delivering conditions of brightness, often glare, with more illuminance than is necessary or recommended for the workspace. In both MES and UMNO, direct penetration of sunlight occurred across a significant portion of the buildings in the afternoon. The two Conventional buildings are more conservative in admitting natural light, but it is not clear if this necessarily due to a better understanding of comfort needs. These buildings may simply have been restrained by Singapore's OTTV code as this limits a building's overall WWR and glass shading coefficient.

The present study has argued the importance of the building's users as arbitrators of their own comfort. This occurs, first, in the behaviour and interventions with which they interact with their environment. Related to this are the comfort expectations that they bring with them, which guide their response, delineating what is preferred from what is tolerated.

Passive features and strategies are also shown to matter in the making of comfort. These findings concur with past studies (Olgyay, 1963; Givoni, 1969; Powell, 1989) which suggest that the envelope is a indoor-outdoor filter, and recent research on the role of the envelope in the making of comfort (Arasteh, Hartmann, & Rubin, 1987; Chen, Kamimura, & Watanabe, 1999; Lyons, Arasteh, & Huizenga, 2000; Prasad, 1995b). Noteworthy amongst present findings is the extent to which EST participates in the making of ambient indoor conditions. It has been shown here that the permeability of the envelope and resultant ESTs create a diurnal and weather-related ebb-and-flow of light and temperature, most visibly on the plan periphery.

On the question of comfort, both the Conventional and Bioclimatic buildings appear to be driven by an *outside-in* approach, i.e. they address comfort through considerations of form and envelope, the deployment of passive and active modes. The present study offers an *inside-out* view of comfort by exploring how comfort expectations are structured vis-à-vis activity and modes.

It has been noted also that current design practice appears to be driven by a need to deliver indoor conditions that are uniform and stable. The present study suggests that this is not necessary, that within the context of an air-conditioned building, indoor differentials of 2K+ and energy savings of 2.9% are possible (see Section 6.2). These margins do not, however, fully exploit the potential of the activity criterion for comfort. Nor does the act of tweaking temperature settings, within the context of an existing all-AC building, lend itself to a rethink of the Office Building. The key question, then, is how findings from the present study might address the future office building. It would have to be a framework that accounts for comfort expectations, one that is prescriptive in nature and yet offers designers creative latitude. These are the core objectives of the new model proposed in Section 8.2.

8.2. The Psychoclimatic Model

> *Properly accounting for thermal comfort will significantly alter the operation and the energy performance of the building [making it possible] to find optimal strategies in terms of the potential for saving energy as well as satisfying minimum comfort requirements.*
>
> Coutier et al. (1985, p. 68).

The present thesis supports this argument through its exploration and application of comfort expectations. The key finding here has been the criterion of *Activity*, on the basis of which the office building is divided into three activity zones, *Work, Support and Transit*, and three modes of operation, *Passive*, *Active* and *Mixed*. A new comfort-based approach, one that integrates a critical assessment of the Bioclimatic Model with an adaptive framework for comfort, is presented here as the Psychoclimatic Model. The Model is so named because it is premised on human perception and behaviour, deriving its logic from the psychology of comfort.

In addition to activity, two further criteria are considered: indoor variability and the question of architectural aesthetics. With regard to indoor variability, the Work zone is identified as being critical because variability and passive-reliance are less tolerated. Here, it becomes important how the building's shell and its electro-mechanical systems are integrated. With regard to aesthetics, it is suggested here that prescriptive measures that are less likely to impinge on the building's appearance have a better chance of success. Both these issues are elaborated in Sections 8.2.2 and 8.2.3.

In prescribing modes, rather than ambient conditions, the new Model is prescriptive without being overly specific. Coldicutt, Williamson and Penny (1991) suggested that there is a need to bridge design and research with proposals that establish parameters of acceptability, as opposed to ones that deliver specifics such as a temperature for thermal neutrality. The tri-modal template of the Model (see Figures 8.1 and 8.2) is an implicit acknowledgment that the design process consists of a series of tradeoffs and value-based judgements. Every user group will bring with it associations with the words *Active, Passive* and *Mixed*, based on what they are culturally exposed to and familiar with. The Model leaves room for new meanings and technologies, for instance, in the development of mixed-mode solutions.

The Psychoclimatic Model is, in effect, an extension of the Bioclimatic Model. Section 8.2.1 shows how the new Model deals with the issues of thermal and visual comfort. This is then expanded to address the following:

- Solar control through design of *Form and Envelope* (Section 8.2.2)
- Activity- and envelope-based *Comfort Zones* (Section 8.2.3)

8.2.1. Thermal and Visual Comfort Templates

Figures 8.1 and 8.2 summarise the new tri-modal strategy for office building, adapted from the diagram of the Bioclimatic building (see Section 2.2.2, Figure 2.5). These represent the Psychoclimatic Model and propose that an office building can be zoned according to the three modes of operation. Two templates are shown - one for thermal and the other for visual condition. These are an amalgamation of the matrix shown in Section 7.3.4 (see Table 7.18) which summarised response to the sorting procedure.

The templates take the matrix a step further by actually assigning a mode to each space[1]. In the act of prescribing, a judgment is made on the criticality of preference. In some spaces, such as the workspace or auditorium, preference for active modes is critical and less open to compromise. In other cases, for instance, the cafeteria, it may be preferred (as suggested by the predominance of AC votes in the first sort), but remains open to compromise (as suggested by the shift towards FA votes in second sort). In opting for acceptance where tenable, user preference is balanced against energy consumption.

An inner ring denotes the extent to which the envelope affects indoor variability. The auditorium, for instance, is situated in the inner zone, because control and predictability of light and air temperature are critical to its function. In other spaces, where this is less so, for instance, the cafeteria, there is no such differentiation between perimeter and centre zones. There is nevertheless a recommendation for a provision of transitional spaces adjacent to the passive- and mixed-mode areas. These spaces have been shown to dampen indoor variability and are likely to be seen as useful here; for instance, as a semi-outdoor siting area for the cafeteria.

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[1] Two additional spaces are introduced to the original list of 15: mechanical and electrical rooms (M&E rooms) and service corridors. Even though these had not been tested in the sorting exercise, they are shown here as they tend to be commonplace 'service' areas found in office buildings.

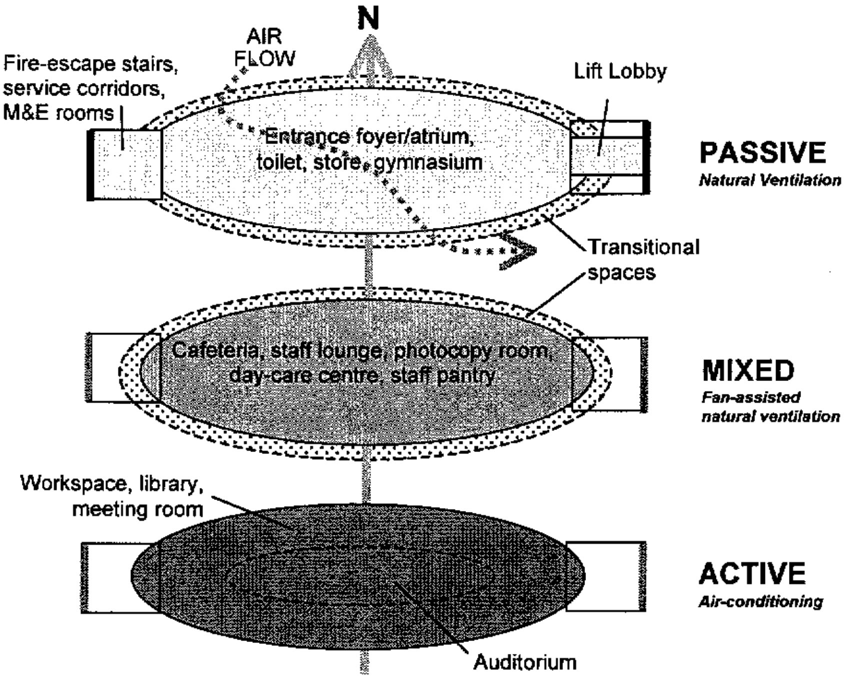


Figure 8.1. Psychoclimatic Model for the thermal condition in office buildings

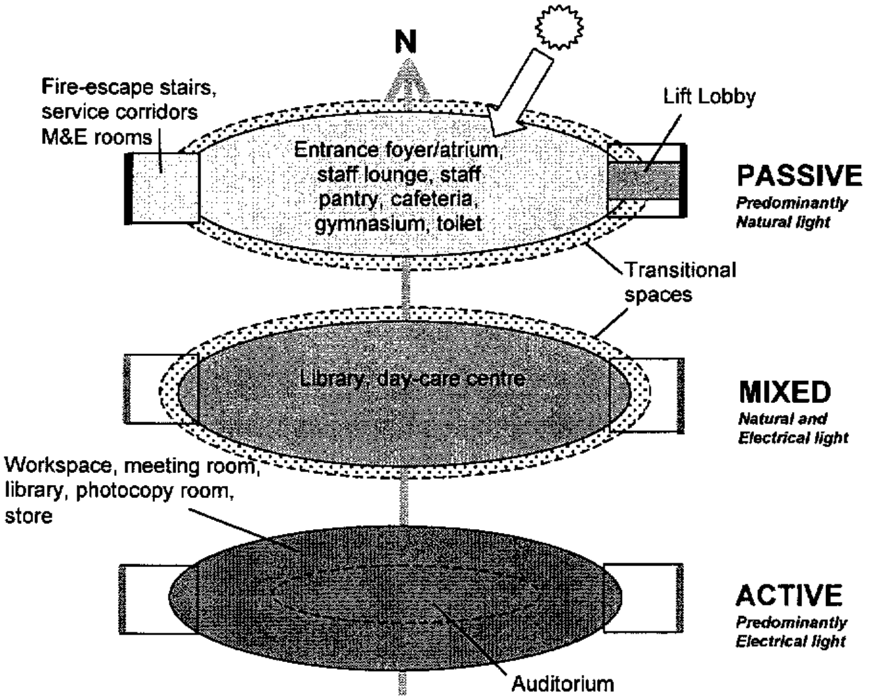


Figure 8.2. Psychoclimatic Model for the visual condition in office buildings

A corollary to the Psychoclimatic model is that it facilitates a gradient of conditions linking outdoors with the indoor environment (see Figure 8.3). Kwok (2000) spoke of the desirability of creating *"thermal gradients"* and *"transition zones"*, a strategy for minimising, what she called *"thermal boredom"* (p. 641). This reduces the contrast of conditions experienced in moving between public and private spaces and corresponds with the notion of privacy gradients that emerged from Survey 2.

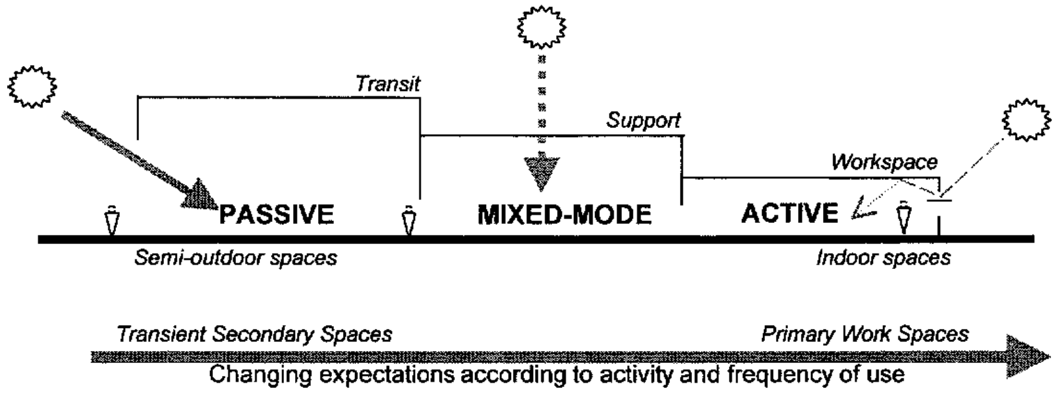


Figure 8.3. Indoor/Outdoor gradients

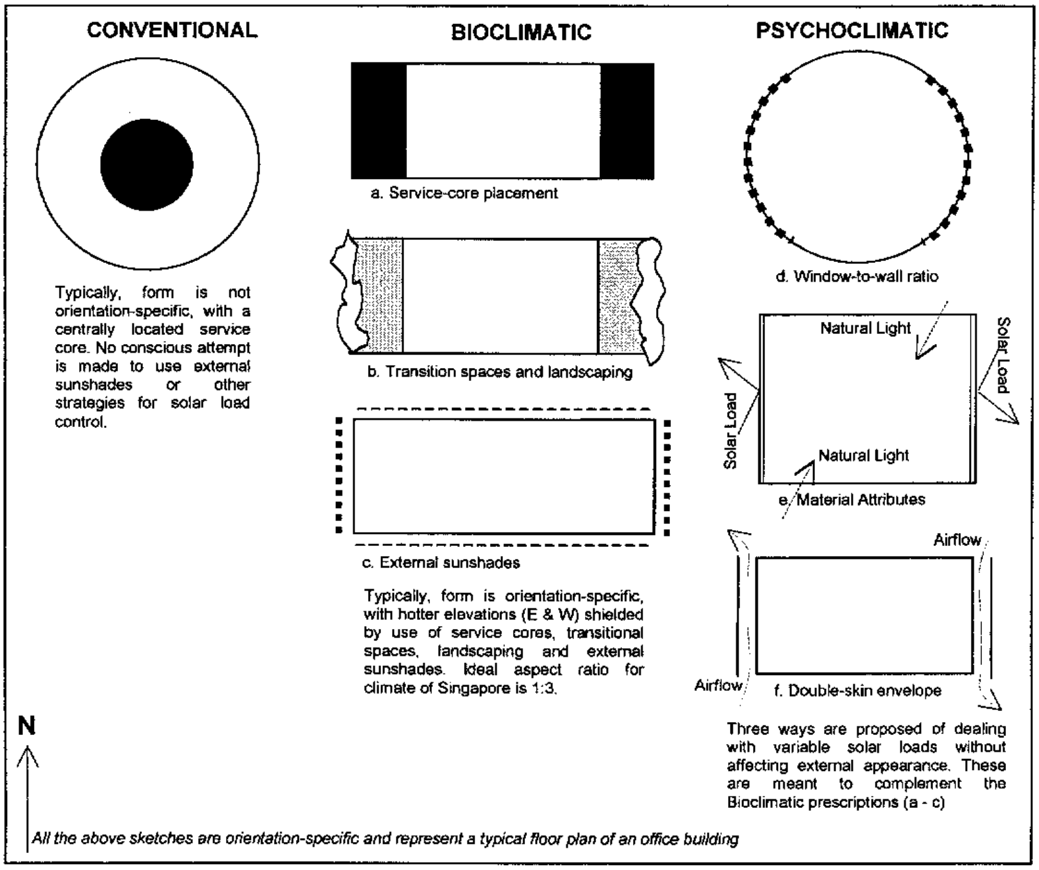
8.2.2. Form and Envelope

Banham (1984) spoke of the marginalisation of the building's systems and services in the history of 20th Century architecture in which only the exterior of the building was celebrated. Rivard, Bedard, Fazio and Ha (1995) likewise argued that the importance placed on envelope appearance should not be underestimated:

> *The aesthetic quality of a building is of prime concern to the architect since the envelope is what is seen first in a building. [However] form, colour, texture and pattern can be modified without influencing envelope performance, thus aesthetic quality does not affect other requirements such as durability, heat transfer, noise insulation, etc.*
>
> Rivard et al (1995, p. 392)

In this regard, the Bioclimatic Model, with its rules of geometry and need for solar-control features, is at a disadvantage when applied to the Conventional building, which (theoretically) allows a designer greater latitude for aesthetic expression. Several options are reviewed here that can potentially balance considerations of appearance and performance (see Figures 8.4 and 8.5).

In the Psychoclimatic Model, the question of solar load and orientation is extended to material attributes and envelope systems (see Figure 8.4). This does not preclude the list of Bioclimatic options, rather expands on it.



Typically, form is not orientation-specific, with a centrally located service core. No conscious attempt is made to use external sunshades or other strategies for solar load control.

Typically, form is orientation-specific, with hotter elevations (E & W) shielded by use of service cores, transitional spaces, landscaping and external sunshades. Ideal aspect ratio for climate of Singapore is 1:3.

Three ways are proposed of dealing with variable solar loads without affecting external appearance. These are meant to complement the Bioclimatic prescriptions (a - c)

All the above sketches are orientation-specific and represent a typical floor plan of an office building

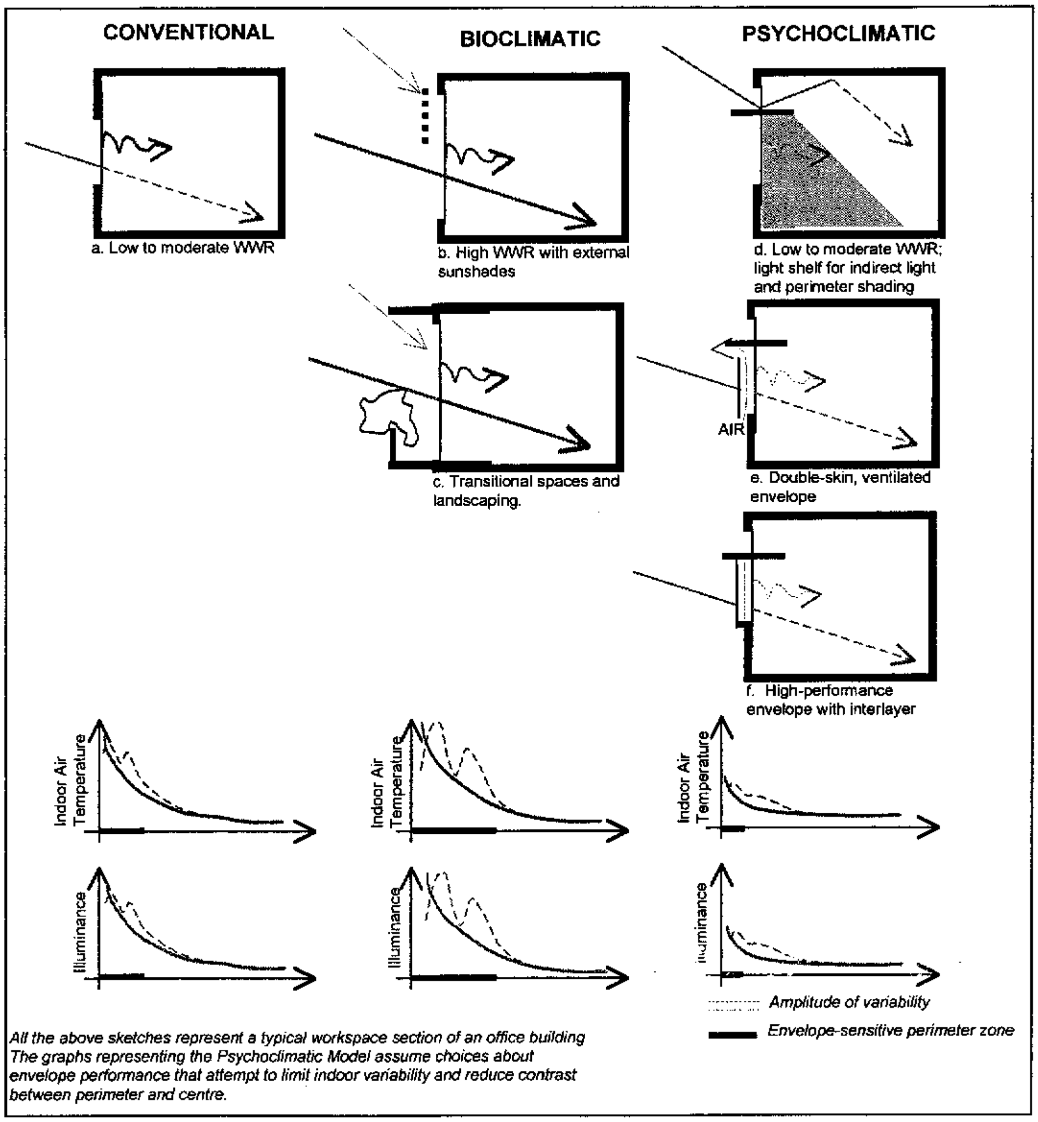
Figure 8.4. Form and orientation strategies

WWR, for instance, is an attribute that can be varied with orientation without necessarily being visible from the exterior. With curtain wall systems that deploy glass spandrels over walls and other structural components, the external appearance of facades in a building will seem uniform, even if actual permeability varies with orientation.

Glass performance is another attribute that can be varied with solar load. Glass types have been shown to differ in their impact on heat gain (Prasad, 1995b) and thermal comfort (Lyons et al., 2000). The range of glass products, interlayers and coatings, which give windows selective insulation and spectral properties, have been reviewed in depth by Chua (1997) and Daniels (1997).

A ventilated double-skin envelope was suggested in a study by Etzion and Erell (2000) as a strategy for diminishing solar load in hot conditions, in which a naturally-occurring thermodynamic process draws air through the gap, thereby reducing envelope permeability to solar load.

In the Psychoclimatic Model, the balance of heat and natural light may also be managed via a 2-tier window system (see Figure 8.5). The upper tier in such a system would consist of light shelf and a single glazed panel that would facilitate the penetration of natural light. The lower tier would be double-skinned for greater heat insulation and lower natural light penetration in the perimeter zones. This would effectively flatten the contrast between perimeter and centre zones, reducing the amplitude and extent of indoor variability in the perimeter.



a. Low to moderate WWR

b. High WWR with external sunshades

c. Transitional spaces and landscaping.

d. Low to moderate WWR; light shelf for indirect light and perimeter shading

e. Double-skin, ventilated envelope

f. High-performance envelope with interlayer

All the above sketches represent a typical workspace section of an office building The graphs representing the Psychoclimatic Model assume choices about envelope performance that attempt to limit indoor variability and reduce contrast between perimeter and centre.

Figure 8.5. Envelope strategies

8.2.3. Comfort Zones

Two parameters have emerged from the present study linking perception of comfort with occupant location. First, that perception of variability can be attributed to proximity with the envelope. Second, that comfort response is linked with activity. These are discussed here in terms of the integration of a building's shell and its electro-mechanical systems and in the deployment of modes according to population groups.

8.2.3.1. Shell and systems

The present study supports the strategy proposed by Chen et al (1999) that the skin load may be estimated using EST_{Glass}. Findings here suggest that EST_{Glass} is a reliable index of the distribution of fabric loads on a floor plan, which are often asymmetrical and changing.

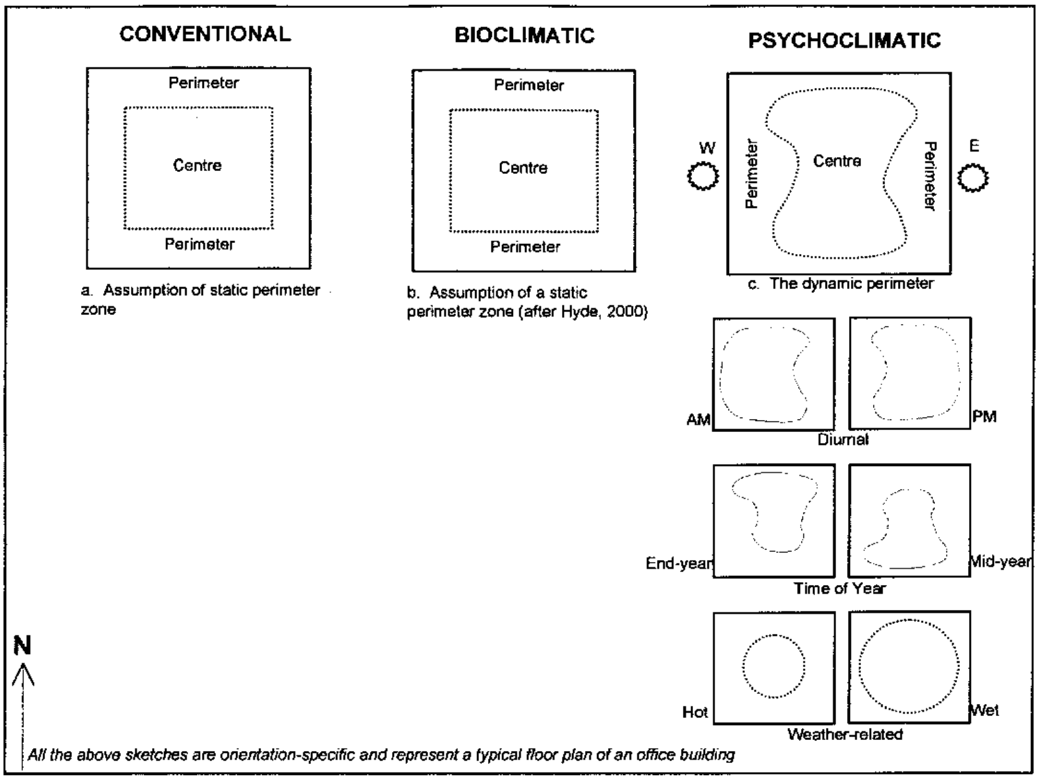
It was found that the range of 30°C – 40°C appears to be fairly prevalent across most buildings. Facades that reached EST_{Glass} in the high 40s were also associated with internal hot spots and occupant discomfort, whilst temperatures below 30°C occurred only when the envelope was protected from direct solar radiation. An index of envelope performance is proposed here on the basis on these outcomes (see Table 8.1)

	Good	Average	Poor
EST_{Glass}	< 30°C	30°C - 40°C	> 40°C

Table 8.1. Proposed index for envelope performance.

Where passive features and systems are ineffective, and envelope temperatures high, electro-mechanical systems may then be used to counter skin load and minimise indoor variability.

In the design of Conventional and Bioclimatic buildings, the perimeter zone is largely assumed to be unchanging. The present study has shown that this zone is dynamic, its depth dependent on time of day, time of year and weather conditions (see Figure 8.6).



All the above sketches are orientation-specific and represent a typical floor plan of an office building

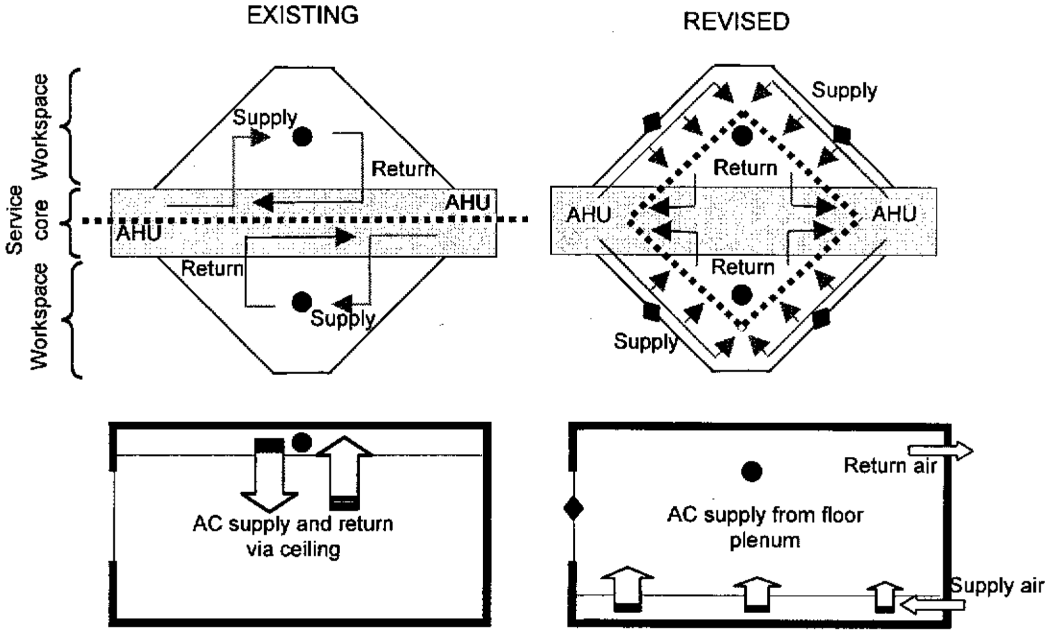
Figure 8.6. Envelope-related zones

The Psychoclimatic Model expands on findings of Chen et al. (1999) by suggesting that the design of AC system could incorporate varying flow-rates according to skin loads, much like the human body adjusts capillary flow rates near the skin in response to changing thermal conditions.

This notion of using AC controls to track diurnal and seasonal changes has been suggested by Roaf (2001) and Boisvert and Rubio (1999), the latter suggesting that an intelligent thermostat can also be programmed to learn occupant behaviour. Auliciems (1990) spoke of *thermobile* controls, as opposed to *thermostats*, which allowed for indoor settings to be pegged to outdoor conditions. This was, however, to bring indoor temperatures in line with seasonal shifts in the weather. It is proposed here that intelligent building automation systems be deployed to counter diurnal, weather-related and seasonal fluctuations, using EST_{Glass} as its index. The present study has shown this to be a meaningful indicator of envelope performance with quantifiable impact on indoor conditions, particularly at the plan perimeter in the context of time of day, weather conditions and time of year (see Section 4.3.3).

The AC system at RevH is used here to illustrate this integration of shell and skin. In the existing system of the building (see Figure 8.7), airflow is supplied by, and returns to, ceiling-mounted ducts. Thermostats are situated in the ceiling space[2] (presumably to protect them from tampering) and the floor plate is divided into two halves, each served by an Air Handling Unit (AHU).

In the revised scheme, air would be supplied via an under-floor plenum. The rate of airflow would increase with proximity with envelope, pegged to readings from EST_{Glass} sensors mounted on each façade. These readings would supplement those from thermostats, mounted in the same space that occupants use. With this feedback loop to the building's central control system, airflow could respond to changing outdoor conditions (such as were shown in Figure 8.5c) and internal loads, thereby creating a relatively more stable and uniform set of conditions.



a. Schematic plan and section of existing RevH AC distribution

b. Schematic plan and section of revised RevH AC distribution

● Thermostat

◆ EST_{Glass} Logger

▪▪▪▪▪ Thermal zones

Figure 8.7. Existing and revised RevH AC system

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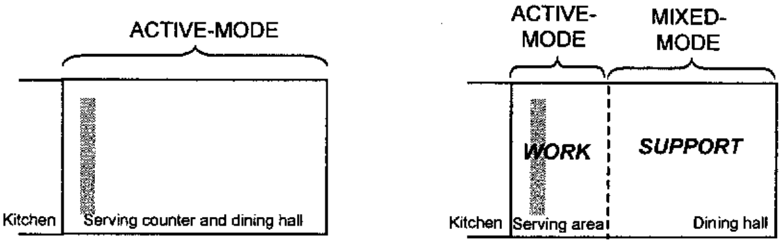
[2] The location of thermostats might explain the cooler than setpoint indoor air temperatures. The space above the ceiling, which consists of return air, is likely to be warmer than the air in the space below the ceiling.

8.2.3.2. Activity-based delineation

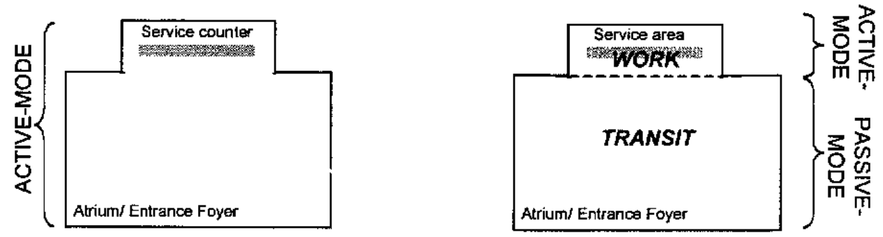
There can be a conflict between the needs of two or more population groups in some zones. A cafeteria, for instance, is a Workspace to the individuals who serve food, yet is also a Support space to those who dine there.

Elder and Tibott (1981) raised the issue of conflicting comfort needs in a review of the literature on light. They illustrated this with the observations by Ne'eman and Longmore (1973) that patients in a hospital ward were found to be significantly more tolerant of sunshine than the nursing staff that worked there. In RevH, a similar observation was made in Survey 4. Whilst the diners were tolerant of higher air temperatures, the staff were less tolerant of the same.

In another instance of conflicting needs, the atrium in URA has public service counters permanently manned by staff. In an activity-based strategy for comfort, these two areas would have been subdivided according to the needs of the two population groups (see Figure 8.8). In RevH, the cafeteria might have been subdivided into a serving area, which would be reliant on the active-mode and a separate dining area reliant on mixed-mode. In URA, the same segregation would have allowed the atrium/entrance foyer to be conceived as a passive-run space.



a. RevH Cafeteria



b. URA Entrance Foyer

EXISTING REVISED

Figure 8.8. Activity-based strategy for mode deployment

8.2.4. Summary of the Psychoclimatic Model

Typically, the multi-mode building has been advocated for temperate and cooler climates where for a significant part of the year outdoor conditions are deemed comfortable. The idea of *fresh-air architecture* (Hartkopf et al., 1993; Shepard et al., 1995) appears to have the greatest potential in climates with significant seasonal changes.

The present study suggests that in hot humid conditions, where seasonal shifts are insignificant and wind speeds are low and unreliable for much of the year, passive and mixed-mode alternatives have little chance of matching active modes, particularly in terms of providing thermal comfort at the workplace. In these climates, AC is also a lifestyle choice, pegged to affluence and expectations.

Aside from Yeang's bimodal strategy (exemplified by UMNO), Hyde (2000) tackled the notion of a dual-mode office building for hot humid climates of Australia. He suggested that the spaces next to a building's envelope might be passive-run by virtue of their proximity to climatic resources, such as daylight and air movement. Thermal zoning, on the basis of envelope-proximity, would be a means of deciding how much of the building is passive-run and how much, active-run.

On the basis of findings from the present study, it is suggested that this 2-zone approach is unlikely to work in Singapore, any more than Yeang's did in Malaysia. Thermal zoning, with only climate as a premise for indoor comfort, was deemed to be flawed in a study on Australian homes where it was found that it did not, as such, reflect what people wanted in their homes.

> *It is suggested that thermal zoning is part of a 'conceptual set' [from] design for climate preconceptions... part of a mindset of some architects and authors of design guidelines, but not of the users themselves.*
>
> Samuels, Ballinger, Coldicutt and Williamson (1993, pp. 151 and 156)

The key difference between the models of Yeang and Hyde and the Psychoclimatic proposal here, is that the latter is premised on occupant expectations. Figure 8.9 summarises the difference between these three approaches.

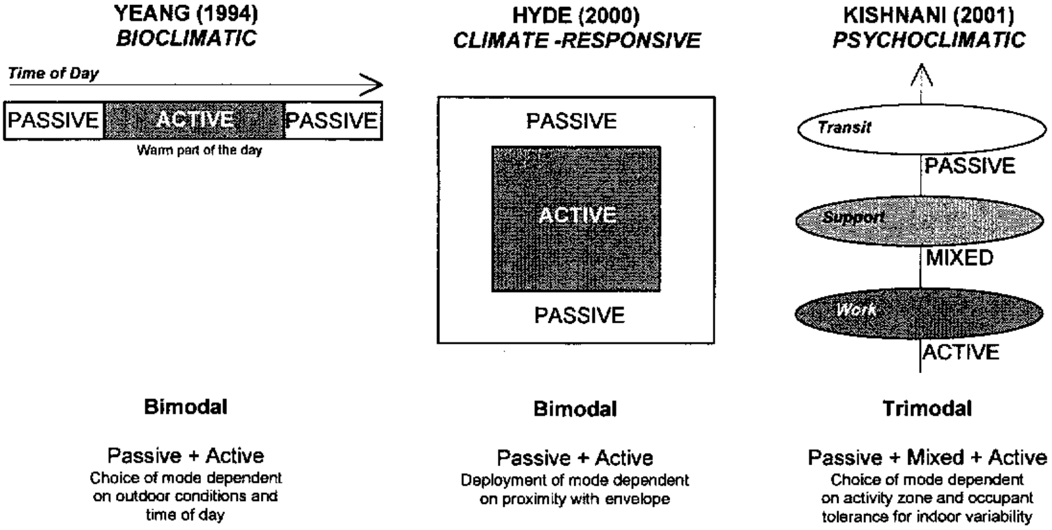


Figure 8.9. Overview of multi-mode models for hot humid climates

In light of the Psychoclimatic Model presented here, it would be useful to re-visit the only tri-modal design found within the context of the hot humid climate: the Shinawatra University campus (see Section 2.2.4). Even though findings from the present thesis pertain specifically to office buildings in Singapore, juxtaposing the proposed model with the Bangkok campus sheds light on how the model might affect design decisions. It could be argued, for instance, that the deployment of a mixed-mode system for cooling of circulation spaces that link campus buildings (Olgyay and Boonyatikarn, 2000) is unnecessary. These transit spaces are visited infrequently and for short periods at a time; they have a narrow plan depth that could be easily be naturally ventilated, without sacrificing occupant acceptance. The campus cafeteria, on the other hand, would switch from the passive mode prescribed by the designers to mixed-mode under the Psychoclimatic Model. It was noted in RevH that this support space experienced an occupancy surge for periods of up to 2 hours every day. The weak wind conditions of a hot humid climate, such as of Singapore, cannot be relied on for comfort cooling.

Table 8.2 summarises the key differences between the Conventional and Bioclimatic approaches and the Psychoclimatic Model proposed in this section.

	CONVENTIONAL	BIOCLIMATIC	PSYCHOCLIMATIC
Premise	Design of indoor conditions based on universal standards of comfort. Objective is to create uniform and stable indoor conditions relying on electro-mechanical devices. Climate-building interface not seen as significant. Envelope permeability is low to moderate. Climate is seen primarily as a constraint.	Design of indoor conditions based on universal standards of comfort. Variability of occupant preference acknowledged in the creation of bimodal systems, and the provision of transitional spaces. Climate-building interface seen as critical. Envelope permeability is generally high. Climate is seen primarily as an opportunity.	Comfort is seen to be specific to climate and building type. Comfort expectations are specific to activity. Expectations are addressed by simultaneously utilising passive, active and mixed modes. Climate-building interface seen as critical. Envelope permeability is low to high. Climate is seen as part opportunity, part constraint.
Delineation of Zones and Deployment of Modes	Air-conditioning and electrical lighting used throughout, with some reliance on natural light for secondary spaces, such as the atrium. Perimeter zone of 4-6m recommended for design of AC thermal zones and offsetting EL with daylight.	A mix of AC and NV, with significant amounts of natural light throughout. Deployment of modes depends on time of day: AC during daytime when it is hotter and NV in the evening, when cooler. In the rest of office building, spaces are divided into primary work-related areas and secondary supporting areas. The former are active-run and the latter, passive-run. In Hyde's climate-responsive model, thermal zones are premised on proximity to envelope. The perimeter zone is passive-run and inner zone, active-run.	A mix of passive, active and mixed modes deployed across three activity zones: Workspace Support and Transit. Deployment based on occupant expectations of thermal and visual comfort.
Shell and System Interface	Impact of outdoor conditions is reflected in the design of electro-mechanical systems through delineation of perimeter zones.	For active modes, approach is essentially the same as Conventional building. There is no delineation in the case of passive modes.	In Workspace, active systems are designed to minimise envelope-induced indoor variability. In Support and Transit areas, passive features assume a more prominent role for their impact on indoor variability in the perimeter zone. These are used to dampen temperature (and other) gradients.
Thermal and Visual Comfort	Combined impact of temperature and light on occupant comfort is not a design consideration.	High WWR and abundance of natural light indoors suggests that thermal and visual comforts are designed for in relation to each other.	Interaction seen to be critical, particularly in Workplace and peripheral zones. In the Workspace, only indirect light admitted to create low levels of ambient illumination. Peripheral zones shaded throughout.
Appearance vs. Performance	Building envelope appears to be largely style-driven. The most prevalent styles observed in office buildings in Singapore are Modern and International Styles. Performance is commonly discussed in terms of energy savings through building intelligence and efficiency of electro-mechanical systems.	Building envelope appears part performance-driven, and part style-driven. Style has been described as an offshoot of Regionalism. Performance is commonly discussed in terms of energy savings through reliance on passive modes, attributes and systems.	The Psychoclimatic Model is not style-driven, but acknowledges the need for aesthetic freedom. Performance is measured both in terms of energy consumption and occupant comfort. Envelope systems and attributed are used to facilitate performance without limiting aesthetic freedom.

Table 8.2. Comparison of Conventional, Bioclimatic and Psychoclimatic Models

	CONVENTIONAL	BIOCLIMATIC	PSYCHOCLIMATIC
Pros	Focus on predictable and quantifiable comfort.	Variety of indoor conditions.	Variety of conditions that create a gradient between outdoors and indoors.
		Visual connectivity with outdoors.	Visual connectivity with outdoors.
	Approach deemed to be universally applicable.	Approach specific to climate.	Approach is specific to climate, country, building type and activity. Solution likely achieve optimal comfort and minimal energy waste.
Cons	High energy use and unnecessary cooling. Energy waste due to overcooling, occupant behaviour, high fabric loads and air seepage (particularly the atrium/entrance foyer).	Approach does not account for national/cultural differences. High thermal permeability with outdoors. Energy waste due to occupant behaviour and high fabric loads.	A context-specific approach requires investigations during the design process, which may be time and resource consuming. The absence of data and industry standards makes this difficult to implement on a case-by-case basis.

Table 8.2. Comparison of Conventional, Bioclimatic and Psychoclimatic Models
(continued from preceding page)

8.3. Regulatory Control

Khosla (1997) argued that in Singapore, regulatory control might be the best strategy for changing the way that designers approach climate and energy consumption. Roaf (2001) likewise suggested that, in general, it would be best to combine market forces and legislation.

The Singapore authorities have already taken steps in these directions. A government initiated study recommended that building regulations should incorporate performance benchmarks that are routinely reviewed and adjusted (IACEE, 2000). The BCA has initiated new envelope design guidelines and has promised further performance-specific revisions to existing codes (Goh, 2001; Koo, 2001). Against this backdrop, an annual ASEAN-wide energy-efficiency competition is held, creating a *"platform to promote energy efficiency and replicate energy-efficient design practices"* (Lee Siew Eang quoted in the Straits Times, 2000).

There is, nevertheless, a gap between the rhetoric and the rules. Policymakers speak of energy conservation but the rules, in some respects, inhibit the use of passive features or shy away from being too prescriptive. For instance, in the calculation of a building's allowable area, a transitional space (if covered) is deemed to be part of the computed Gross Floor Area. This implies that a semi-outdoor space, such as a balcony, is created at the expense of indoor space that might otherwise be leased. In another instance of the rules not going far enough, a BCA spokesman, when asked why the OTTV limit does not extend to the design of individual facades, replied that it would unduly inhibit creative freedom of architects (Singapore Energy Website, 2001a).

The question asked here, in the context of the present study, is how its findings affect present-day codes. Is there, for instance, a need to prescribe bandwidths of indoor temperature at all? Should there be, instead, recommendations on the use of modes? Table 8.3 summarises existing regulations for office buildings in Singapore, vis-à-vis the envelope, operational modes and incentives for the passive design.

	Current Singapore Regulations	**Findings from Present Study**	**Proposed Revisions**
Envelope Control			
OTTV *(existing)*	Upper limit: 45 W/m^2 – computed average of all facades. Roof limit (RTTV): 45 W/m^2	OTTV and ETTV do not address the form and shape of the building, nor encourage appropriate building-climate interface.	In addition to OTTV and RTTV, there should be an upper limit on façade value, i.e. a Façade Thermal Transmittance Value.
ETTV *(under trial)*	Upper limit: 35 W/m^2 –computed average of all facades. Roof limit (RTTV): 45 W/m^2. OTTV submissions are made after detail design stage, i.e. after the building form and shape have been finalised.	Design tradeoffs result in high thermal transmittance of some facades with potential asymmetry of indoor conditions.	A *climate-response* submission should be made at an early stage of the design process, followed by detailed calculations of envelope loads and predicted impact on occupant comfort.
Active Modes			
Thermal	Indoor air temperature: 23°C – 27°C Relative humidity: 75% (max.) Air movement: 1.25 m/s (max.)	Almost all spaces surveyed were on the low side of the temperature range. Occupant sensitivity and perception of relative humidity is low for RH between 53 and 78%	Temperature range could be broken down into three bandwidths based on activity zones, like illuminance . Lower limit on RH should be introduced, at say, 60%, so as to minimise the energy used in removal of moisture.
Visual	Offices Illuminance: 300-750 Lux (recommended 500 Lux) Lighting load: 20 W/m^2 (max.) Lobbies/Foyers Illuminance: 100-200 Lux (recommended 150 Lux) Lighting load: 10 W/m^2 (max.) Circulation Illuminance: 50-100 Lux (recommended 75 Lux) Lighting load: 10 W/m^2 (max.)	A building is often designed for nighttime loads and used as such in the day.	Differentiation between day and nighttime loads, particularly for secondary areas, such as entrance foyers and circulation spaces. These could rely on daylight and should have lower daytime lighting load of, say, 5 W/m^2.
Passive Strategies/ Modes	No incentives for use of external sunshades and transitional spaces. Windows for passive-run rooms must be equal or more than 15% of room floor area, of which 50% must be operable.	Almost none of the buildings deploy passive features and strategies as per the Bioclimatic model.	Incentives and exemptions for use of passive features and strategies, as long as they are demonstrably part of a climate-response strategy. This may imply, for instance, the exclusion of semi-outdoor spaces from a building's floor area calculations.

Table 8.3. Implications on Singapore statutory controls

8.4. Thermal comfort

Equally important as regulatory codes, are the norms guiding the design process. Codes must complement design practice (and vice versa) if there is to be a meaningful impact on energy use. It makes little difference that the present Singapore code requires that the *design* of AC systems facilitate IATs from 23°C to 27°C (PWD, 1983) when recent recommendations suggest that these spaces may be *operated* at 22.5°C to 25.5°C (Singapore Energy Website, 2001b). At best, these two bandwidths are confusing signals about the role of designers versus that of a building's operators.

Many experts in the field have argued for the need for new standards that address developments in the theory of thermal comfort, vis-à-vis the adaptive model (Brager & de Dear, 2001; Oseland, 1993). Nicol and Humphreys (2001) suggested that these new standards should address "*indoor environments most likely to provide comfort [through] a range of acceptable conditions.*" (p. 53).

The paradox of the adaptive model is that it seeks to make prescriptions that are not too prescriptive. There is an acknowledgment that standards are needed and that they should be specific to climate, type of building, and seasonal variability (Nicol & Humphreys, 2001). It has also been suggested that comfort cannot be divorced from national biases in the form of socio-economic expectations (Olweny, Williamson, & Sufianto, 1999).

The first task is to find an appropriate format for presenting these variables. Figure 8.10 attempts this; it speculates on the relationships between the three dimensions of thermal response - sensation, comfort and acceptability - for four climate types and three conditions within the same climate. This is only a notional representation of the impact of climate as a variable, not supported by the present study but based on the finding that comfort response is a question of mode, activity and variability (see Section 7.3.4).

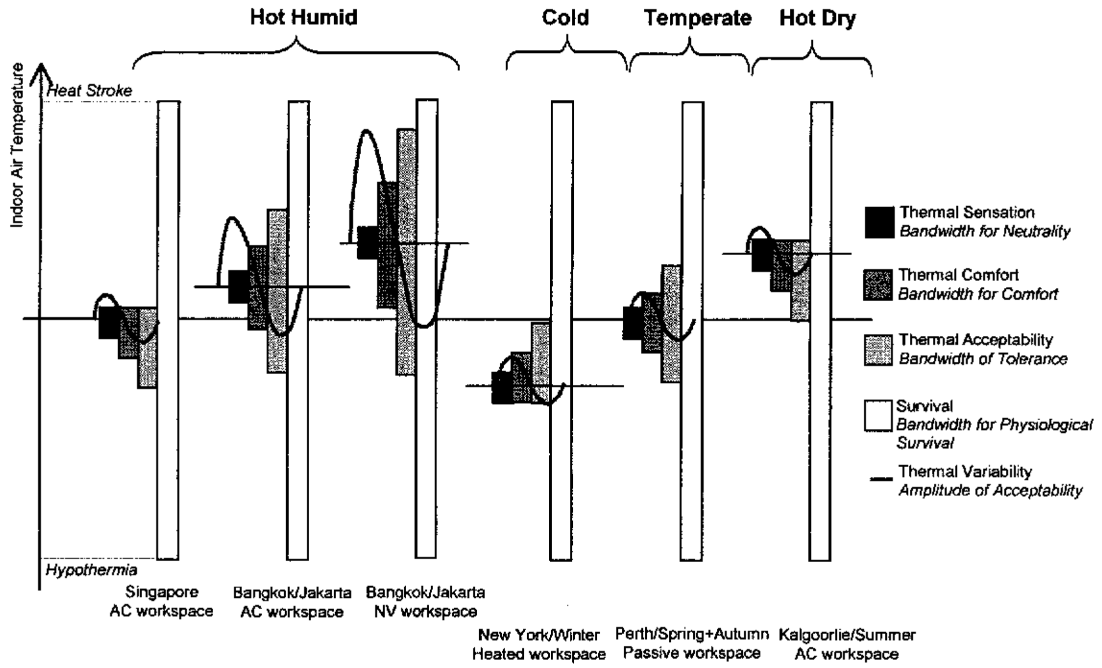


Figure 8.10. Thermal comfort in relation to country and climate

In comparing comfort at the workspace across four climates, the diagram suggests that the relationship of sensation, comfort and acceptabilty is likely to be asymmetrical in hot and cold climates, veering towards cooler sensations for hot climates (Singapore and Kalgoorlie) and warmer sensations for cold climates (New York/Winter)[3]. In temperature conditions (Perth/Spring+Autumn), it is likely that comfort will occur anyhwere between slightly warm and slightly cool.

In terms of ambient conditions, it is suggested that the workplace in cold climates might function effectively at temperatures lower than in hot climates. The question

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[3] This stipulation on the probable link between sensation, comfort and acceptability is different climate types is speculative, premised on the past studies which suggest that relationship is not static (see Section 7.3.2.1).

of acceptable amplitude of variability is speculated will be the same in all workspaces that are active-run, irrespective of climate.

The last point made here is that of national bias. In comparing the Singapore workplace with AC and NV office buildings in Jakarta, it is suggested that higher temperatures and greater amplitudes of variability may be tolerated in Jakarta, more so than in Singapore, largely due to lifestyle expectations and population affluence.

8.5. Further Research

In electing to focus on hot humid climates, Singapore, the office building and thermal comfort, the thesis has raised questions about how its findings and approach might potentially apply to other contexts. Listed below are several recommendations of how the present study can be built upon. Future studies may either re-examine the issues in other contexts or expand on findings that have emerged here.

8.5.1. Building Types, Countries and Climates

Apart from the office building, residential environments are a critical building type because they represent, in Singapore at least, the other major consumer of energy amongst building types (Quek, 2000). It has been shown that these two settings differ in terms of comfort response (de Dear et al., 1991c). Unlike the workplace, AC in the home is likely to be deemed a necessity in only a small minority of spaces, whilst the majority are likely to be preferred as having both passive- and mixed-mode options. Griffiths et al (1988) suggested that user attitudes play a part in energy use. In the home, reliance on active modes may be influenced by the cost of use, which is typically borne by the occupant directly. Here, an individual also has the option to move away from the perimeter zone, should there be discomfort. This is unlike at the workspace, for which the organisation pays the energy bill and in which the individual is often immobile for a significant part of the day. This notion of *'forgiveness'*, where the undesirable impact of an environment is tolerated because there is choice (Leaman & Bordass, 1997), is likely to result in greater acceptance of passive and mixed modes in the home. Transitional spaces (balconies, verandahs) which were observed to not be utilised in office buildings, might be viewed differently in a residential settings where they are viewed as potential extensions to the living space.

In this section, a Psychoclimatic outcome is speculated for residential environments such as high-rise condominium housing in Singapore (see Figure 8.11). This is a template for future research, intended to make the case that the multiple sorting procedure may lend itself to the broader question of design.

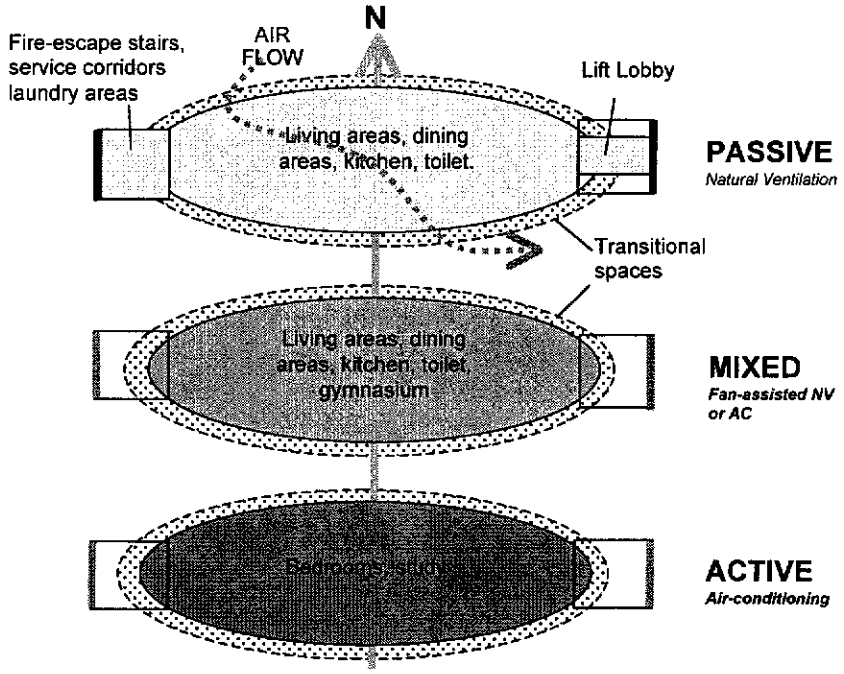

Figure 8.11. Psychoclimatic Model
applied to thermal condition in residential buildings

It is suggested in Figure 8.11 that the majority of spaces in a residential setting might be bi-modal. A living room, for instance, might be used in the passive mode when wind conditions permit reliance on NV, or in mixed mode (i.e. fan assisted ventilation) when outdoor conditions are still. It is worth speculating if UMNO, with its bimodal strategy for thermal comfort, abundance of natural light and transitional spaces, might have had greater success as a residential building, instead of a workplace setting.

Other building types to consider might be commercial settings, such as shopping centres and hotels, educational settings such as schools and universities. There is sufficient repetition of these to warrant research.

In Section 8.4, the question of thermal comfort was speculated for other climates and countries. It had been suggested in Figure 8.10 that perception of the thermal environment vis-à-vis neutrality, comfort, acceptability and variability may differ according to climate type and national context, the latter summarising population's affluence, attitudes and expectations. This is yet to be supported by data and may involve repeating the present study in other national and climate settings.

8.5.2. Energy and the Commercial Office Building

The present study has relied upon government and owner-occupied office buildings, where there is often a direct link between comfort-related action and energy cost. The temperature resetting at RevH, for instance, was sanctioned by the organisation that owned and operated the building, hence stood to gain from such an adjustment.

There should be examination of the forces driving outcomes in commercial office buildings. In a situation where an office building is leased to tenants, the link between action and consequence is broken. The developer, often a real estate speculator, acts as mediator during the design stages; a building manager, after it becomes operational. They act on behalf of a building's users but their actions also represent other interests.

The case with UMNO, the only commercial building in the present study, illustrates this conundrum. The building's operators could not insist that their tenants opt for NV for fear of losing them to a competitive real-estate market.

On a related note, it was reported in Survey 2 that occupants of some buildings associated active modes with image and prestige, denoting a building's desirability and 'class'. It is conceivable that potential tenants assess a building by the presence of these systems, and that their absence may therefore represent a loss to the building's owner in the long run.

Clearly, the commercial office building faces a distinct set of pressures from its occupants, who are often transient and may not view energy and comfort in the same manner as those in owner-occupied buildings. Future research could look at how a building competes commercially for tenants, and where comfort and operational modes fit into the equation.

8.5.3. Climate, Comfort and Organisational Culture

It appears that the internal layout of offices can facilitate or hamper climate and comfort-related objectives. It is difficult to imagine how, for instance, the NV option for UMNO might have been reconciled with the use of full-height partitions (assuming, that is, its occupants had a preference for passive modes). All office interiors surveyed in the present study reflect their organisation's culture and needs. Partitions and workstations are typically laid out in response to rank and status of its occupants, their needs for privacy and security. In this regard, UMNO was either designed for a specific organisation type (that failed to materialise) or had ignored the question of organisational culture altogether.

The Singapore workplace, as seen in the buildings studied, is a combination of open-plan layout and full height partitions. Its occupants are immobile for most of the day, each is assigned to a workstation but is also reliant on some shared space. It is unclear how the objectives of Yeang's Bioclimatic Model could be met here, or indeed those of Hyde (2000) and Loftness et al. (1999). Future research might address the question of organisational culture by looking at, for example, Duffy's (1997) categories of Hive, Cell, Den and Club, and seeking out specific strategies for climate and comfort-related interventions.

8.5.4. Energy and the Psychoclimatic Model

The energy savings summarised at the end of Chapter 6 showed that a non-uniform indoor environment is viable. This study was, however, carried out in the context of an operational building, RevH, in which occupants were accustomed to an active-run thermal condition, and where limits on discomfort had been placed by the building's management. It was not possible, as such, to switch to passive or mixed modes. This constraint clearly limited the energy outcome, which should be viewed as conservative.

It stands to reason that greater savings would result from a tri-modal setting, such as is proposed by the Psychoclimatic Model. An estimation of this might be carried out via a simulation study.

8.5.5. Design Process

The design process has been the subject of much deliberation (Papamichael & Selkowitz, 1990; Zeisel, 1981), specifically in the context of environmental decision-making (Coldicutt, 1992; Watson, 1984). The process is, however, seen as finite, ending with the completion of the building.

The present thesis has highlighted the role that the occupant plays in modifying his/her environment. This was illustrated, for instance, with the solar tints in MES, which were installed long after the building had been completed. The notion that design ends at the start of occupancy is worth reviewing.

Future research might look into the broader continuum of decisions made across the life of a building, perhaps to seek out a framework of interventions for statutory controls and theoretical models. Statutory controls, in such a framework, might be targeted at the varying stages of a building's life, instead of just at the design stage, such as is the case with OTTV. This might be an interval of, say, 10 years, a timeframe that would allow for changes in population expectations and new technologies.

8.5.6. Mixed-Mode Options

The question of modes, it was suggested, should begin with a review of all available means of climate-control and modification, starting with traditional techniques and technologies and the principles they embody. In Singapore and hot humid conditions in general, there are few mixed-mode options. The most common thermal options consist of ceiling fans used in conjunction with NV (Rohles, Konz, & Jones, 1983) or AC (Lim, Rao, & Rao, 1979). Future research clearly needs to address the shortage of mixed-mode know-how.

The present thesis has suggested a further dimension to this notion of combining modes. It was noted in Survey 1 (see Section 5.1.3.4) that perception of light level correlated with thermal comfort, but not thermal sensation, a finding that was borne out by an earlier study (Rohles, Bennett, & Milliken, 1981). It is conceivable that the interaction between thermal and visual perception is climate-specific, that those living in warm climates may prefer less natural light as compared with those in cooler climates. Indeed, the manipulation of light may have an effect on thermal comfort that goes beyond sensation. If substantiated, this thermal-visual connectivity may be used to generate desired perceptions of comfort. Understanding and exploiting such interactions would give a new meaning to the notion of mixed-mode.

8.6. Thesis Conclusion

Research Question and Hypothesis

The thesis began by asking if there exists a gap between theory and application in terms of a building's response to the climate. It was a broad question in that it required an exploration of what it means to be climate-responsive and how a building might potentially perform if it were so. In the face of several definitions of the climatic approach, the thesis turned to the Bioclimatic Model by Yeang (1994). It cited evidence to suggest that gaps exist in the deliberation of climate, comfort and energy consumption, the three key tenets of the Model. This was followed by a review of the form and envelope of twenty-seven Singapore buildings and the logging of indoor conditions found in ten.

It was observed that the office building did not incorporate Bioclimatic principles of building shape, orientation and service core placement. The shell and electro-mechanical systems of these buildings appeared to make minimal effort in addressing climate. Climate exclusion, such as was in evidence, is in itself implicit of an approach, one in which outdoor conditions are either viewed unfavorably, or where climate ranks low in the face of other priorities. The importance of aesthetics, the outward appearance of the building, was noted to be one such competing priority.

The importance of the building skin as a communicator of design intent appears to be a significant factor in the design of the Singapore buildings, all of which show stylistic consistency predominantly in the manner of the Modern or International Styles. In the context of this aesthetic bias and the prevalence of curtain-wall systems, there appears to be an implicit and unresolved conflict between appearance and performance. Prescriptions of the Bioclimatic Model that have implications on the building's exterior, such as sunshades and side core placement, are clearly at odds with the question of style.

This ambivalence over style and performance was surprisingly evident in the two Bioclimatic buildings as well. Principles of Yeang's Model were compromised in MES and UMNO, in what appeared to be a prioritisation of the building's appearance over climatic response. This suggests that a designer's need to make a visual statement is a powerful force in architecture.

With regard to conditions inside the buildings, there appeared to be a greater level of climate-inclusion in the design of the visual condition than the thermal, as suggested by the large windows and attempts to bring in daylight to supplement artificial lighting. There was virtually no attempt to seek out alternatives to AC. The sole exception to this was UMNO, the newer of the two Bioclimatic buildings, in which NV was designed to be a workplace option.

It was noted that passive modes were often at odds with internal layouts, which appear to be driven by organisational culture, reflecting hierarchy and status. The role of organisational culture was also in evidence in the attire worn by building's occupants, typically ties and jackets, which appeared to contradict comfort needs. Subjects surveyed seemed to view active modes as creating a favorable public perception of their organisation.

Having found evidence of the gap between theory and application, the thesis turned to the question 'why?' In this regard, it was hypothesised that this was due, in part at least, to the question of occupant comfort, specifically comfort expectation vis-à-vis indoor variability. This was premised on the difference between a building that is climate-responsive and one that is not. The climate-responsive building will, by virtue of its link with the climate, be more variable in terms of indoor conditions than one that relies on electro-mechanical systems.

To test this hypothesis the present study monitored indoor variability and occupant response. It was found that variability was prevalent, even in active-reliant spaces, and that occupant tolerance for the same was lowest in the workspace. Findings from the multiple sorting procedure showed that variability was a criterion affecting comfort expectations and that it was contingent on activity. The office building could be, on the basis of activity, be delineated into three zones: Work, Support and Transit, each representing differing levels of acceptance for operational modes and indoor variability.

With this finding, the thesis hypothesis turned from question to proposition. A tri-modal model for office building, premised on comfort expectations, was proposed. The question asked then was if it could be supported in a real-world setting and what, if any, would be its impact on energy consumption.

The final phase of the thesis attempted to answer this via a longitudinal survey and energy monitoring at RevH, an exercise that supported the model and showed energy savings as a results of thermostat re-setting based on the three thermal zones. A tri-modal strategy for comfort in office buildings in hot humid conditions, named the Psychoclimatic Model, was shown to be useful and applicable.

Theory, Knowledge and Action

The thesis has shown the limitations of both the Bioclimatic and Conventional approaches. Evidence suggests that neither is able to adequately address how buildings should respond to climate and comfort. The Bioclimatic building is not able to live up to the Model on which it is based, partly due to competing agendas and assumptions about the nature of comfort. The Conventional building does not address climate in a positive manner, perhaps due to concerns that occupant comfort might be compromised as a result.

Critical to the equation, and missing from both approaches, is the voice of the building occupant. The Bioclimatic advocates, such as Yeang and Hyde, speak of comfort as a key objective, yet the two Bioclimatic buildings studied here were deemed uncomfortable by their occupants. This was established through direct feedback or inferred from the fact the buildings are altered and their systems not used as intended. In the Conventional buildings, the prevalence of adaptive response, particularly use of jackets, and failure to engage environmental controls, such as light switches and blinds, suggest that here too, assumptions about user needs are inadequate.

Coldicutt's (1995) Taxonomy of Ignorance, first discussed in Chapter 2, is used here to summarise the Bioclimatic and Psychoclimatic Models and their applicability to problem solving. The four questions from her taxonomy - Confusion, Uncertainty, Inaccuracy and Absence - are addressed in Table 8.4 and Figure 8.12 in the context of the two Models.

Taxonomy of Ignorance	**Bioclimatic Model**	**Psychoclimatic Model**
CONFUSION *"How should the key concepts be defined?"*	Comfort and energy consumption seen as a product of the design process, which consists of a series of inputs and outputs. Users are assumed to be willing participants in the management of their comfort via manipulation of environmental controls.	Comfort and energy consumption are outcomes of an act of negotiation that continues into the building's operational stage. User willingness to participate is taken into account in the deployment of environmental controls. In the work-areas, for instance, the objective is to provide stability and uniformity without a need for user intervention.
UNCERTAINTY *"What degree of certainty is relevant?"*	The Bioclimatic building incorporates passive and active modes in which the user is given the choice of which mode to operate. It is assumed that uncertainty, defined here as variability of indoor conditions due to links with outdoors, will be deemed acceptable at certain times of the day.	The deployment of modes is made on the basis of activity zones: Work, Support and Transit. These, in turn, are premised on occupant expectations. 'Certainty' is critical in the Work zone, where users prefer active modes and appear reluctant to intervene with regularity.
INACCURACY *"How accurate does it need to be?"*	Accuracy deemed critical in both active and passive modes. In the case of UMNO, for instance, this is achieved through detailed scientific investigation of airflow, for which a system of operable doors and windows was created for purposeful regulation of air movement for comfort cooling.	Accuracy deemed critical only in the Work zone via active modes that stay within a narrow bandwidth of conditions. The need for accuracy diminishes with Support and Transit zones.
ABSENCE *"What should be present in or absent from the problem?"*	See Figure 8.12 for a summary of Absence.	

Table 8.4. Taxonomy of Ignorance

Figure 8.12 is an elaboration of Yeang's Bioclimatic Approach (see Section 1.2). The dark inserts indicate the original framework, the shaded and dotted inserts refer to 'Absences'. These are variables that are known, from past and present studies, to affect outcomes of comfort and energy consumption.

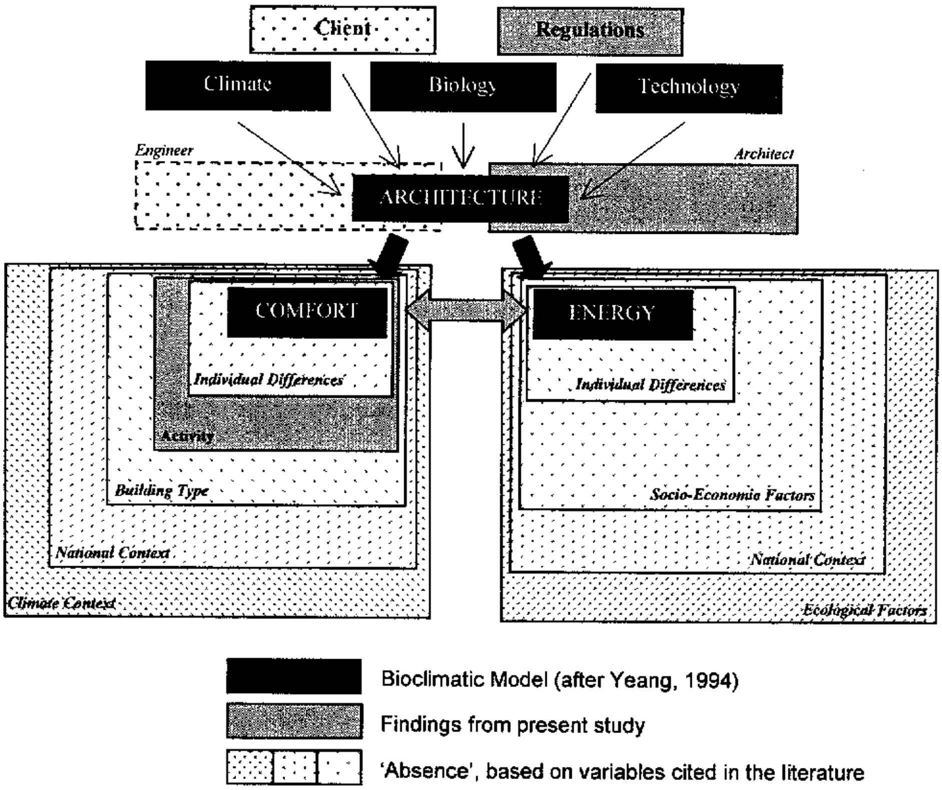

Figure 8.12. 'Absence' & 'Confusion' and the Bioclimatic approach[4]

With regard to the topmost tier of 'inputs', it was found that the extent to which clients and codes are supportive of climatic response is critical to outcome. Yeang (personal communication, September 13, 2001) suggested that clients do not always share the same concerns as architects, especially when solutions, such as external sunshades, represent additional cost. The present study has suggested that regulatory control mechanisms, such as OTTV, play a significant role but often do not go far enough.

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[4] Absence addresses the question 'is the relevant knowledge present and sufficiently emphasised?' Confusion addresses the question 'is there a distortion in definition of the kind of knowledge, resulting in a definition that is not fully relevant to the problem?'

The present study has also shown that a building's envelope is important to the architect as a means of making an aesthetic statement. A preference for a particular style affects the likelihood of a designer addressing climate at the conceptual stage when the form and envelope of a building are being decided. It is not clear from the present study what drives the engineer and how s/he might view climate vis-à-vis the electro-mechanical systems. This could perhaps be another avenue for future research.

Finally, the thesis suggests that an occupant's perception of comfort affects energy consumption through decisions made by its users in the everyday acts of interacting with the building. In this regard, the key contribution of the present thesis has been the proposal of the Psychoclimatic Model which emerged from findings that a building's performance, in terms of climate, comfort and energy consumption, is ultimately contingent on occupant comfort expectations.

The Psychoclimatic Model synthesises findings on comfort expectations, vis-à-vis activity and variability, with the nature of indoor variability during active and passive modes. It acknowledges that in the making of buildings there can be competing agendas, such as the appearance of the building, and priorities, such as those of the client. As a template that is targeted at the design process, the Model tables user's expectations in a manner that is prescriptive and yet flexible and context-specific.

This represents an advancement over the Bioclimatic Model, shown in the present thesis to be an approach that is largely technical, focussed around the question of climate and energy consumption. The Bioclimatic approach to occupant comfort appears to be underpinned by assumptions of universality of need.

The potential of Psychoclimatic Model has been illustrated here, first, in terms of possible energy savings, and second, as a strategy for operating the office building as a non-uniform entity. In this regard, the present thesis has challenged the assumed need for uniformity of indoor conditions on the basis of which office buildings in Singapore appear to be designed and operated. It has also highlighted the role that the building envelope plays in the presence of indoor variability. The proposed Model suggests that envelope permeability and system control can vary across the building in a manner that reduces reliance on active modes. This should yield energy savings without compromising the comfort of the building's occupants.

The key argument of the present thesis is that a building is more than a product that is delivered to its users; the 'design process' continues long after a building has been occupied in the many adaptations and interventions by its occupants. It could be argued that Yeang's Ecological approach (1998), successor to his Bioclimatic Model, suffers from the same oversight as the Bioclimatic Model. The user is briefly mentioned in an extensive list of criteria, actions and imperatives, without acknowledgement that users are not the same the world over, nor indeed share the same concerns. Whilst Yeang is not dogmatic in his prescriptions, there is an implicit assumption that global problems, such as greenhouse gas emissions, require a global solution. The global nature of the problem is assumed to require universally applicable and technology-driven answers.

The new framework sought, in the form of the Psychoclimatic Model, emphasises the needs of the user and a flexibility of outcome. This complexity, however, is unlikely to be viewed as convenient by either the theorist or the design practitioner, each looking for encompassing frameworks and universal guidelines. In doing so, the Model proposed here implicitly suggests that a search for a universal answer to environmental problems, the 'magic bullet' of technical know-how, may well be something of a folly.

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APPENDIX A

Appendix A1. Instruments and Instrumentation

Instruments:

a. Temperature

Instrument: Tiny Talk II Temperature Loggers *(up to 25 loggers used at a time)*
Unit: degree Celsius
Range: -10°C to +40°C
Accuracy: +/- 0.2°C
Resolution: 0.3°C
Inter-logger reliability: +/- 0.2°C

b. Dry Bulb and Wet Bulb Temperature (Relative Humidity)

Instrument: Sling Hygrometer *(up to 4 hygrometers used at a time)*
Unit: degree Celsius
Range: -5°C to 50°C
Resolution: 0.25°C
Reliability between temperature loggers and hygrometer DBT reading: +/- 0.25°C

c. Air Movement

Instrument: Kestrel 1000 Pocket Wind Meter
Unit: metre per second
Range: 0.3 m/s to 40 m/s
Accuracy: +/- 3%
Resolution: 0.1 m/s

Instrument: VelociCalc Plus[1] (multi-parameter ventilation meter – Model 8384)
Unit: metre per second
Range: 0 m/s to 50 m/s
Accuracy: +/- 1.5%
Resolution: 0.01 m/s

d. Illuminance

Instrument: TES Digital Illuminance Meter (Model TES-1334)
Unit: Lux
Range: 0 – 20,000 Lux
Accuracy: +/- 3%
Resolution: 1 Lux

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[1] The VelociCalc Meter was loaned from the Public Works Department of Singapore and available only for the logging of RevH and UMNO buildings.

Instrumentation:

Indoor Air Temperature

Tiny Talk temperature loggers were used for passive and active IAT logging. Each logger is the size of a camera film cartridge and comes with a sensor mounted on a wire that extends from the its body. Prior to use, it is programmed for the number, frequency and start-time of readings, using a proprietary software and cable that interfaces the logger with any PC.

Loggers were typically programmed for half-hourly readings and taped to furniture partitions, 1.8m above floor level. Where the floor was without furniture, they were suspended from the ceiling with a string. Loggers situated in the perimeter zone were shielded with a paper 'umbrella' to ensure that the sensor was always in the shade.

As further protection, each logger was inserted into a 'Ziplock' bag, except for its sensor, and labeled with a tag that explained its purpose and sensitivity. At the start of each period of monitoring, all loggers were tested for inter-instrument reliability. This involved a short period of simultaneous logging, often inside a sealed space (such as a cabinet) that ensured stable and uniform conditions. The output of the loggers, combined into a single file, would highlight any one instrument that deviated from the rest or malfunctioned in any way.

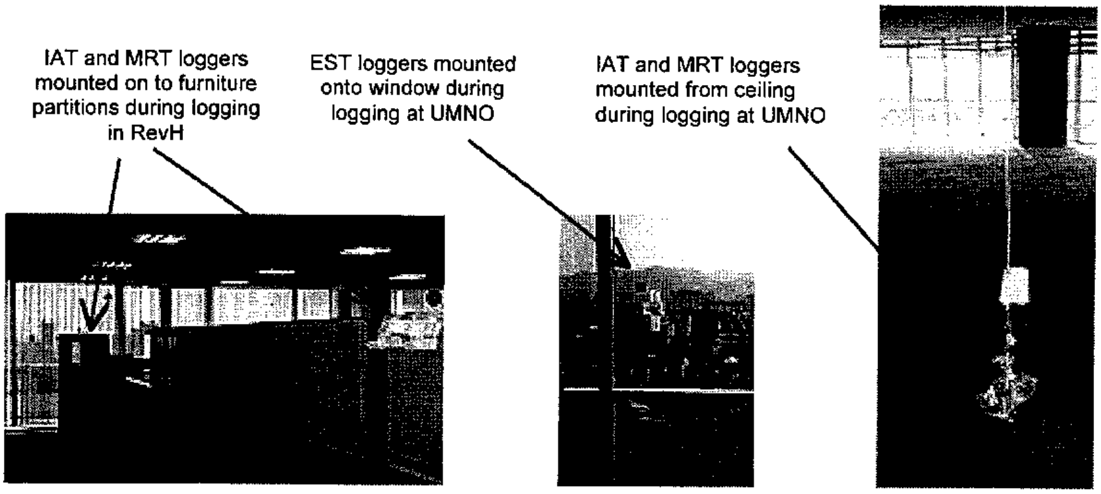


Figure A1.1. Temperature loggers

The sling hygrometers were used primarily during occupant surveys to record IAT and RH at each occupant's workplace. The same hygrometers were also used for the logging of RH during passive and active logging. Inter-instrument reliability was also noted for the four hygrometers at the start of each period of logging, typically by taking simultaneous readings at a particular location.

Mean Radiant Temperature

Tiny Talk temperature loggers were adapted for MRT readings by inserting the sensor of the logger into a ping pong ball that had been painted matt black and pierced to create a single small hole. The sensor, once inserted, was held in place with non-reflective tape. When each logger was retrieved, at the end of a period of logging, the sensor was checked to ensure that it had remained fully inserted throughout the period of logging, i.e. there had been no tampering.

Envelope Surface Temperature

EST readings were taken with Tiny Talk temperature loggers. The logger was taped onto the surface being monitored, always on the face *inside* the building. The sensor was held in contact with the glass or wall surface using a silver reflective adhesive tape that was at least 6x6 cm in size. With glass surfaces, a second matching piece of the tape was stuck to the outside surface at precisely the same location as the first tape on the inside, creating a sandwich effect. This was intended to protect the sensor from direct and indirect solar radiation from either side of the glass panel.

Air Movement

The Kestrel Wind Meter yielded reliable readings at air speeds above 0.3m/s, particularly where air movement was variable and gusty. The VelociCalc Meter was reliable at wind speeds below that threshold, but only if the airflow was steady and directional. In cases of low air speeds, incense sticks were used to generate a stream of smoke, which allowed for observation of the direction of airflow.

Outdoor onsite readings were not reliable due to turbulence around the building's perimeter. Outdoor wind speeds presented in the present thesis were recorded at the nearest meteorological station, during the period of logging.

Indoor Illuminance

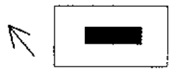
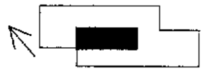
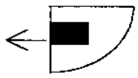
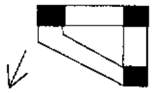
During Survey 1, the light meter was placed at several locations at an occupant's desktop and averaged. In all other cases the meter was held in a position, at approximately desktop height, facing the source of light (typically the windows).

Outdoor light readings were often not possible as the instrument upper limit was easily reached on sunny days.

Outdoor DBT and MRT

Each period of logging was supplement by outdoor readings of dry bulb and mean radiant temperature. Tiny Talk loggers were used in the same manner as IAT and indoor MRT readings, but with added protection to ensure weather protection. This involved extra layers Ziplock bags and adhesive tape. The outdoor DBT logger was mounted in a location where it would be in perpetual shade. The outdoor MRT logger was mounted in a position where it would be exposed to the maximum amount of solar radiation.

Appendix A2. Summary of 27 Buildings Surveyed via Archival Search

Case Building *Design strategy and site*	**Gross Floor Area**	**Total Façade Area**	**OTTV**	**WWR**	**Form, Orientation, Placement of Service Cores**
Capitaland Tower - 1 *52-storey tower & podium in high-density area within CBD*	119494	39218	39.00	57.96	Central core 
Capital Square @ China Square – 2 *16-storey tower in high-density area in the CBD*	55899	15112	44.65	52.00	Central core 
Prudential Tower @ China Square - 3 *30-storey tower in high-density area in the CBD*	Not Available	13271	44.42	50.73	Central core 
John Hancock Tower – 4 *20+-storey development in high-density area within CBD*	Not Available	7985	26.28	34.23	Single side core (NW) 
The Exchange – 5 *20+-storey development in high-density area within CBD*	Not Available	17604	19.74	13.70	Single side core (N) 
JTC Building – 6 *32-storey tower & podium on green-field site in the West*	72651	30325	37.83	50.94	Central core + sunshading on NE façade. 
German Centre – 7 *Podium development in medium-density area in the West*	Not Available	7113	44.55	36.83	Two side cores (N & W) 
Primefield Landmark Building – 8 *Podium development in medium-density area in the West*	Not Available	3720	41.07	44.84	Side cores on three corners 
URA Building– 9 *16-storey tower & podium in high-density area within CBD*	47033	6195	29.39	39.95	Two side cores (NE&SW) + sunshades on all windows 
NKF Building- 10 *12-storey tower & podium on green-field site just outside CBD*	9825	4913	43.97	37.00	Side core (SE) 
Paragon Extension –11 *14-storey tower in high-density area within CBD – one façade abutting existing development*	22275	10151	41.45	33.72	Two side cores (NW and SE) 
Raffles Link @ Nicoll Highway – 12 *7-storey podium in high-density area within CBD*	43588	11054	34.82	56.90	Two cores; one on side (SW) Sunshading on NW façade 
Development @ Hill Street – 13 *5-storey podium in medium-density area within CBD*	Not Available	4414	37.60	56.53	Central core 
Development @ Carpenter Street/ New Bridge Road - 14 *6-storey podium in medium-density area within CBD – one façade abutting an existing development*	Not Available	659	39.3	79.70	Single side core (NW) 

All arrows indicate North.
Dark insert indicates a building's service core.

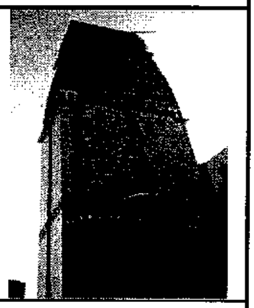
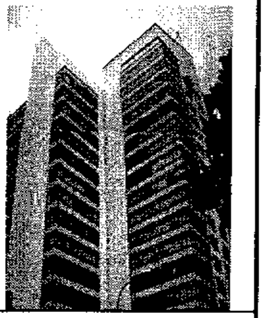
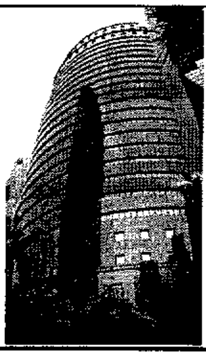
Table A2.1. Data from Archival Search

Case Building *Design strategy and site*	**Gross Floor Area**	**Total Façade Area**	**OTTV**	**WWR**	**Form, Orientation, Placement of Service Cores**
Development @ Tampines Central 1/2 – 15 *8-storey podium in medium-density area in the East*	14868	5088	43.96	43.17	Central core 
Development @ Scotts Road – 16 *18-storey tower in high-density area in the CBD*	17815	9618	35.88	58.00	Single side core (NE) 
Development @ Carpenter Street – 17 *6-storey podium in medium-density area within CBD – one façade abutting an existing development*	1471	650	44.30	45.20	Single side core abutting existing development 
Development @ Maude Road – 18 *4-storey podium in medium-density area within CBD – one façade abutting an existing development*	1457	443	38.22	23.50	Single side core (NW) 
Development @ Armenian Street – 19 *4-storey podium in medium-density area within CBD – two façades abutting existing developments*	2484	715	40.69	24.00	Single side core (E) 
Development @ Tanjong Pagar – 20 *11-storey tower in high-density area within CBD – one façade abutting an existing development*	3722	1397	44.40	60.00	Single side core abutting existing development 
Development @ Havelock/Magazine Road – 21 *7-storey development in high-density area within CBD*	Not Available	4947	42.90	42.20	Not Available
Development @ Jalan Afifi/Paya Lebar Road – 22 *8-storey development in high-density area within CBD*	5200	2095	37.77	46.30	Not Available
Alexandra Point – 23 *20+-storey development in high-density area outside CBD*	Not Available	13593	38.89	61.40	Not Available
79 Anson Road – 24 *20+-storey development in high-density area within CBD*	Not Available	9368	41.24	50.42	Not Available
NTUC Income @Tampines Central 6 – 25 *Podium development in high-density area in the East*	Not Available	2402	32.26	39.47	Not Available
DBS Centre @Tampines Central 1 – 26 *Podium development in high-density area in the East*	Not Available	4809	43.24	36.04	Not Available
8-Storey Development @ Tampines Central/6 – 27 *Podium development in high-density site in the East*	Not Available	4950	33.70	41.07	Not Available

All arrows indicate North.
Dark insert indicates a building's service core.

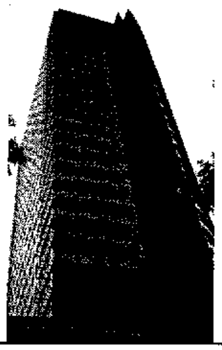
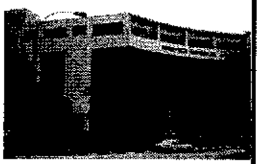
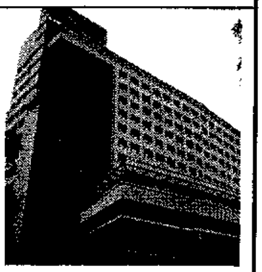
Table A2.1. Data from Archival Search
(continued from preceding page)

Appendix A3. Summary of 10 Buildings Surveyed for Indoor Conditions

	ATRIUM / ENTRANCE FOYER	LIFT LOBBY	CAFETERIA	OFFICES	TOILET	IMAGE
Case 1 Capitaland Towers	24.3°C*/ 61%* Full-height glass. No sunshades. Much daylight	24.0°C / 53% 60 Lux No windows	21.0°C / 67% Full height glass on one side Much daylight	23.5°C / 64% 560 Lux* Full height windows with blinds Ceiling gird of flourescent lights Senior staff situated along perimeter	27.0°C / 50% 340 Lux No windows	
	Location: Central Business District Type: Commercially leased office space Observations: High partitions on plan perimeter Curtain wall exterior/ International Style design with Post-Modern elements					
Case 2 Capital Square (China Square, Church Street)	24.0°C / 61% 650 Lux Full height glass. Much daylight	23.0°C / 60% 170 Lux No windows	No Cafeteria	23.5°C* / 58%* 570 Lux* Full height windows with blinds and shades – mostly shut Ceiling grid of flourescent lights Full height partition offices along perimeter	24.5°C / 57% 130 Lux No windows	
	Location: Central Business District Type: Commercially leased office space Observations: Full height partitions on plan perimeter Curtain wall exterior/ International Style					
Case 3 Prudential Towers (China Square, Cecil Street)	25.0°C / 68% 550 Lux Full height glass Much daylight	21.8°C/ 65% 100 Lux No windows	No Cafeteria	23.1°C*/ 61%* 610 Lux* Full height windows with 2 shades Ceiling grid of flourescent lights	24.8°C / 56% 600 Lux 2/3 height windows with frosted glass	
	Location: Central Business District Type: Commercially leased office space Observations: Full height partitions on plan perimeter Curtain wall exterior/ International Style					
Case 4 John Hancock Tower	28.0°C/ 81% (door to exterior left open + high ceiling with poor AC throw) 350 Lux Mostly daylight due to poor reach of electrical light	23.0°C/67% 50 Lux Window with frosted glass letting in very low levels of daylight	No cafeteria	21.6°C* / 63%* 520 Lux* Full height windows with shades – mostly shut. Ceiling grid of flourescent lights	25.5°C / 50% 60 Lux No windows	
	Location: Central Business District Type: Commercially leased office space Observations: High partitions on plan perimeter Curtain wall exterior/ International Style					
Case 5 The Exchange	29.3°C / 74% Semi outdoor entrance foyer in passive mode Mostly daylight	22.5°C / 68% 80 Lux No windows	No Cafeteria	21.3°C* / 74.5%* 505 Lux* Half-height windows with blinds Full height partitions along perimeter Ceiling grid of flouresecnt lights	Not Accessible	
	Location. Central Business District Type: Commercially leased office space Observations: High partitions on plan perimeter Curtain wall exterior/ International Style					

** Value shown here represents the mean of several readings taken in the same space.*

Table A3.1. Summary of Indoor Conditions

	ATRIUM / ENTRANCE FOYER	LIFT LOBBY	CAFETERIA	OFFICES	TOILET	IMAGE
Case 6 Jurong Town Corporation – The Summit	23.3°C / 71% 530 Lux Glass envelope with large skylight External sunshades present Much daylight	23.8°C / 64% 380 Lux No windows	23.1°C* / 61%* 160 Lux Near skylight	23.1°C* / 61%* 500 Lux* Two-third height windows with shades – mostly shut Ceiling grid of flourescent lights	26.5°C / 80% 340 Lux no windows	
	Location: Central Business District Type: Commercially leased office space Observations: Full height partitions on plan perimeter Curtain wall exterior/ International Style					
Case 7 German Centre	20.8°C / 59% 620 Lux Full height glass on one side Bright ceiling lights	23.5° / 59% 90 Lux Windows letting in some daylight	22.5°C / 65% 150 Lux Full height glass on one side No blinds and much daylight	23.7°C* / 56%* 315 Lux* Two-third height windows with blinds Ceiling grid of flourescent lights Senior staff on periphery	28.5°C / 71% 120 Lux Small windows Negligible daylight	
	Location: Business Park outside city centre Type: Commercially leased office space Observations: High partitions on plan perimeter Modern Style exterior with strip windows					
Case 8 Primefield Landmark	23.0°C / 59% 390 Lux Full height glass on one side with moderate amounts of daylight	27.5°C / 59% Mechanical ventilation 135 Lux No windows	No cafeteria	21.4°C* / 62%* 375 Lux* Two-third height windows – lower half tinted No blinds or shades Ceiling grid of flourscent lights	28.5°C / 64% 160 Lux High windows with frosted glass Some daylight	
	Location: Business Park outside city centre Type: Commercially leased office space Observations: Modern Style exterior with extensive glazing					
Case 9 URA Building	21.5°C / 65% 360 Lux Skylight	22.5°C / 65% 270 Lux Half-height windows to one side	No cafeteria	23.3°C* / 60%* 670 Lux* Half-height windows with external sunshades and internal blinds Ceiling grid of flourescent lights	27°C / 53% 330 Lux No windows	
	Location: Central Business District Type: Owner-occupied, government building Observations: High partitions on plan perimeter Extensive external sunshading and window recesses.					
Case 10 Revenue House**	24.5°C / 50% 400 Lux Full height glass envelope With much daylight	22.5°C / 50% 200 Lux No windows	23°C / 57% 200 Lux Two-third height windows are one end blinds drawn	22°C*/ 53%* 175 Lux* (ambient lighting) Two-third height windows with blinds Ceiling grid of flourescent lights with desktop lamps	25.5°C/ 53% 50 Lux No windows	
	Location: On the perimeter of the Central Business District Type: Owner-occupied, government building Observations: High partitions on plan perimeter Curtain wall exterior/International Style.					

** Value shown here represents the mean of several readings taken in the same space.*

*** Case 10 in this table is a new building that does not correspond with Case 10 in sample of 27 case studies for envelope review in the earlier section*

Table A3.1. Summary of Indoor Conditions
(continued from preceding page)

Appendix A4: Summary of 4 Buildings Surveyed for Passive and Active Logging

A4.1. URA Centre

1. Year Built: 1997
2. Location: Singapore
3. Site: Urban, high-density plot within CBD
4. Form: Tower and podium + 2 basement carpark levels
5. Tenancy: Owner-occupied, statutory board
6. No. of Floors : 16 (inclusive of 4-storey podium)
7. Floor to floor height Unknown
8. Gross Floor Area: 34059 m^2
9. Air-conditioned Area: 22562 m^2
10. Floor Depth: 23 m (from window to window)
11. OTTV: 28.39 W/m^2
12. Window to Wall Ratio: 40%
13. Passive Features: Recessed windows with horizontal fins. Skylight in atrium (covering 20% of total roof area). Strategy for daylighting.
14. Active Systems: Central air-conditioning. Ceiling grid of fluorescent light fittings. Dimmer control and energy saving lamps. Variable speed drive for AHUs equipment and BTU load sequencing which is controlled and monitored by the building automation system.
15. Occupant Control: Occupants have no direct control over temperature. Thermostats are not accessible to individuals – all problems with thermal discomfort have to be referred to the management. Ambient electrical light is zoned according to sections of the floor covering groups of workstations with 2-3 lighting zones per floor. Each workstation has desktop lighting. Blinds are provided for windows, giving those sitting next to windows some control over light levels.
16. Accolades: Shortlisted as one of three Singapore entries for the Year 2000 'ASEAN – Energy Efficient Award.' Reportedly one of the best examples of intelligent buildings in Singapore.

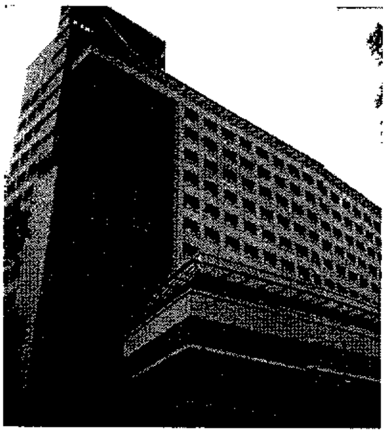


Figure A4.1.URA Centre

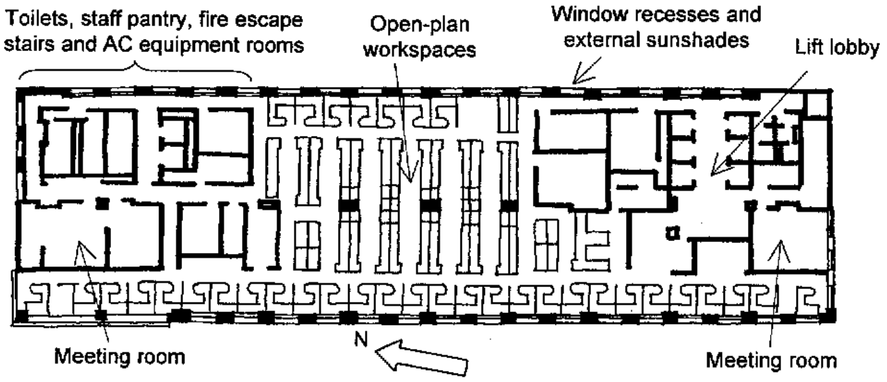


Figure A4.2.Typical URA Office Floor

A4.2. Revenue House

1. Year Built: 1995
2. Location: Singapore
3. Site: Urban, high-density plot outside CBD
4. Form: Tower and podium +3 basement carpark levels
5. Tenancy: Owner-occupied, government department
6. No. of Floors: 24 (inclusive of 4-storey podium)
7. Floor to floor height 4.3 m
8. Gross Floor Area: 108,000 m^2
9. Air-conditioned Area: 83,300 m^2
10. Floor Depth: 48 m (from window to window)
    18 m (from window to core)
11. OTTV: 34.5 W/m^2
12. Window to Wall Ratio: 40%
13. Passive Features: Service cores face East and West orientations. Double-glazed tinted windows with 19mm air-gap. External sunshades (podium level only). Strategy for daylighting.
14. Active Systems: Central air-conditioning. Ceiling grid of fluorescent light fittings. Perimeter photocells for adjustment of indoor light levels according to availability of daylight. Air-conditioning system responsive to load fluctuations.
15. Occupant Control: Blinds for windows. 2-3 lighting zones per floor supplemented with task lighting. Thermostat control is central.
16. Accolades: Winner of the Year 2000 ASEAN award for Energy Efficiency.

Figure A4.3.Revenue House

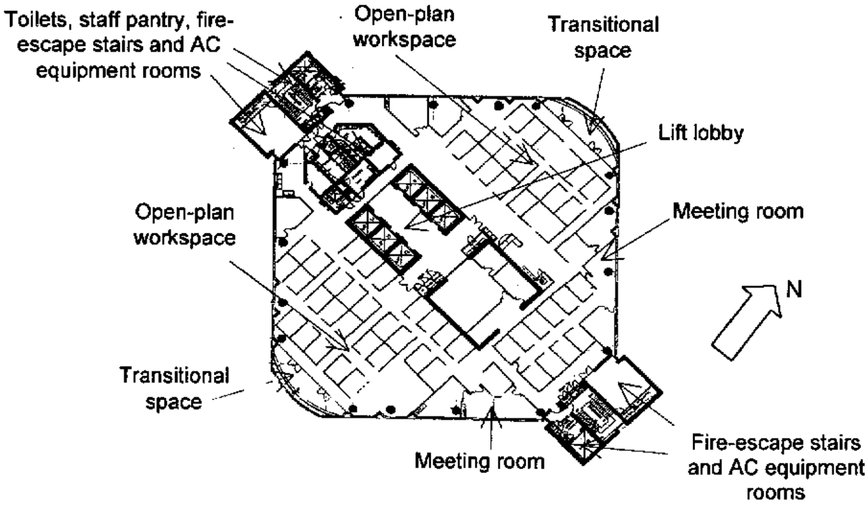


Figure A4.4. Typical RevH Office Floor

A4.3. Menara Mesiniaga

1. Year Built: 1992
2. Location: Kuala Lumpur, Malaysia
3. Site: Suburban green-field site next to motorway
4. Form: Tower and podium with semi-basement parking
5. Tenancy: Owner-occupied, private company
6. No. of Floors: 14.5
7. Floor to floor height 3.9 m
8. Gross Floor Area: 11,364 m^2
9. Air-conditioned Area: 7,100 m^2
10. Floor Depth: 30 m (from window to window)
    23 m (from window to core)
11. OTTV: Not available
12. Window to Wall Ratio: 80 % on all sides except E(20%)
13. Passive Features: Service core faces East. External sunshades designed to relate with solar load. Conscious strategy for daylighting. Lift lobbies, escape staircases and service spaces naturally ventilated and lit. Transitional spaces (balconies) on every office floor. Solar tints on most windows (user-installed) to reduce glare.
14. Active Systems: Central air-conditioning. Ceiling grid of fluorescent light fittings. Lighting in office space adjustable to 25%, 50% or 100% intensity, depending on time of day and usage. Variable-air-volume supply for optimal delivery. Provision for future solar-cell installation.
15. Occupant Control: Occupants have no direct control over temperature or light. Electrical light switches are zoned according to sections of the floor covering groups of workstations. 2-3 Lighting zones per floor. No blinds are provided for windows. Thermostat control is central. Thermostats are not accessible to individuals – all problems with thermal discomfort have to be referred to the management.
16. Accolades: Regarded as one of the first examples of an office building in the hot-humid tropics designed with Bioclimatic principles. Winner of PAM Architectural Excellence Award, the Aga Khan Award, RAIA International Award and AIA citation.

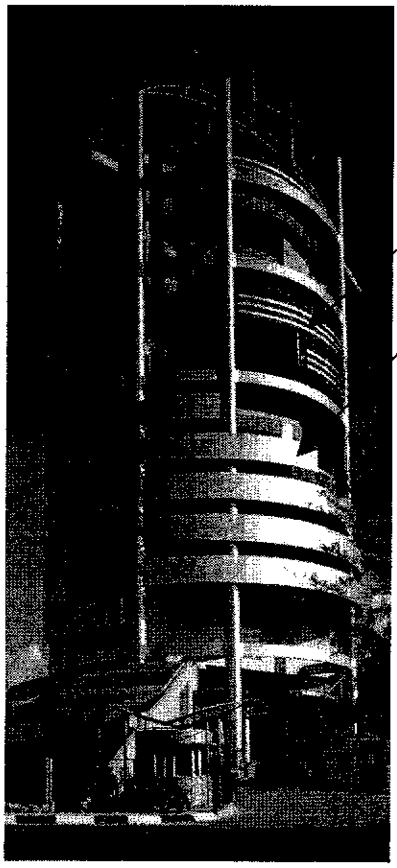


Figure A4.5. Menara Mesiniaga

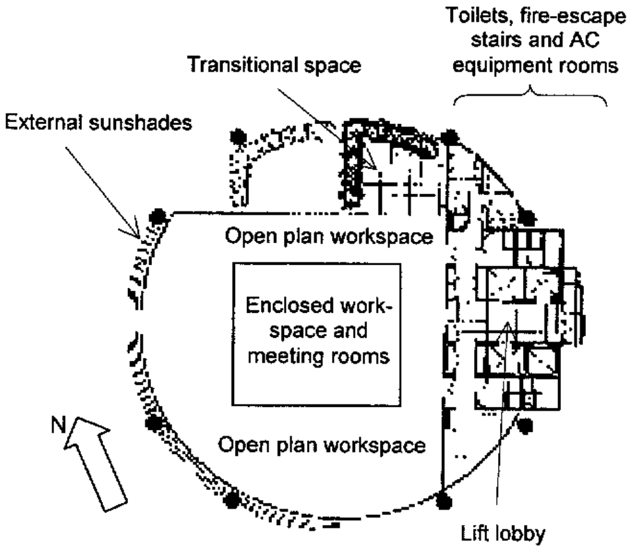
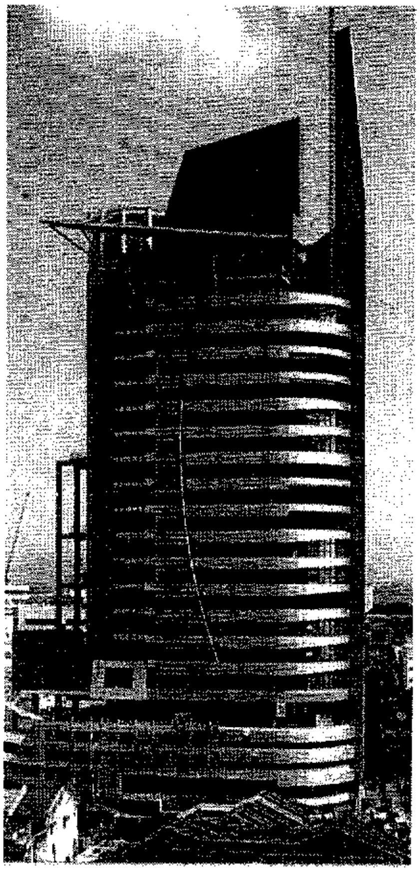


Figure A4.6. Level 9 MES
(see Appendix B10 for all other floors)

A4.4. Menara UMNO

1. Year Built:	1998
2. Location:	Penang, Malaysia
3. Site:	Urban high-density plot within city centre
4. Form:	Tower and podium (parking from levels 3-5)
5. Tenancy:	Commercial lease with multiple tenants
6. No. of Floors:	21
7. Floor to floor height	3.85
8. Gross Floor Area:	10,900 m^2
9. Air-conditioned Area:	7,400 m^2
10. Floor Depth:	18 m (from window to core)
11. OTTV :	Not available
12. Window to Wall Ratio:	80% except SE facade

13. Passive Features: Service core faces SE. External sunshades designed to relate with solar load. Strategy for daylighting. Lift lobbies, escape staircases and service spaces naturally ventilated and lit. Transitional spaces (balconies) on every office floor. "Wind wing-walls" designed to bring natural ventilation option to all tower floors.
14. Active Systems: Central air-conditioning. Ceiling grid of fluorescent light fittings.
15. Occupant Control: Blinds for windows. 2-3 lighting zones per floor. Thermostat control is central
16. Accolades: Highly regarded example of Bioclimatic office building in the hot-humid tropics. Winner of RAIA International Award.



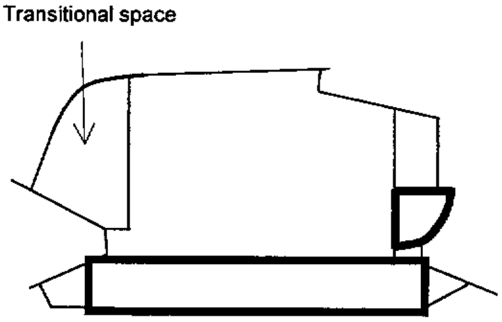


Figure A4.8. Schematic of UMNO floors with W-facing transitional space

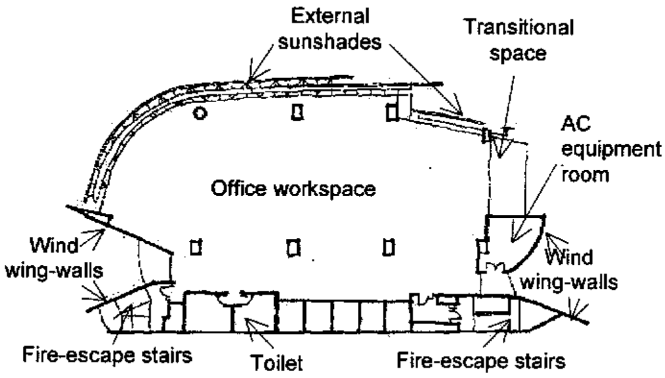


Figure A4.7. Menara UMNO

Figure A4.9. Plan of UMNO floors without W-facing transitional space

Appendix A5: Summary of Weather for Period of Logging

The data presented in this section is a summary of DBT and RH levels recorded at the nearest meteorological station for the respective period of logging. The hourly data from these graphs is available in the Thesis Data CD. Also in the same CD are the ½ hourly Out DBT and Out MRT readings that were recorded with the Tiny Talk loggers in the vicinity of each building.

Meteorological data for wind speeds, global solar radiation and (periods of) rainfall are shown in Appendices A6-A9 and Chapter 4 (Passive and Active logging) against the relevant indoor summarises.

The data is summarised in chronological sequence:

- Revenue House - 26th October to 9th November 1999
- Menara UMNO - 19th to 25th January 2000
- Revenue House - 29th January to 8th February 2000
- URA Centre - 10th March to 20th March 2000
- Menara Mesiniaga - 5th May to 15th May 2000

A5.1. Revenue House – 26th October to 9th November 1999

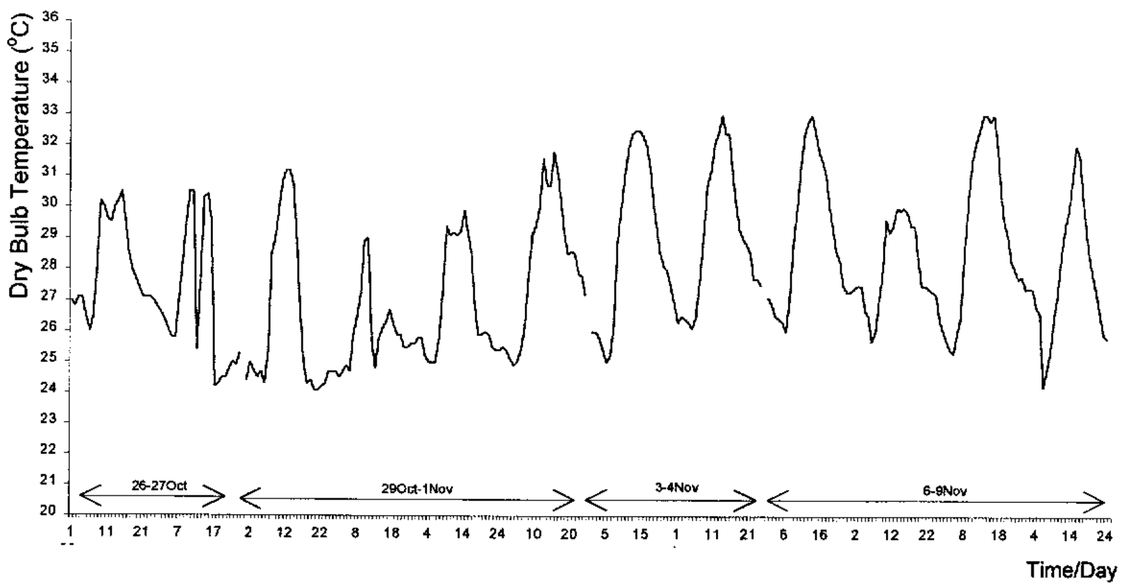


Figure A5.1. Outdoor DBT for RevH (1999)

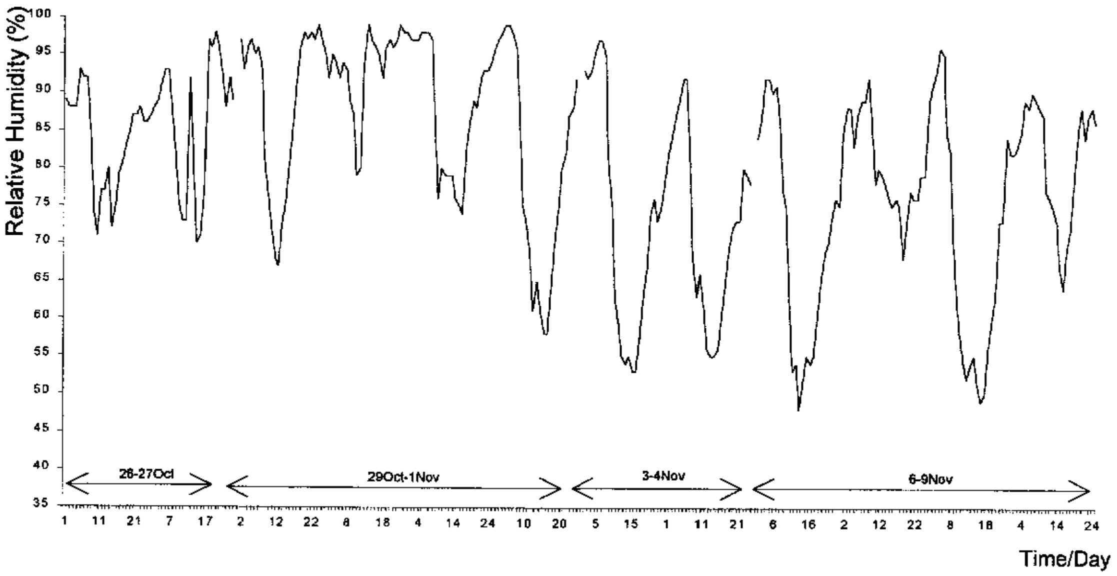


Figure A5.2. Outdoor RH for RevH (1999)

A5.2. Menara UMNO – 19th to 25th January 2000

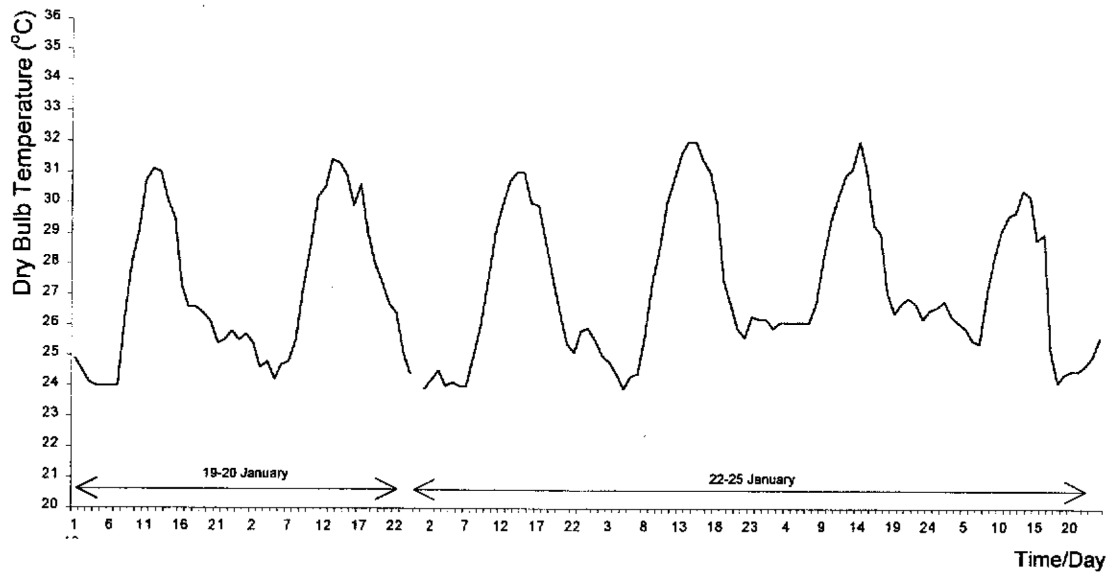


Figure A5.3. Outdoor DBT for UMNO

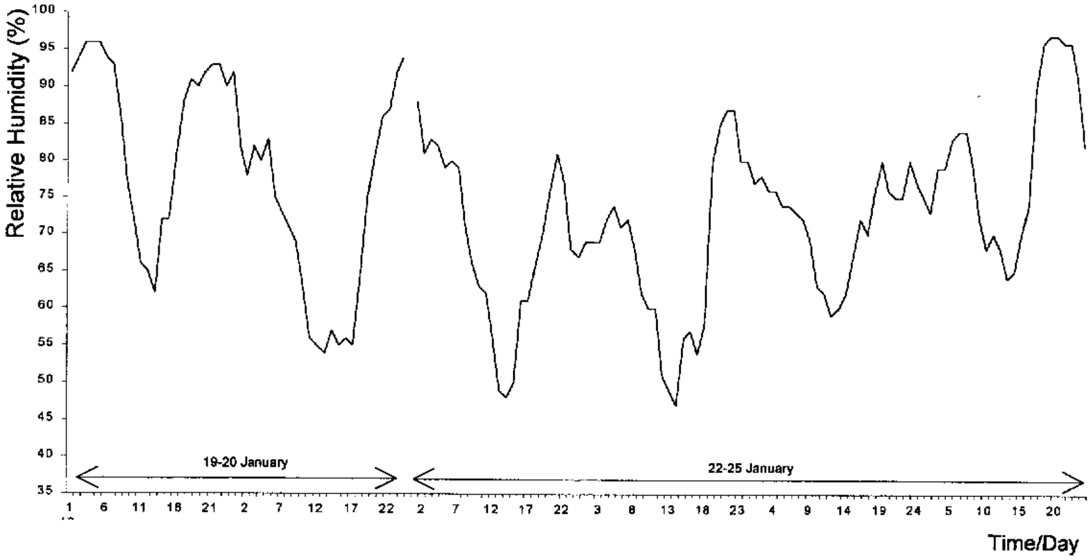


Figure A5.4. Outdoor RH for UMNO

A5.3. Revenue House – 29th January to 8th February 2000

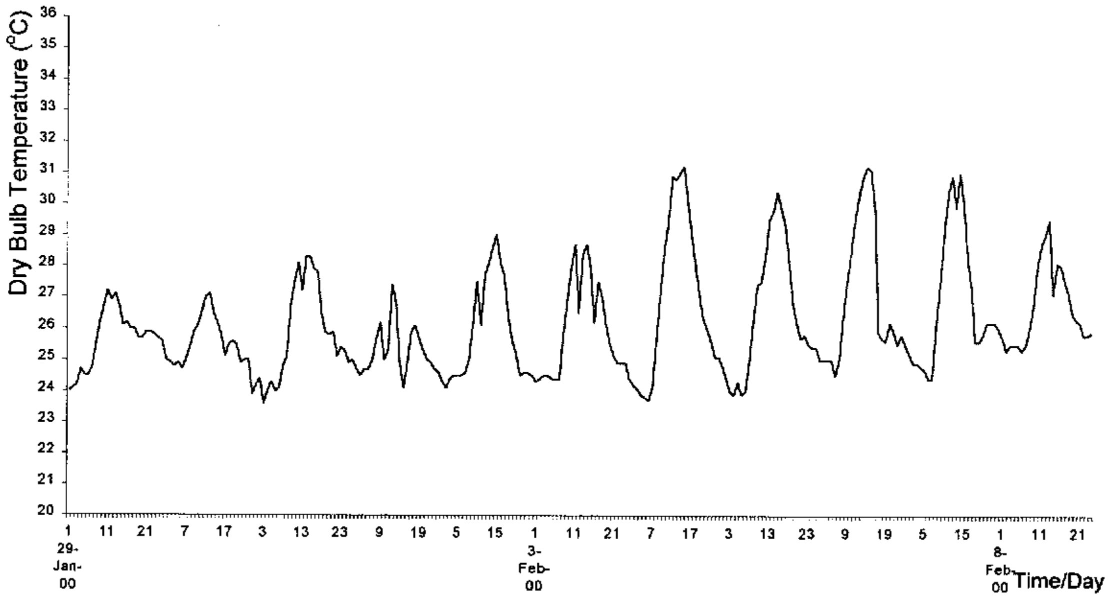


Figure A5.5. Outdoor DBT for RevH (2000)

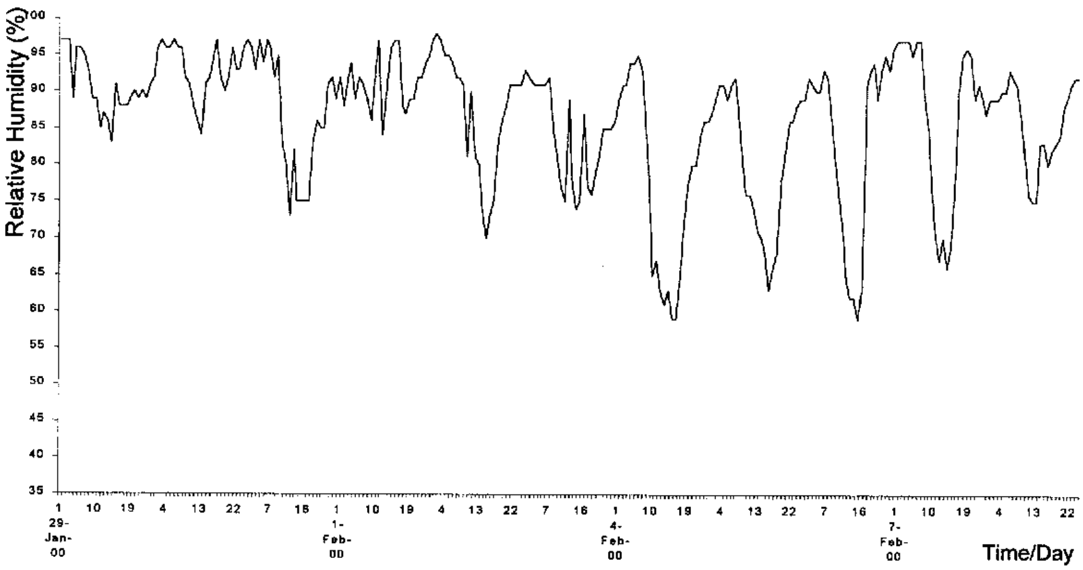


Figure A5.6. Outdoor RH for RevH (2000)

A5.4. URA Centre – 10th to 29th March 2000

On three days of the logging, the pollution index for Singapore rose above the 50 mark (Moderate), due to forest fires in Indonesia. This had an impact of level on direct solar radiation in the afternoons of the 10th-12th.

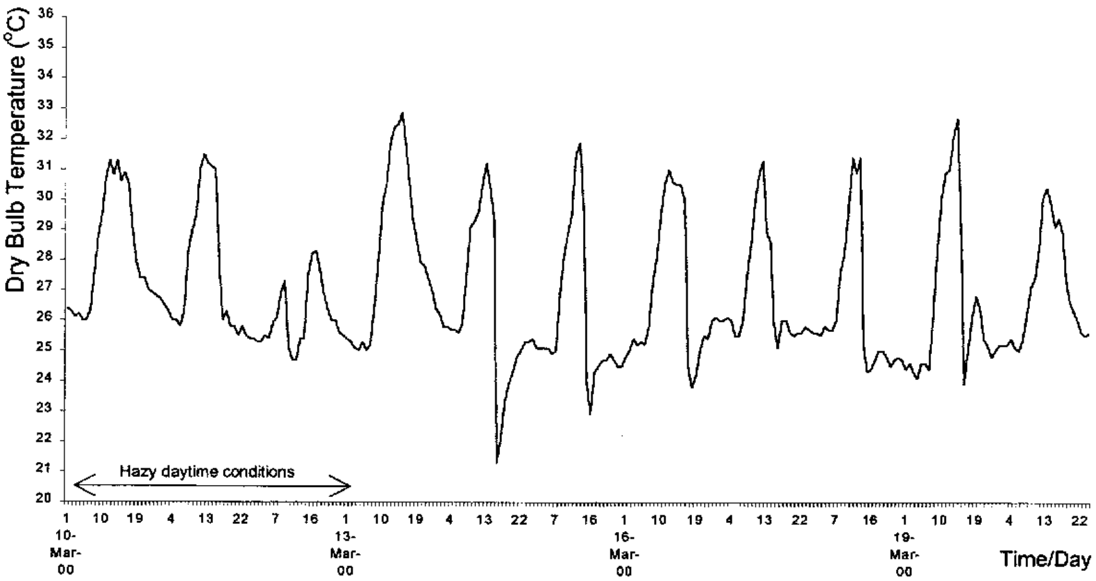


Figure A5.7. Outdoor DBT for URA

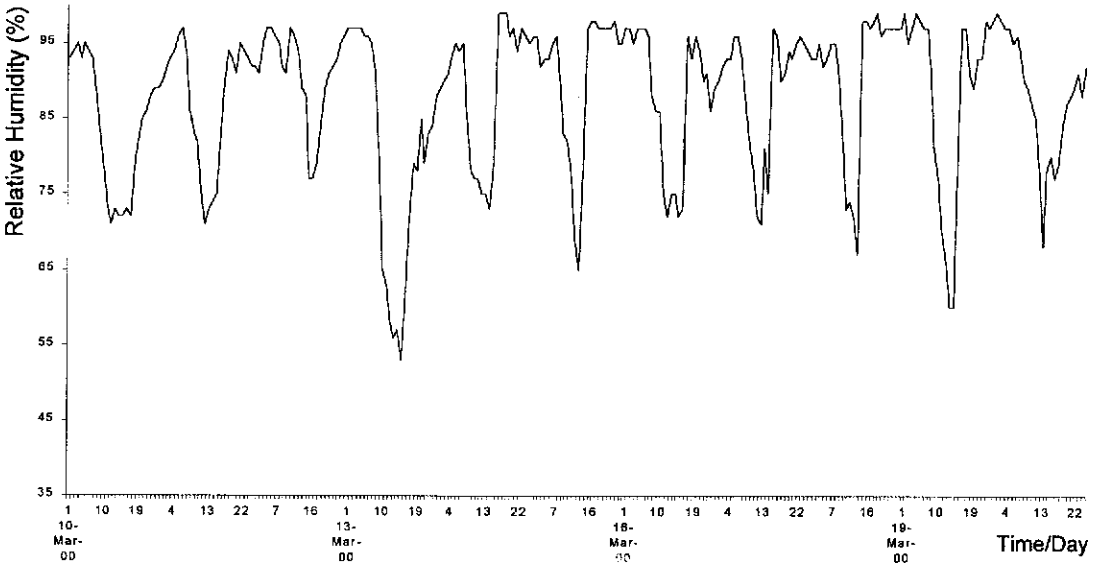


Figure A5.8. Outdoor RH for URA

A5.5. Menara Mesiniaga – 5th May to 15th May 2000

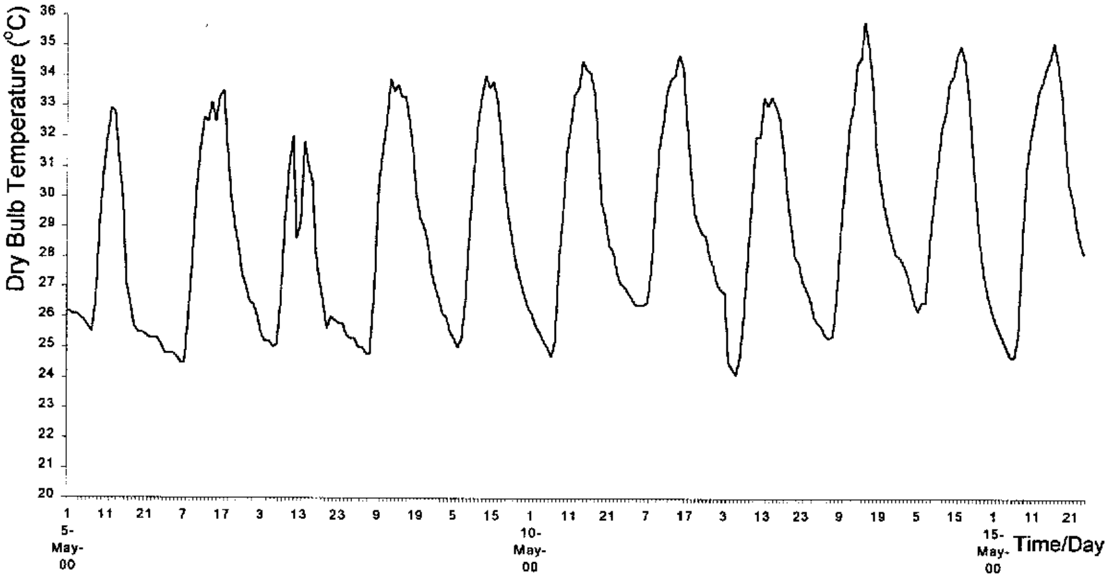


Figure A5.9. Outdoor DBT for MES

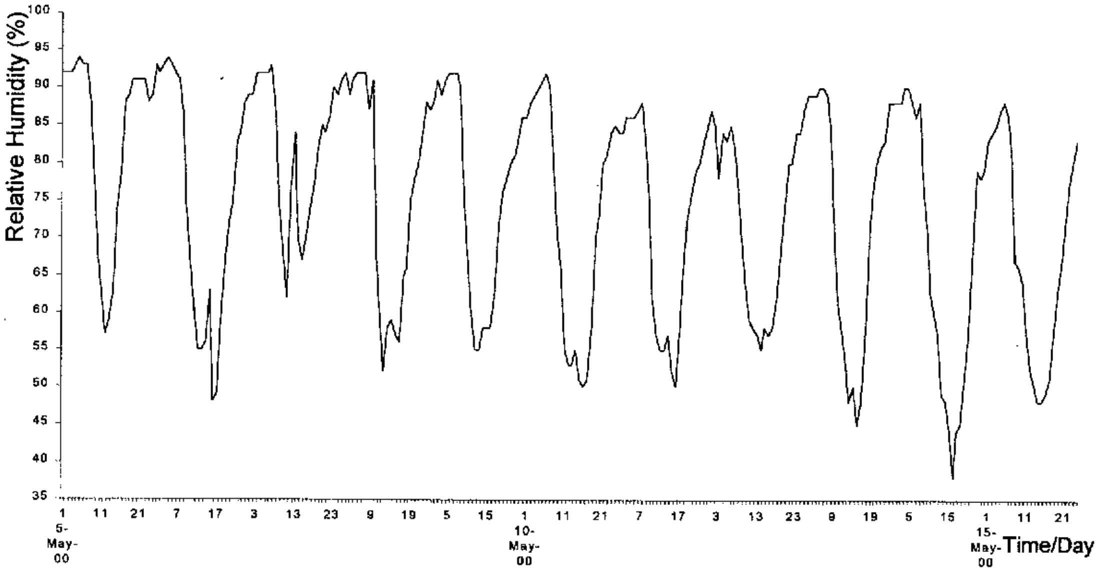


Figure A5.10. Outdoor RH for MES

Appendix A6. Summary of URA Centre Data

A6.1. Indoor Air Temperature

Temperature loggers were positioned on Level 11. IAT and MRT readings were taken over several active days (with air -conditioning) and passive days (without natural ventilation). Presented here is a summary of IAT readings[1].

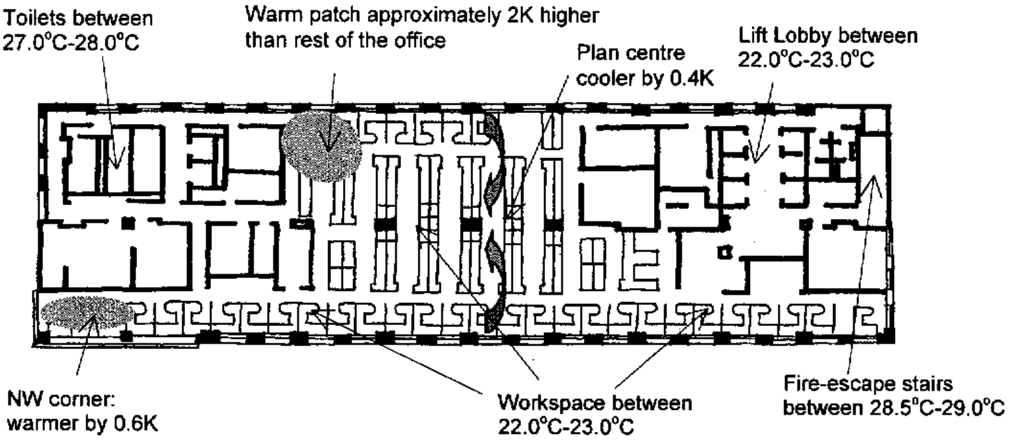


Figure A6.1. IATs in active mode (with air conditioning)

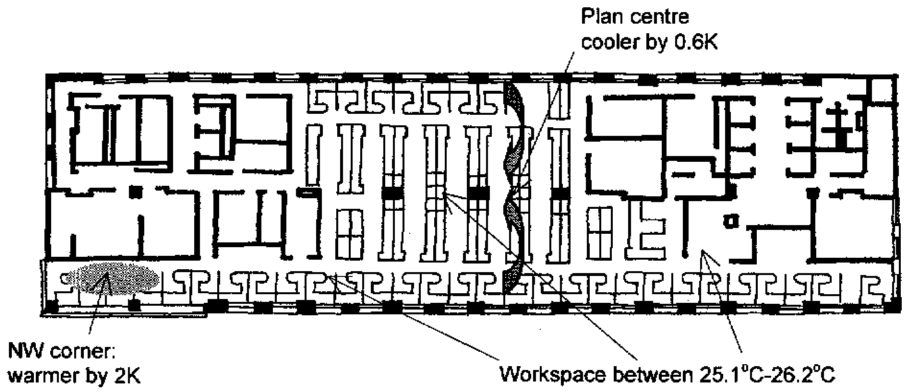


Figure A6.2. IATs in passive mode (without air conditioning or natural ventilation)

▨ Asymmetry of Indoor Air Temperatures ⟿ Temperature Gradients

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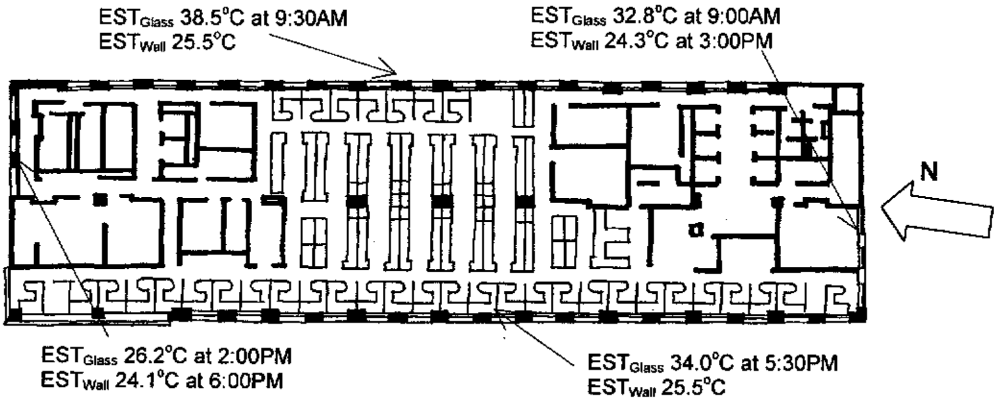
[1] For half-hourly IAT, MRT Out DBT and Out MRT readings of this, and all subsequent buildings, refer to Thesis Data CD.

A6.2. Envelope Surface Temperature

EST loggers were positioned all facades of Level 11. Readings[2] were taken over several active days (with air -conditioning) and passive days (albeit without natural ventilation).



EST$_{Glass}$ 38.5°C at 9:30AM
EST$_{Wall}$ 25.5°C

EST$_{Glass}$ 32.8°C at 9:00AM
EST$_{Wall}$ 24.3°C at 3:00PM

EST$_{Glass}$ 26.2°C at 2:00PM
EST$_{Wall}$ 24.1°C at 6:00PM

EST$_{Glass}$ 34.0°C at 5:30PM
EST$_{Wall}$ 25.5°C

Figure A6.3. Highest surface temperatures recorded

---

[2] For half-hourly EST readings of this, and all subsequent buildings, refer to Thesis Data CD.

A6.3. Light

Light readings were taken on Level 11 on a weekday, in the active mode only (with electrical light). No passive readings were possible due to access restrictions on weekends. Three sets of readings were taken:10:30AM, 1:30PM and 4:00PM.

Figure A6.4. Illuminance levels in active mode (with electrical light)

⬛ <100
🟫 100-500
🟥 500-1000
🟧 1000-5000
🟨 5000-10000
⬜ >10000

A6.4. Relative Humidity

Relative humidity readings were taken on Level 11 in the active mode only. No passive readings were possible due to access restrictions on weekends. Three sets of readings were taken: 9:00AM, 12:00 Noon and 4:00PM. All outdoor readings shown here were recorded at the building perimeter.

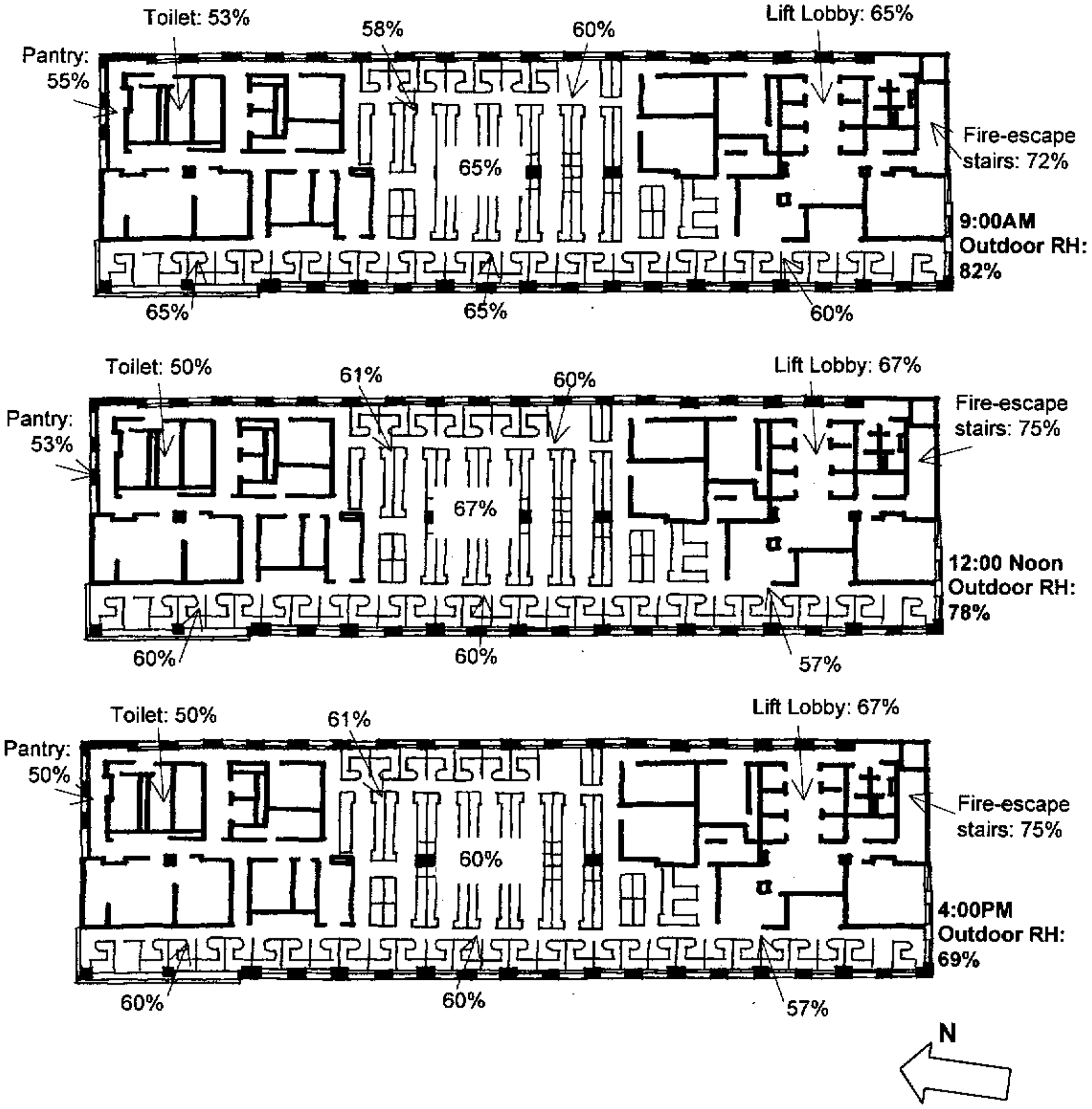


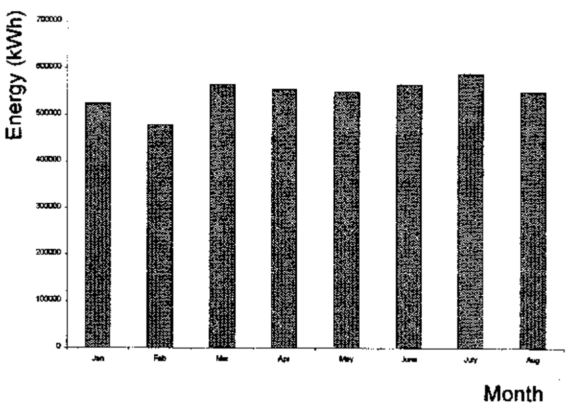
Figure A6.5. Relative humidity in active mode (with air conditioning)

A6.5. Air Movement

No data is available on air movement in passive mode. Passive readings were possible due to access restrictions on weekends. Logging in active mode showed air speeds of less 0.3m/s across the entire floor.

A6.6. Energy Consumption

The building is owner-occupied. Energy bills were made available for the months January to August 1999.



Floor area with air conditioning: 22,562 m^2

Operating hours:
5 working days x 12hours/day = 60 hours
1 working day x 7 hours = 7 hours
Total = 67 hours/week

Consumption for the year Jan-Aug1999 = 4,371,000kWh
Projected consumption for full year = 4,371,000 x 3/2 = 6,556,500 kWh

Energy Index:
6,556,500 /22,562 = 290.6 kWh/m^2/yr

Corrected Energy Index
(55 hour-week)
290.6 x 55/67 = **238.5 kWh/m^2/yr**

Figure A6.6. URA energy consumption for Year 1999

Appendix A7. Summary of Revenue House Data

A7.1. Indoor Air Temperature

Temperature loggers were positioned on Level 22. Readings were taken over several active days (with air -conditioning) and passive days (with natural ventilation). Presented here is a summary of IAT readings.

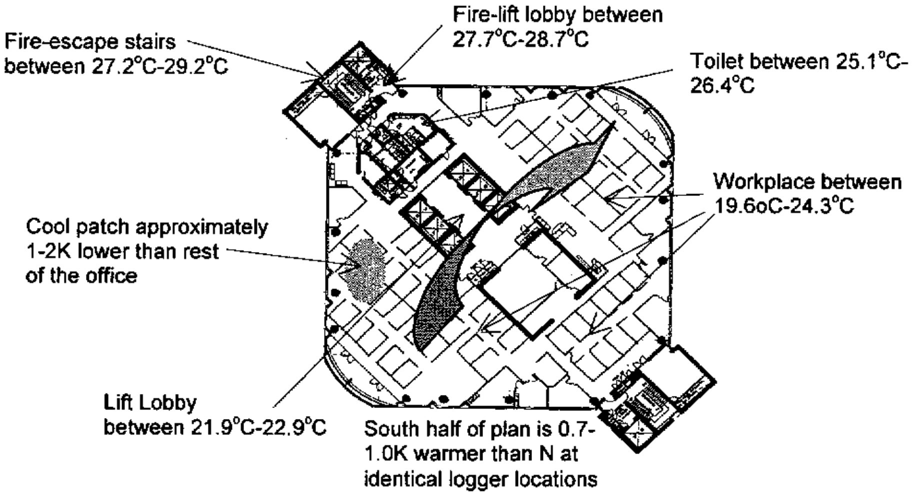


Figure A7.1. IATs in active mode (with air conditioning)

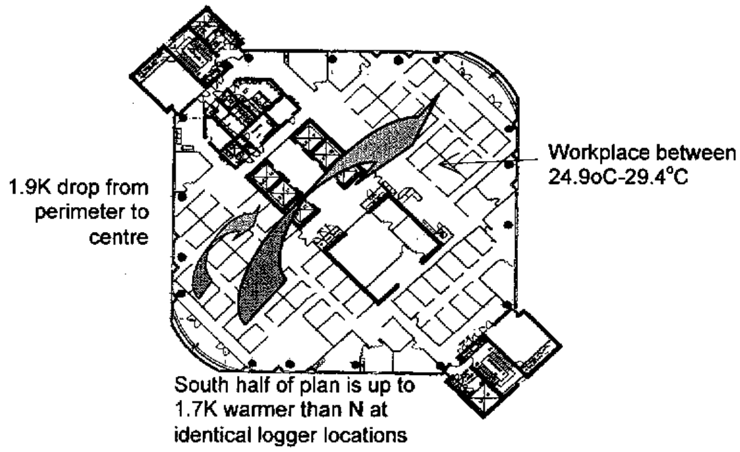


Figure A7.2. IATs in passive mode (with natural ventilation)

▨ Asymmetry of Indoor Air Temperatures ↷ Temperature Gradients

A7.2. Envelope Surface Temperature

The building's façades vary from floor to floor according to two passive variables – *Orientation and Transitional Space* (on the North and South Terraces) - affecting envelope surface temperatures. Temperature loggers were positioned on the façade of Level 22.

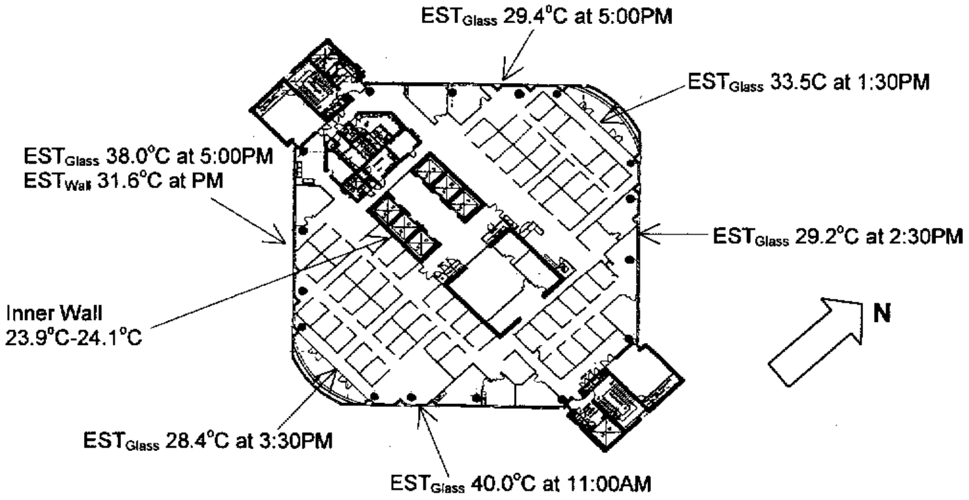


Figure A7.3. Highest surface temperatures recorded

A7.3. Light

Daylight was measured on Level 22 on a weekday in the active mode (with electrical light) and weekend in the passive mode (with natural light only). In the active mode, the blinds were as per occupant discretion; in the passive, they were fully opened[3]. Three sets of readings were taken: 10:30AM, 1:30PM and 4:00PM.

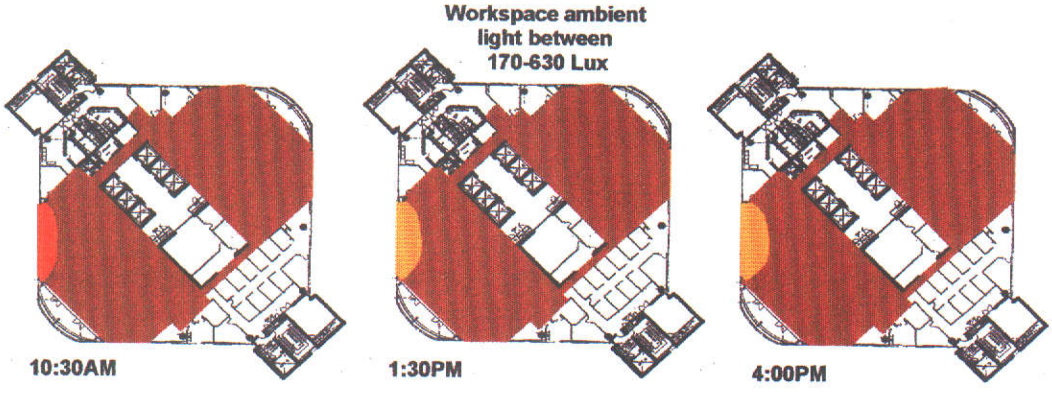
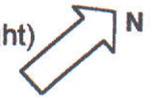


Figure A7.4. Illuminance levels in active mode (with electrical light)



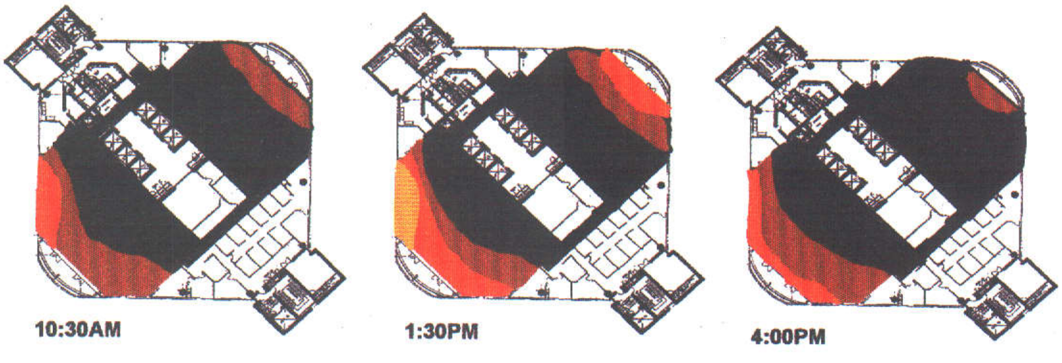


Figure A7.5. Illuminance levels in passive mode (without electrical light)

⬛ <100 🟫 100-500 🟥 500-1000 🟧 1000-5000 🟨 5000-10000 ⬜ >10000

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[3] Typically, light readings in the passive mode in all buildings were taken with blinds opened fully.

A7.4. Relative Humidity

Relative humidity was measured on Level 22 in the active and passive modes. Three sets of readings were taken: 10:30AM, 1:30PM and 4:00PM. All outdoor readings shown here were taken on the North and South terraces. The South terrace was not accessible on the day of the active readings.

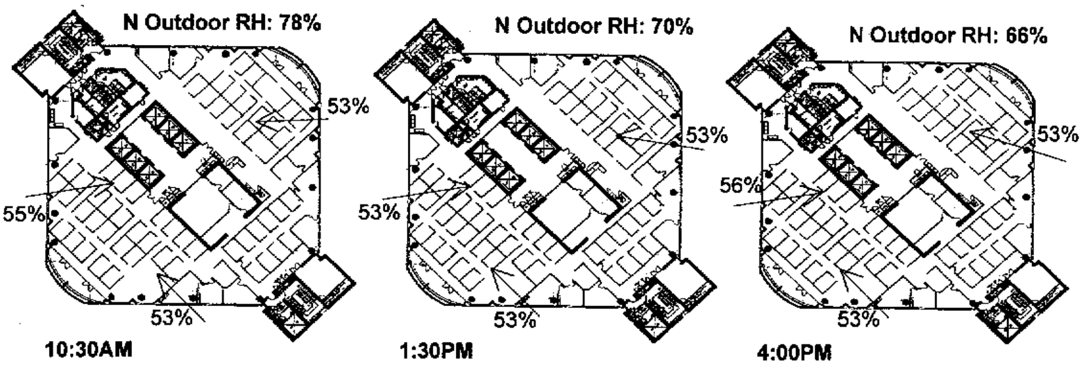


Figure A7.6. Relative humidity in active mode (with air conditioning)

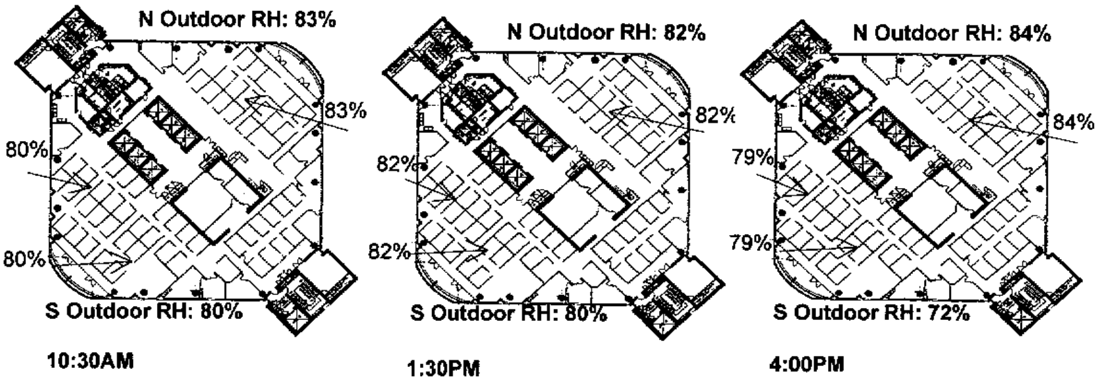
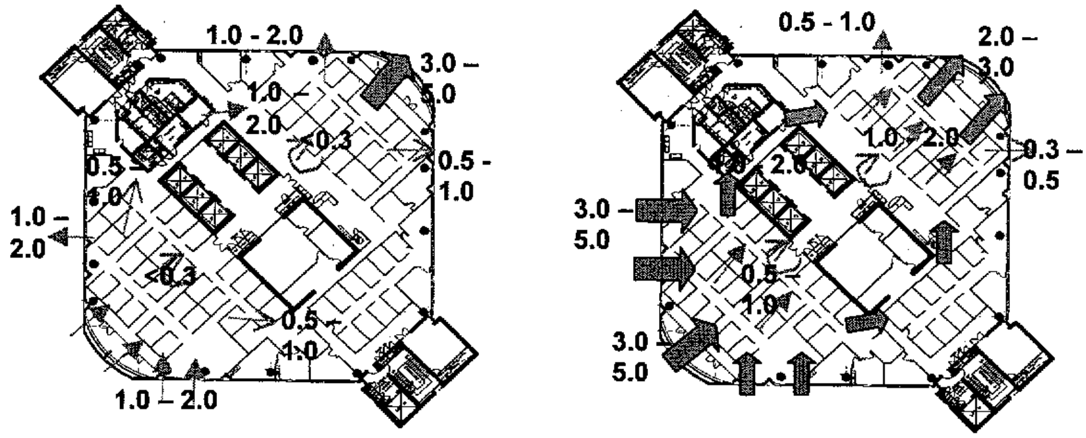


Figure A7.7. Relative humidity in passive mode (with natural ventilation)

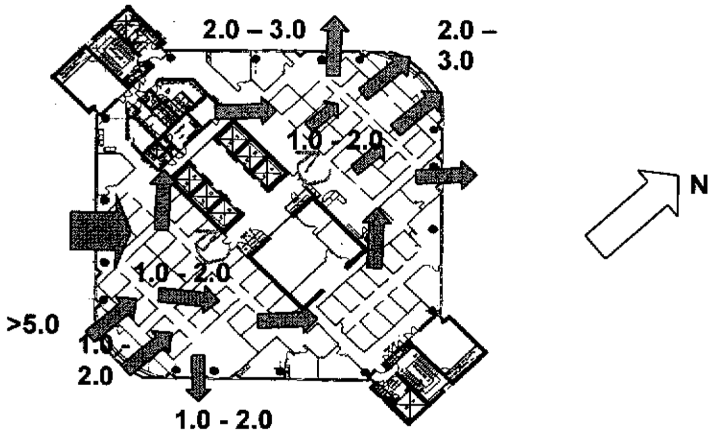
A7.5. Air Movement

Indoor air movement was measured in the passive mode on Level 22. Three sets of readings were taken: 9:00AM, 1:00PM and 4:00PM. Outdoor wind speeds shown here are values recorded by the Singapore Meteorological Service Office[4].



9:00AM
Outdoor Wind Direction and Speed - SE: 2.0 m/s

1:00PM
Outdoor Wind Direction and Speed - SE: 1.9 m/s



4:00PM
Outdoor Wind Direction and Speed - W: 0.7 m/s

Figure A7.8. Air movement in passive mode (natural ventilation)

Logging in active mode showed air speeds of less 0.3m/s across the entire office floor.

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[4] At Changi Airport.

A7.6. Energy Consumption

The building is largely owner-occupied although there are a several office floors that have been leased to other government departments. Energy bills were made available for the months of January to December 1999. FigureA7.9 shows monthly totals that include tenant consumption (averaging 32,668 kWh/month).

Floor area with air conditioning: 83,800m2

Operating hours:
5 working daysx11hours/day = 55 hours
1 working dayx10 hours = 10 hours
Total = 65 hours/week

Total Consumption for the year 1999 = 12,296,047 kWh

Energy Index:
12,296,047 /83,800 = 146.7 kWh/m2/yr

Corrected Energy Index (55 hour-week)
146.7 x 55/65 = **124.1 kWh/m2/yr**

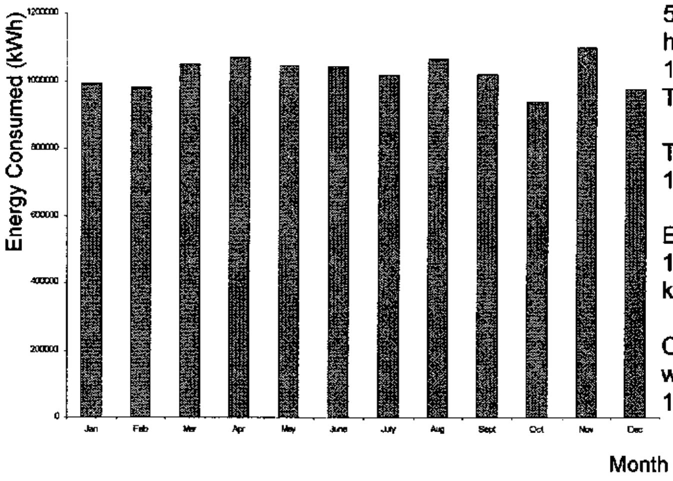


Figure A7.9. Revenue House energy consumption for the Year 1999

Appendix A8. Summary of Menara Mesiniaga Data

MES presented a unique opportunity in two respects. First, unrestricted access was granted to all floors. Second, each floor differed from the next in the presence and location of its passive elements, such as external sunshades, transitional spaces and solar tints. Passive logging of Air and Light was confined to L9, which was unoccupied. Active and passive logging of IAT, MRT and EST was carried out on various floors with loggers situated at up to four levels at time.

A8.1. Indoor Air Temperature

IAT loggers were positioned at various floors highlighted by the occupants as being particularly uncomfortable.

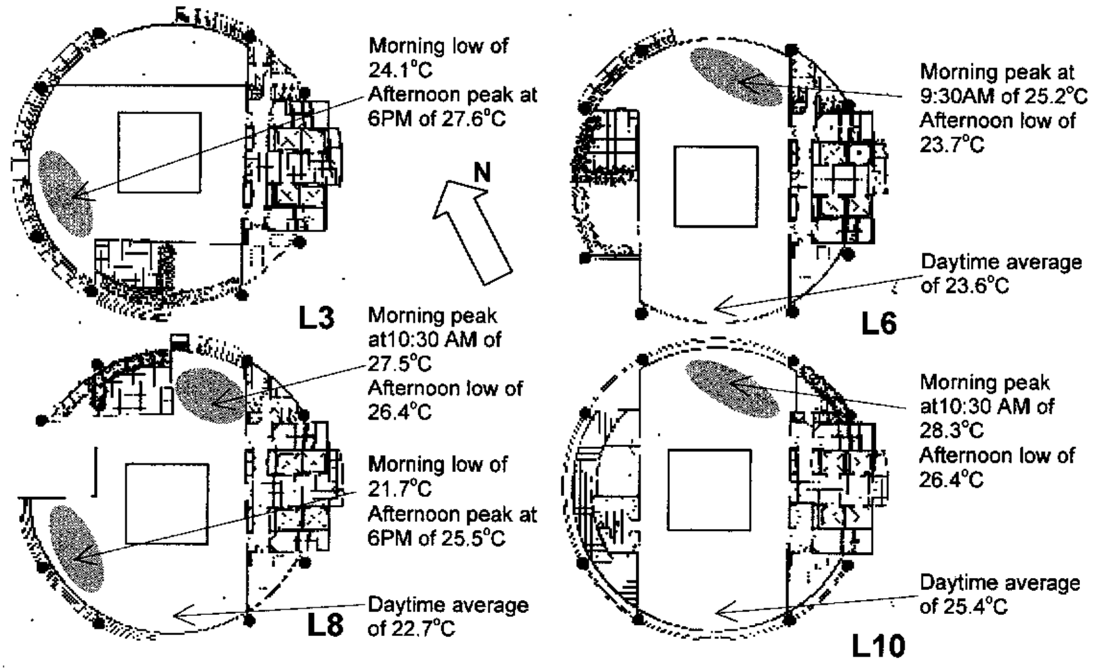


Figure A8.1. IATs in active mode (with air conditioning)

▨ Asymmetry of Indoor Air Temperatures

IAT readings shown in Figures A8.2 and A8.3 were taken manually (along with RH shown in Section A8.5) on the same floor over two days. Outdoor readings shown here were taken at the N-facing transitional space.

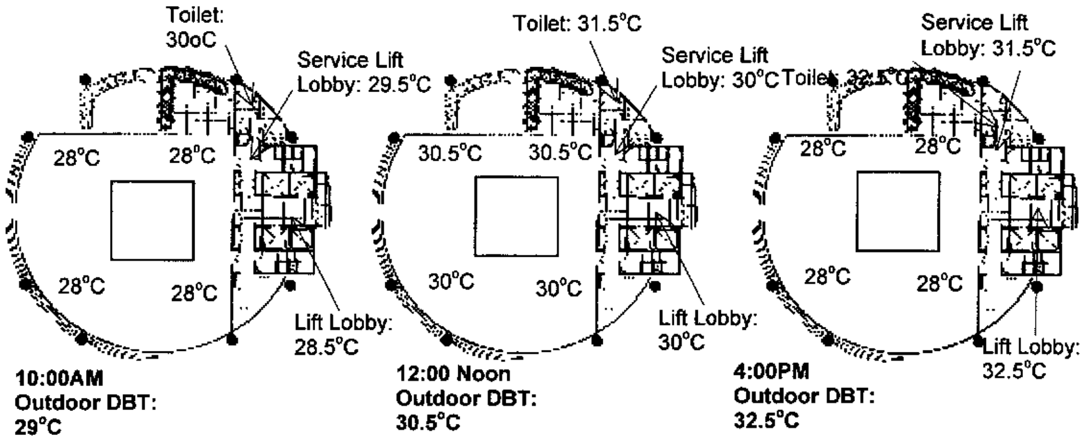


Figure A8.2. IATs in passive mode on L9 (with natural ventilation)

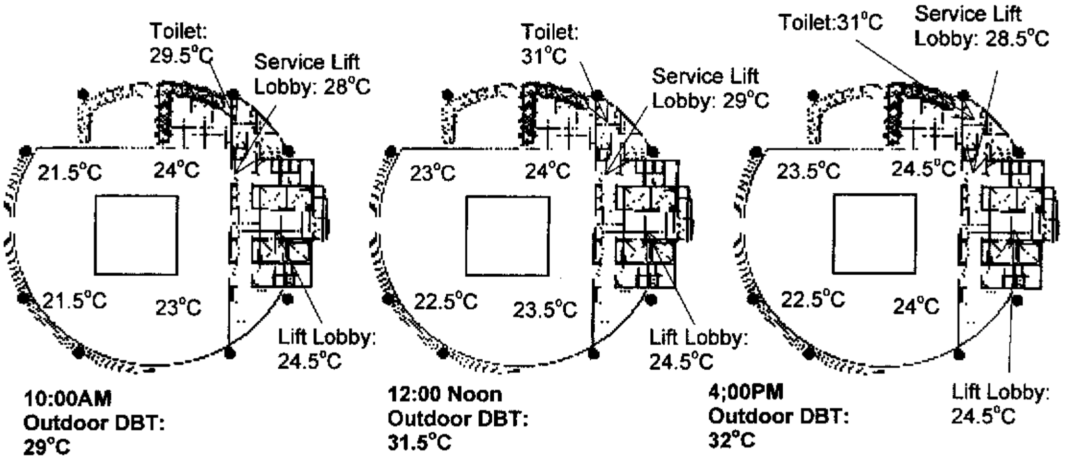


Figure A8.3. IATs in active mode on L9 (with air conditioning)

IAT readings shown in Figure A8.4 were taken across two days with Tiny Talk Loggers spread out on the W-axis.

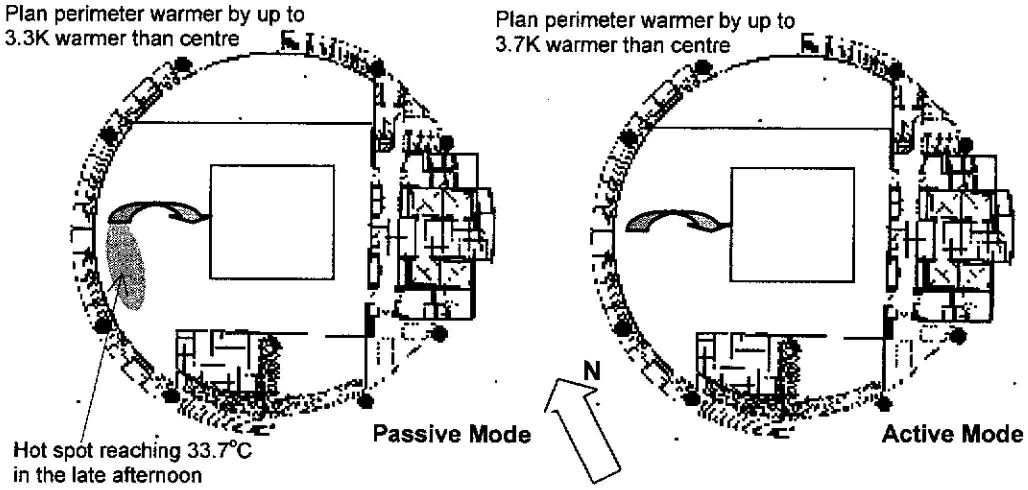


Figure A8.4. Temperature gradients on L3

▨ Asymmetry of Indoor Air Temperatures ⤻ Temperature Gradients

A8.2. Envelope Surface Temperature

EST loggers were positioned on windows facing different orientations and passive elements. Readings were taken over several active days.

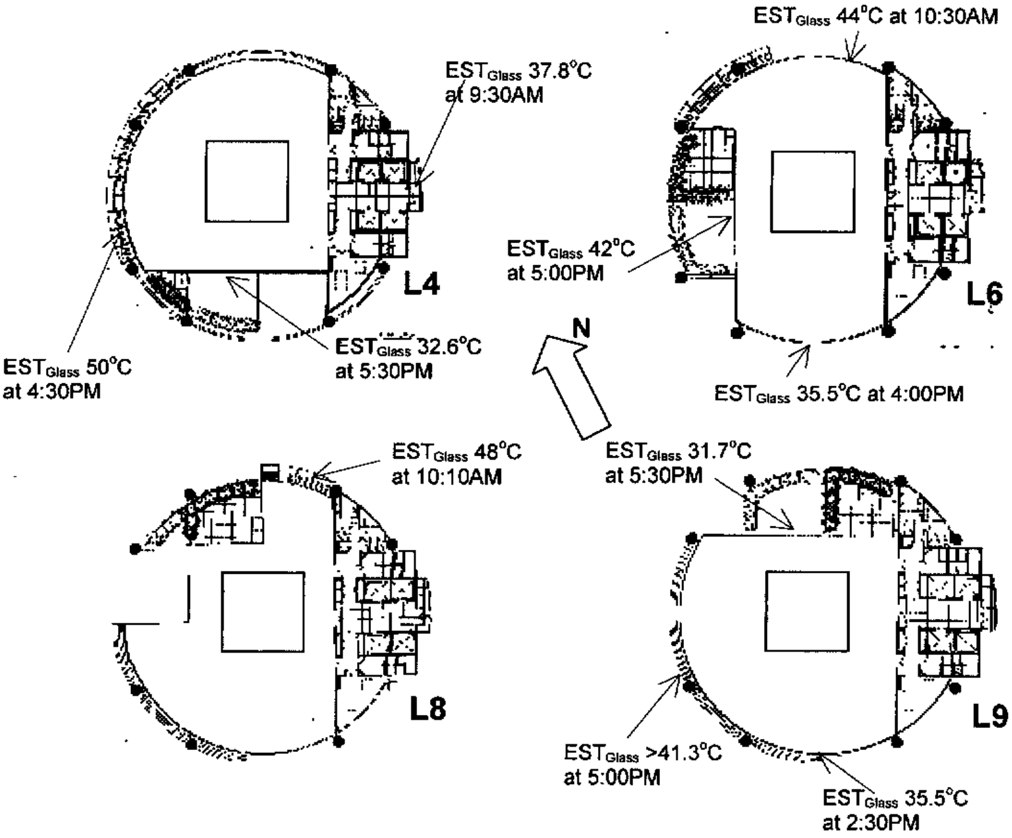


Figure A8.5. Highest surface temperatures recorded

A8.3. Light

Light readings were taken on L9 across two days. Three sets of readings were taken: 10:00AM, 12:00 Noon and 4:00PM.

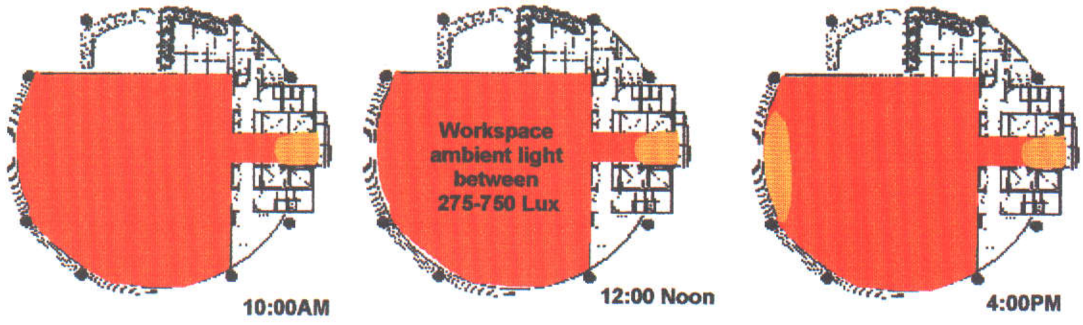


Figure A8.6. Illuminance levels in active mode (with electrical light)

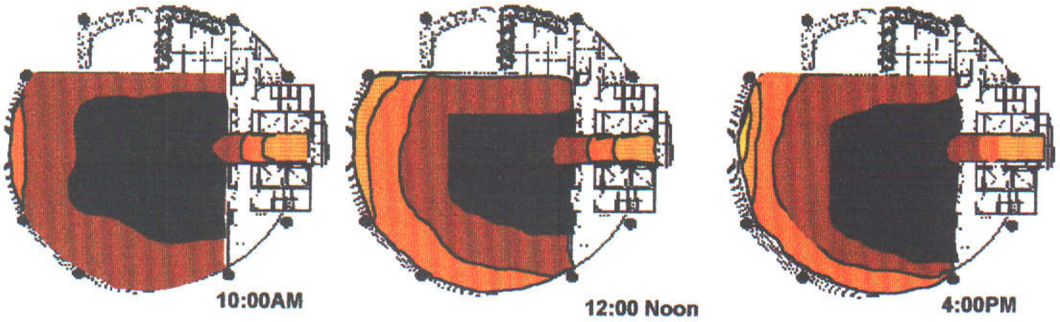


Figure A8.7. Illuminance levels in passive mode (with natural light)

■	■	■	■	■	□
<100	100-500	500-1000	1000-5000	5000-10000	>10000

A8.4. Relative Humidity

RH readings shown in Figures A8.8 and A8.9 were taken on the same floor over two days. Outdoor readings shown here were taken at the N-facing transitional space.

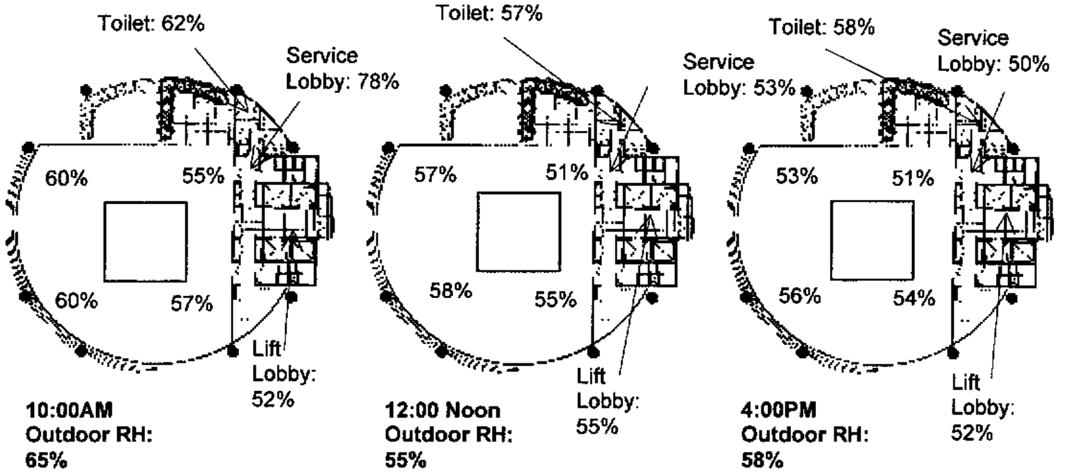


Figure A8.8. Relative humidity in active mode (with air conditioning)

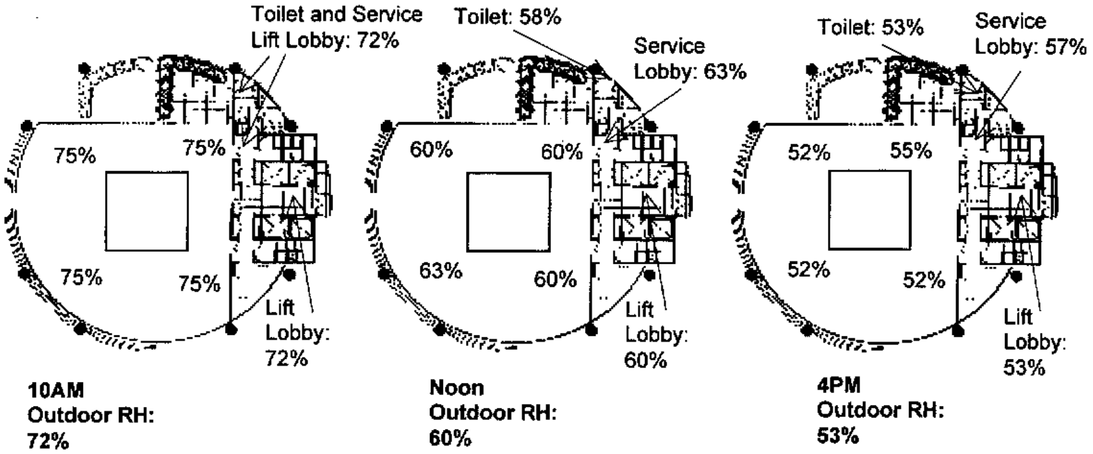
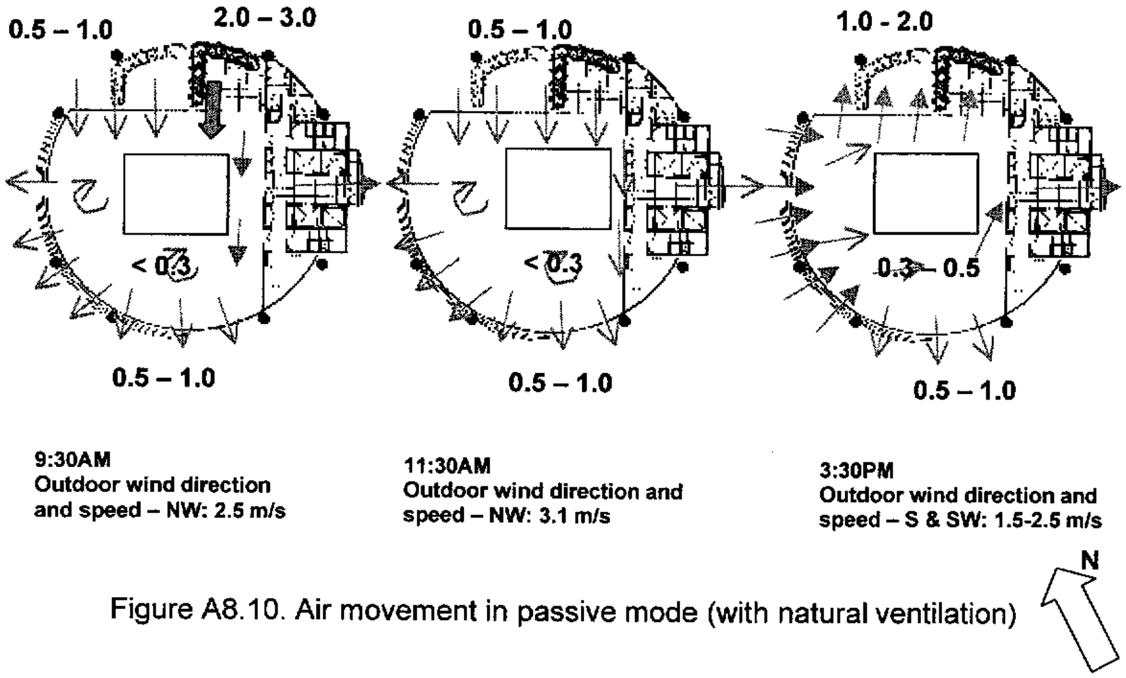


Figure A8.9. Relative humidity in passive mode (with natural ventilation)

A8.5. Air Movement

Indoor air movement was measured in the passive mode on L9. Three sets of readings were taken: 9:30AM, 11:30AM and 3:30PM. Outdoor wind speeds shown here are values recorded by the Kuala Lumpur Meteorological Service Office[5]. Logging in active mode showed air speeds of less 0.3m/s.



9:30AM
Outdoor wind direction and speed – NW: 2.5 m/s

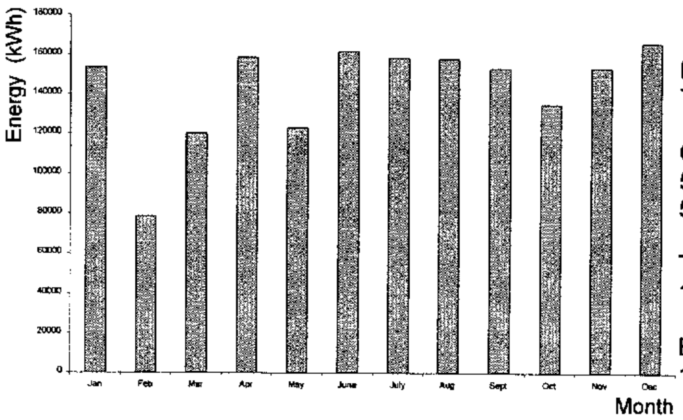
11:30AM
Outdoor wind direction and speed – NW: 3.1 m/s

3:30PM
Outdoor wind direction and speed – S & SW: 1.5-2.5 m/s

Figure A8.10. Air movement in passive mode (with natural ventilation)

A8.6. Energy Consumption

The building is owner-occupied. Energy bills were made available for the months of January to December 1999.



Floor area with air conditioning:
7000m^2

Operating hours:
5 working daysx11hours/day =
55 hours/week

Total Consumption for 1999 =
1,716,200 kWh

Energy Index:
1,716,200 / 7000 = **245 KWh/m^2/year**

Figure A8.11. MES energy consumption for Year 1999

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[5] At Subang Airport.

Appendix A9. Summary of Menara UMNO Data

UMNO presented an opportunity similar to MES in that its floors offered different combinations of passive features. Access to 3 unoccupied floors allowed for an investigation into the impact of these features. The main constraint however, was that only one occupied floor was available for active-mode readings.

The passive modes, particularly NV, were more examined in greater depth. Passive air movement was logged on three days across two floors, to allow for varying outdoor conditions and combinations of openings. Passive logging of IAT, MRT and EST was carried out with loggers situated at up to two levels at time. Active readings were confined to L12, the sole occupied floor with access for logging, which had a W-facing transitional space.

A9.1. Indoor Air Temperature

Temperature loggers were positioned on levels 8, 10, 12 and 17. Readings were taken over several active days (with air -conditioning) and passive days (with natural ventilation).

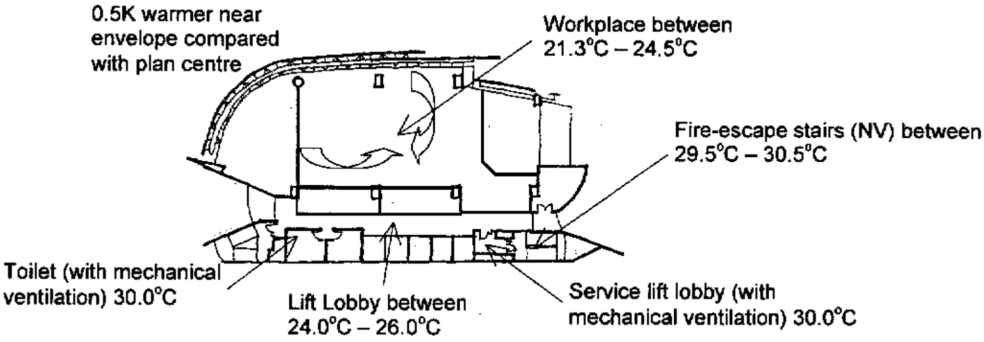


Figure A9.1. IATs in active mode (with air conditioning)

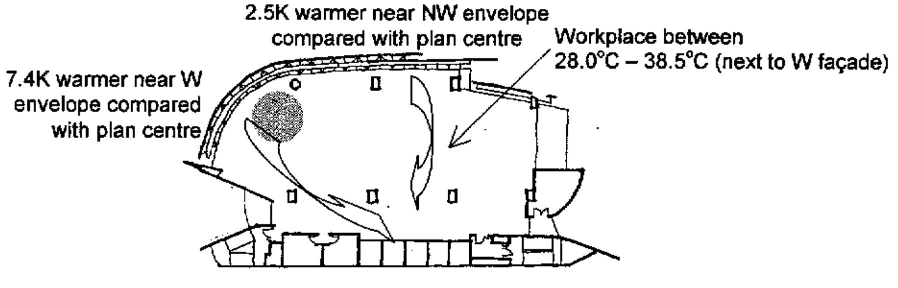


Figure A9.2. IATs in passive mode (with natural ventilation)

▨ Asymmetry of Indoor Air Temperatures ↝ Temperature Gradients

A9.2. Envelope Surface Temperature

EST loggers were positioned at various facades on several floors. Readings were taken over several active days (with air -conditioning) and passive days (with natural ventilation).

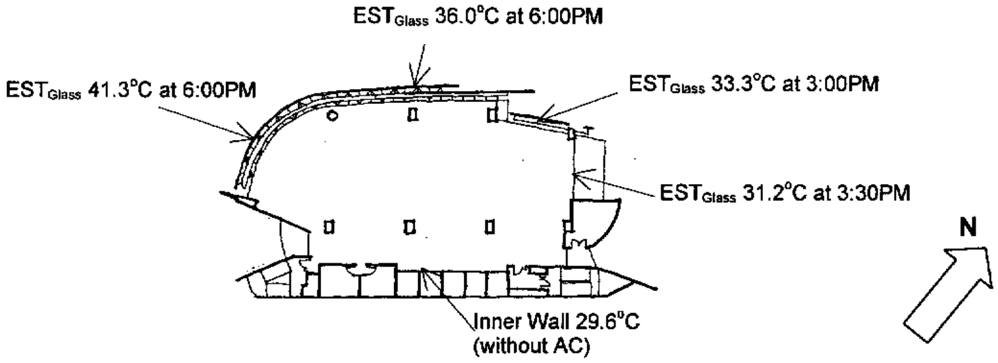


Figure A9.3. Highest surface temperatures recorded

A9.3. Light

Active light readings were taken L12 (see Figure A9.4). Passive readings were taken on L6 (see Figure A9.5). Three sets of readings were taken: 8:30AM, 12:00 Noon and 4:00PM.

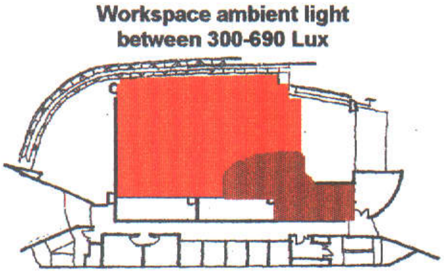


Figure A9.4. Illuminance levels in active mode (with electrical light)

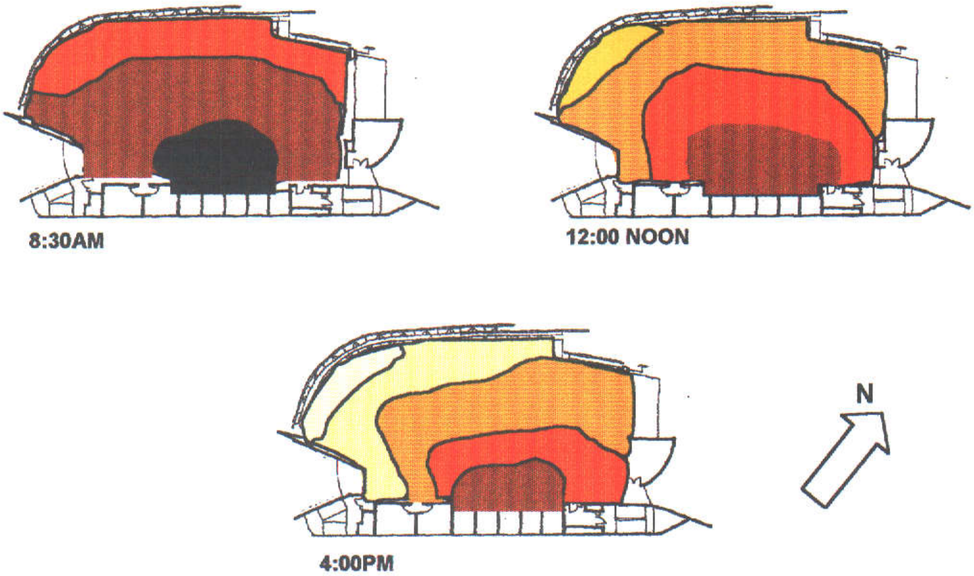


Figure A9.5. Illuminance levels in active mode (with electrical light)

⬛ <100 🟫 100-500 🟥 500-1000 🟧 1000-5000 🟨 5000-10000 ⬜ >10000

A9.4. Relative Humidity

Relative humidity was measured on Level 12 in the active mode and L17 in the passive mode, on the same day. Three sets of readings were taken: 9:00AM, 12:00 Noon and 4:00PM. Outdoor readings shown here were recorded at the building's NE and SW transitional spaces.

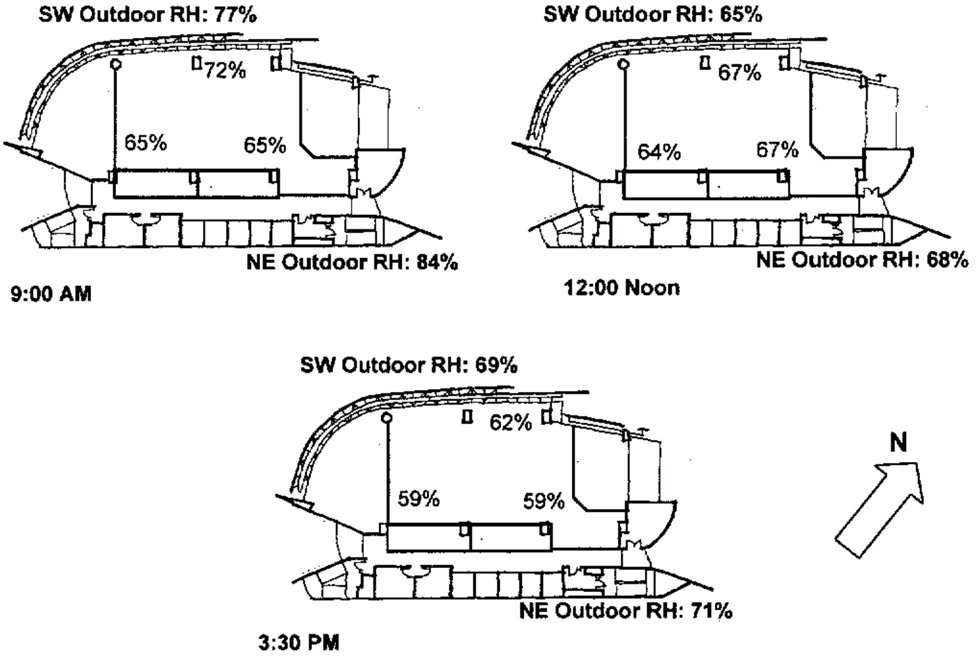


Figure A9.6. Relative humidity in active mode (with air conditioning)

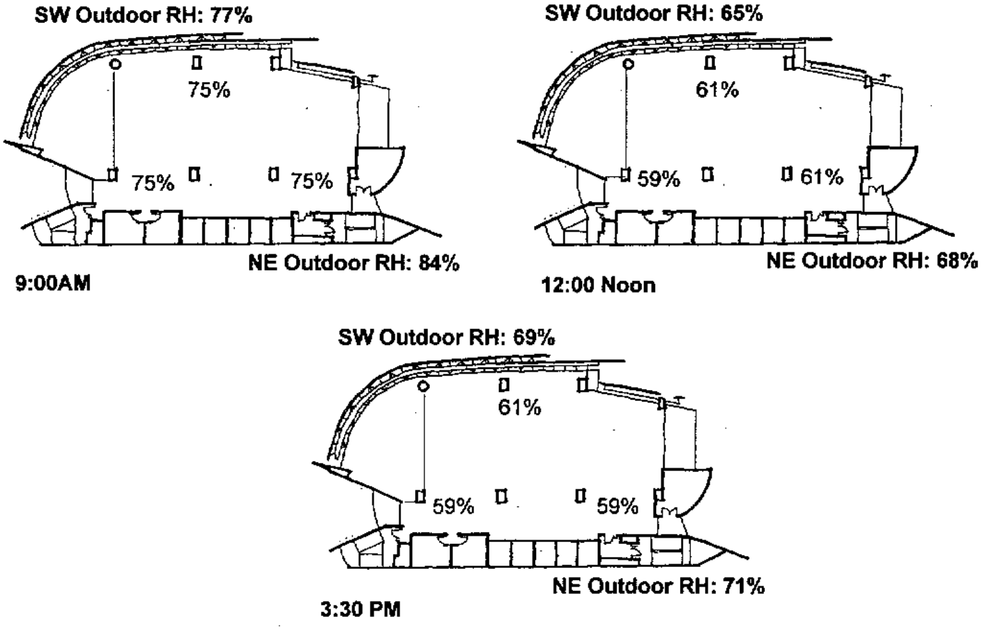
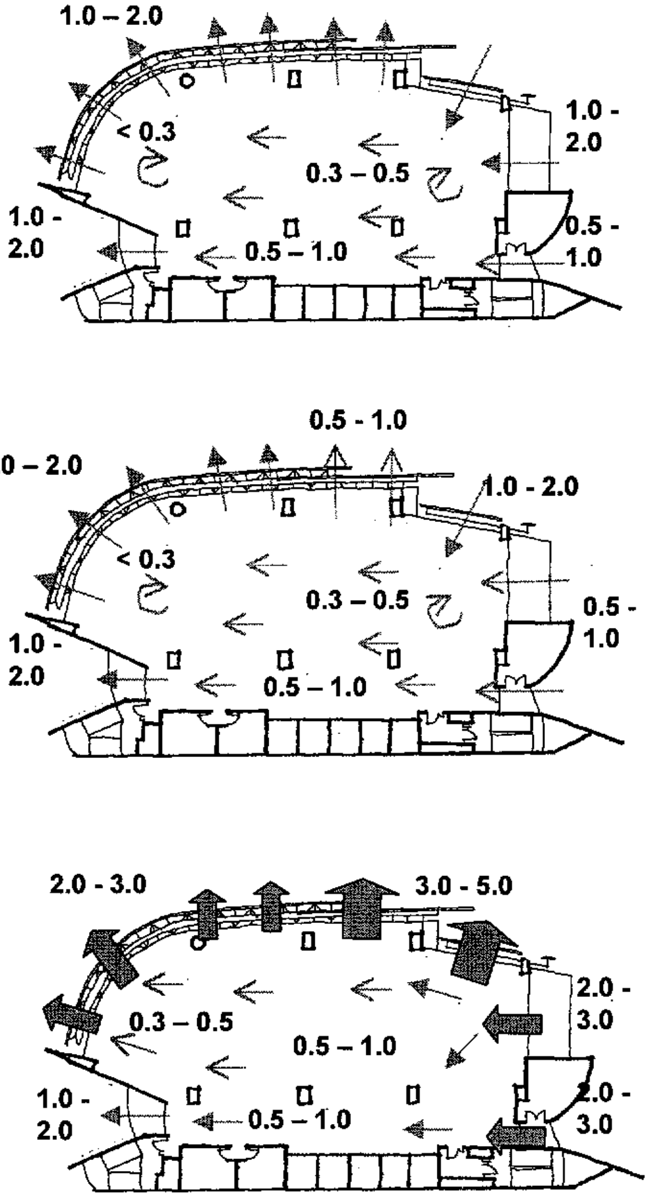


Figure A9.7. Relative humidity in passive mode (with natural ventilation)

A9.5. Air Movement

UMNO was logged in the passive mode on two floors across three consecutive days. On Days 1 and 2, readings were taken on a single floor with all side windows and sliding doors (leading to transitional spaces) kept fully opened. Three sets of readings were taken per day at various points across the floor. On Day 3, readings were taken on the two floors simultaneously, one with windows closed and sliding doors opened, and the other, vice versa. Outdoor wind speeds shown here were recorded at the Penang Meteorological Station[6]. Logging in active mode on L12 showed air speeds of less 0.3m/s.



9:00AM
Outdoor Wind Direction and Speed:
N/4.4 m/s

12:00Noon
Outdoor Wind Direction and Speed:
N and NE/ 4.5 m/s

3:00PM
Outdoor Wind Direction and Speed:
NE/ 2.3 m/s

Figure A9.8. Air movement in passive mode (with natural ventilation) on Day 1

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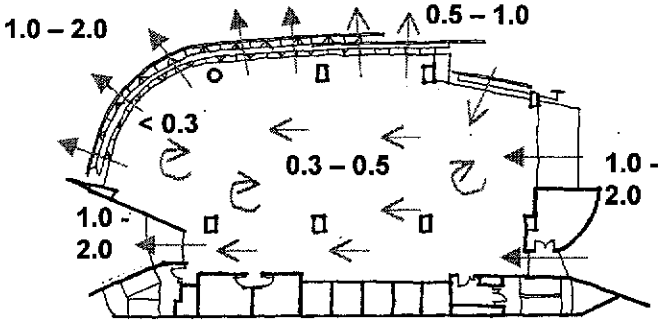
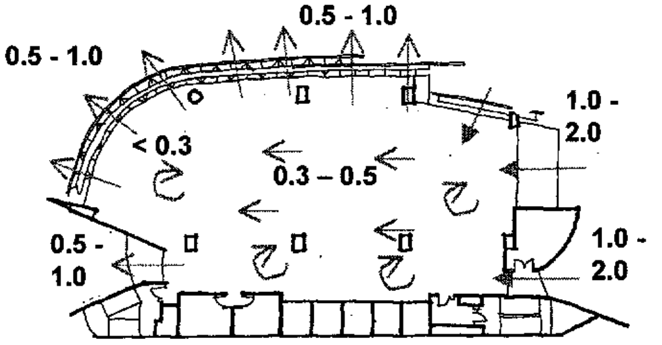
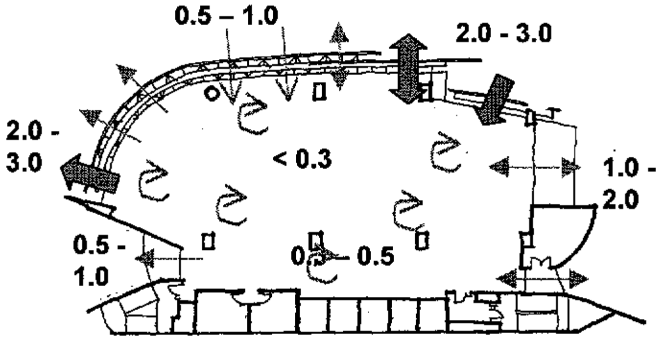
[6] Bayan Lepas Airport



8:30AM
Outdoor Wind Direction and Speed:
NE/ 4-4.4 m/s



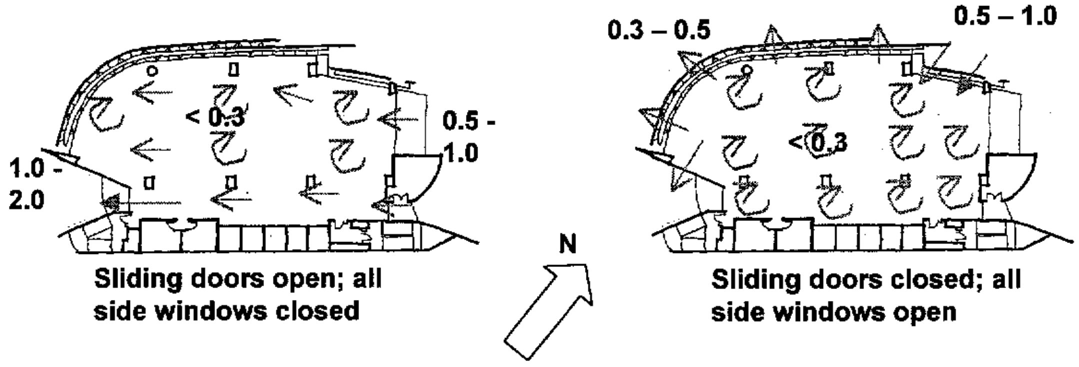
11:30AM
Outdoor Wind Direction and Speed:
NE and E/ 2.5-3.6 m/s



3:00PM
Outdoor Wind Direction and Speed:
W/ 3.1 m/s

Figure A9.9. Air movement in passive mode (with natural ventilation) on Day 2

Figure A9.10 shows a summary of readings taken at 9:30AM and 12:30PM, at which time the wind speeds ranged from 2.5 to 4.4 m/s from the NE and E directions.



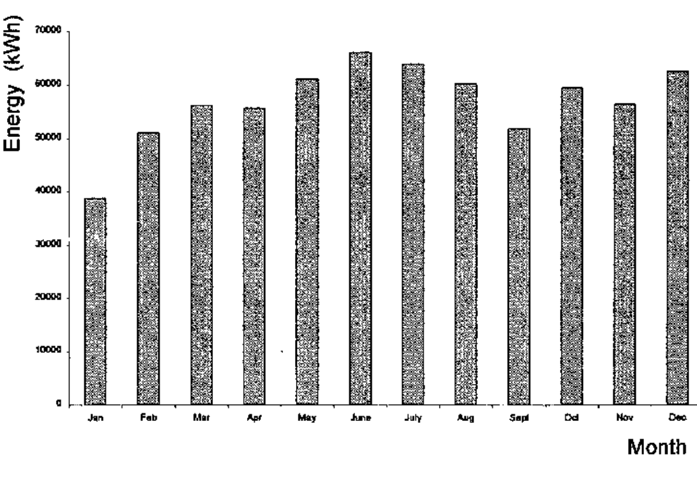
Sliding doors open; all side windows closed

Sliding doors closed; all side windows open

Figure A9.10. Air movement in passive mode (with natural ventilation) on Day 3

A9.6. Energy Consumption

UMNO is commercial office building with multiple tenants; its consumption is a combination of tenant and landlord energy bills. The building, however, was not fully occupied at the time of the study; of the records made available, the tenant on L12 was used as a basis for calculating total an energy index. This basis for selection was that this tenant was representative of an operational workplace, with optimal occupancy and equipment loads. Many others had an excess of meeting rooms or large spaces with only few occupants. An extrapolation for the entire building is carried out using the selected tenant's rate of consumption (kWh/m²/year).



Floor area with air conditioning: 3,060 m²

Operating hours = 44 hours/week

Total Consumption for the year 1999 = 865,965* kWh

Energy Index:
865,965 / 3,060 = 283 kWh/m²/yr

Corrected Energy Index (55 hours/week)
183 x 55/44 = **353 kWh/m²/yr**

Total consumption is based on landlord consumption of 646, 745 kWh and tenant consumption of 219, 220 kWh. The tenant component has been calculated on the basis of a 'representative' tenant that had an index of 113 kWh/m²/ year. This is multiplied by the 1940 m² of total available rent space to give the total projected tenant consumption level.

Figure A9.11. UMNO energy consumption for Year 1999

Appendix A10. Logging Data in Detail

The figures shown here are meant to elaborate on the data that was presented in Section 4.3.3.1, by presenting remaining data from other days of logging. The box insert compares data shown here with that shown earlier.

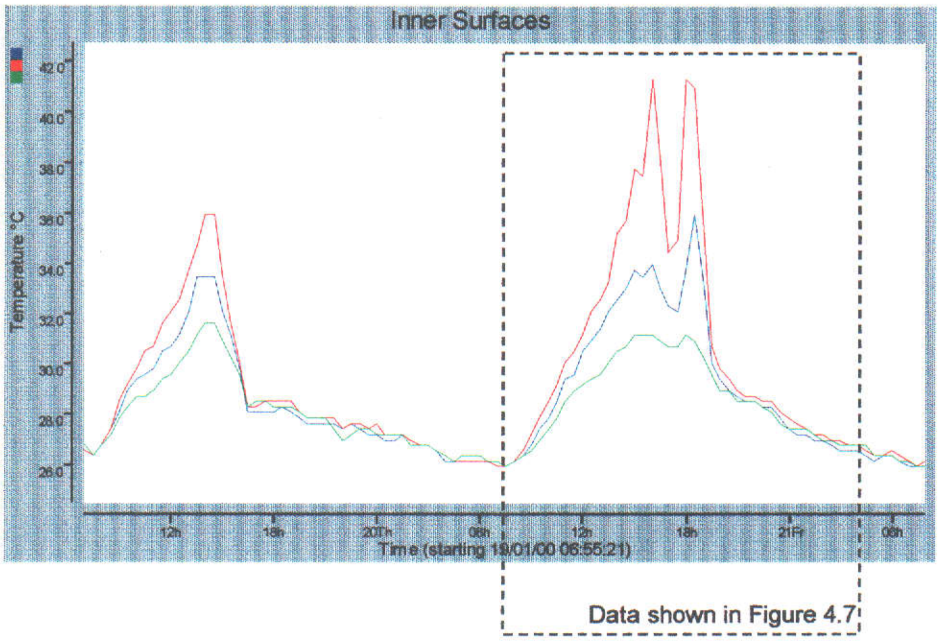


Figure A10.1 EST$_{Glass}$ of UMNO with varying combinations of passive features (2 days)

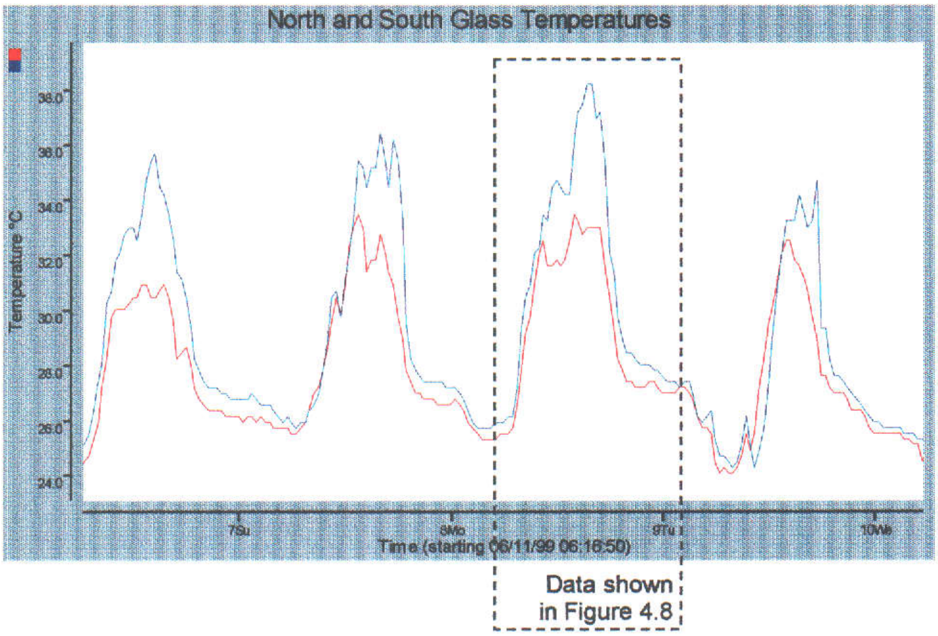
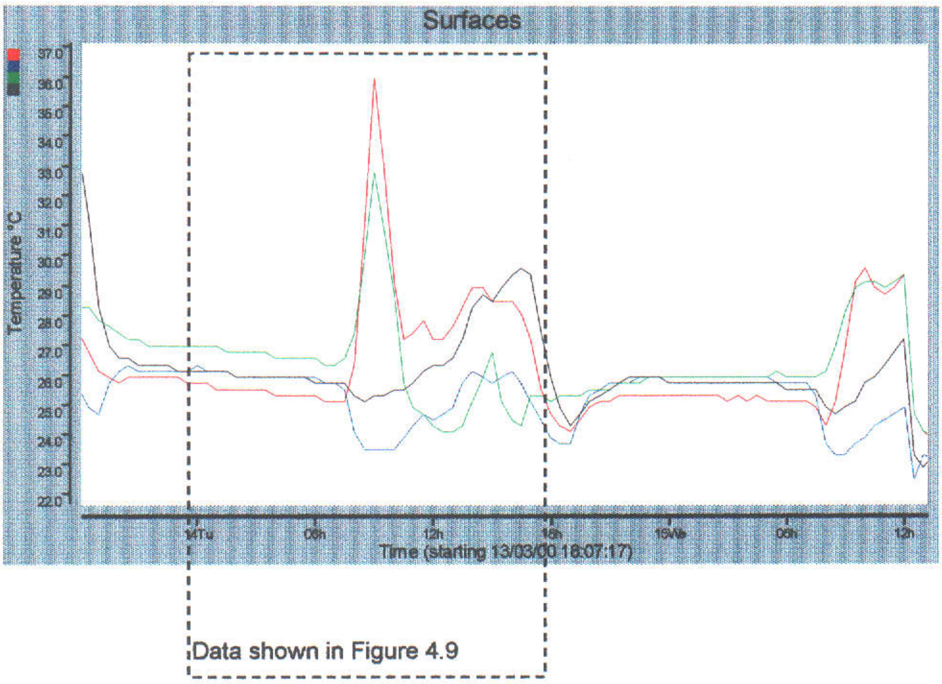
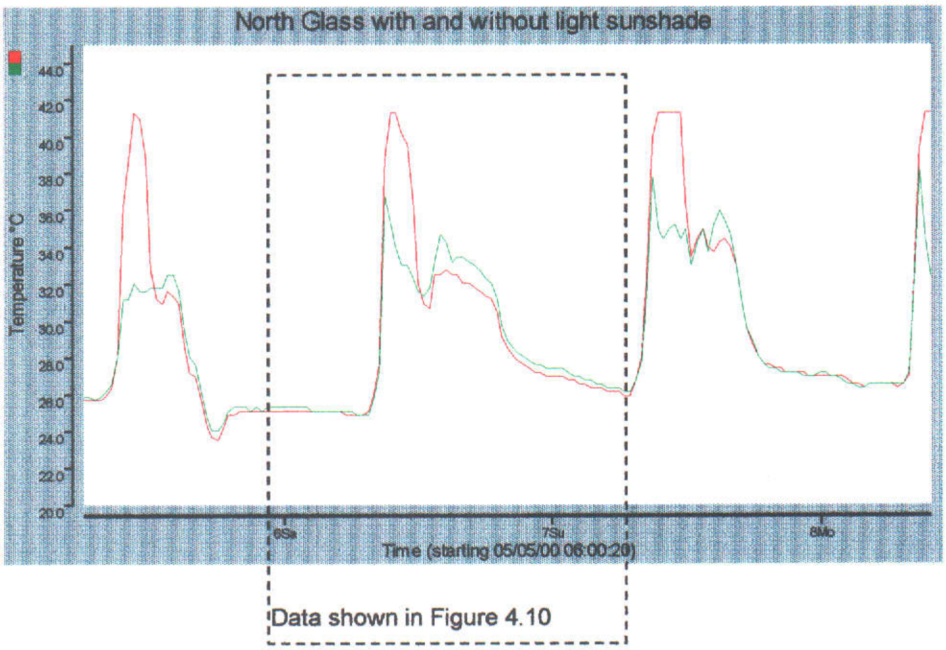


Figure A10.2. N- and S-facing ESTGlass of RevH for impact of orientation (4 days)



Data shown in Figure 4.9

Figure A10.3. NSE and W-facing EST_{Glass} of URA for impact of orientation (2 days)



Data shown in Figure 4.10

Figure A10.4. N-facing EST_{Glass} of MES for impact of light sunshades (3 days)

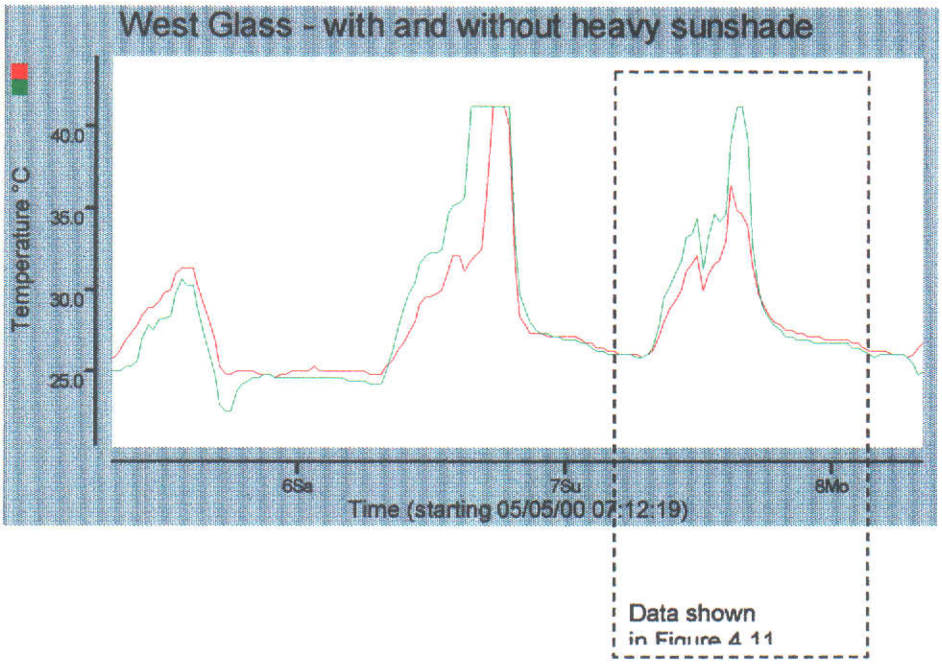


Figure A10.5. W-facing EST_{Glass} of MES for impact of heavy sunshades (3 days)

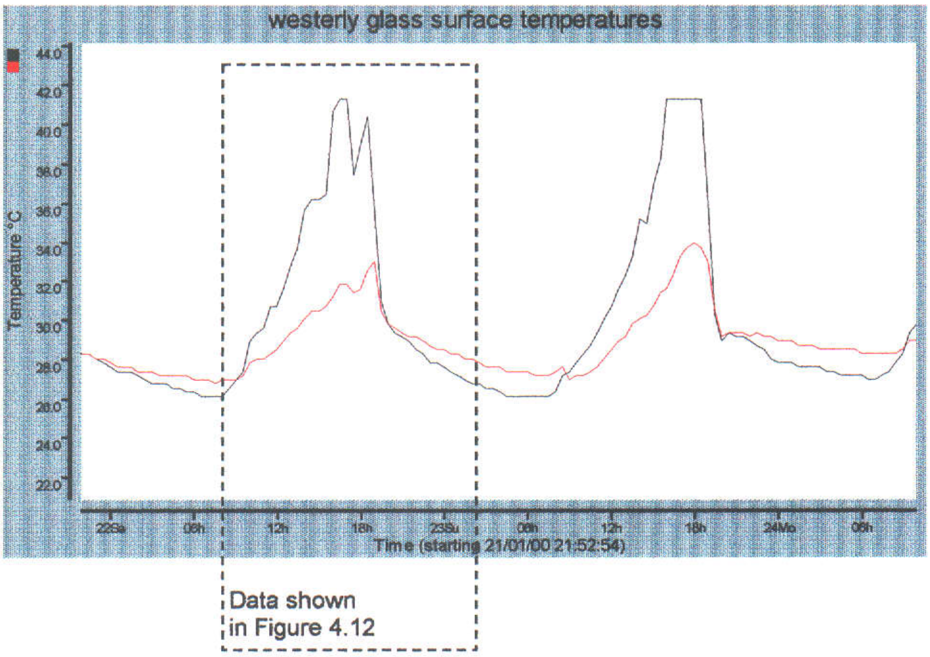
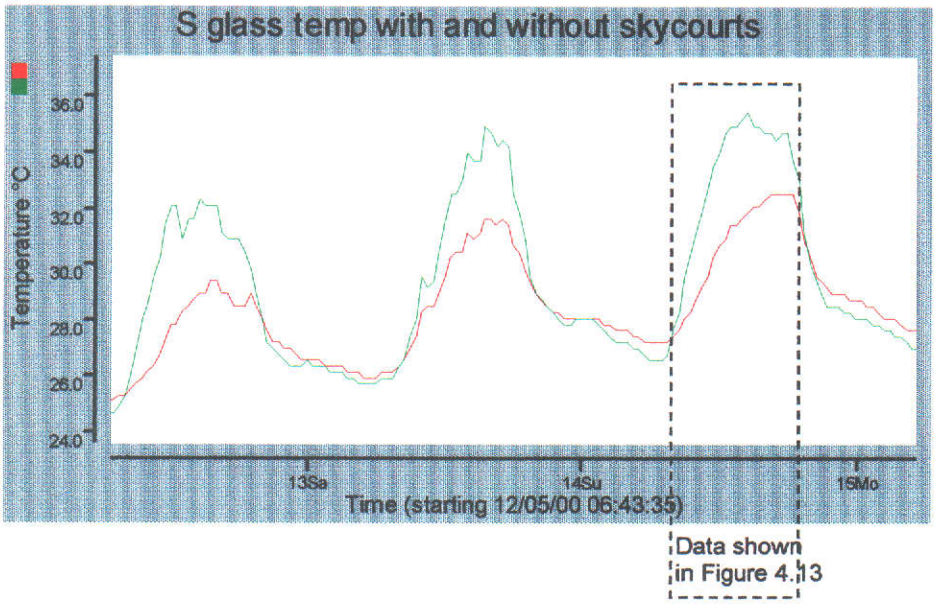
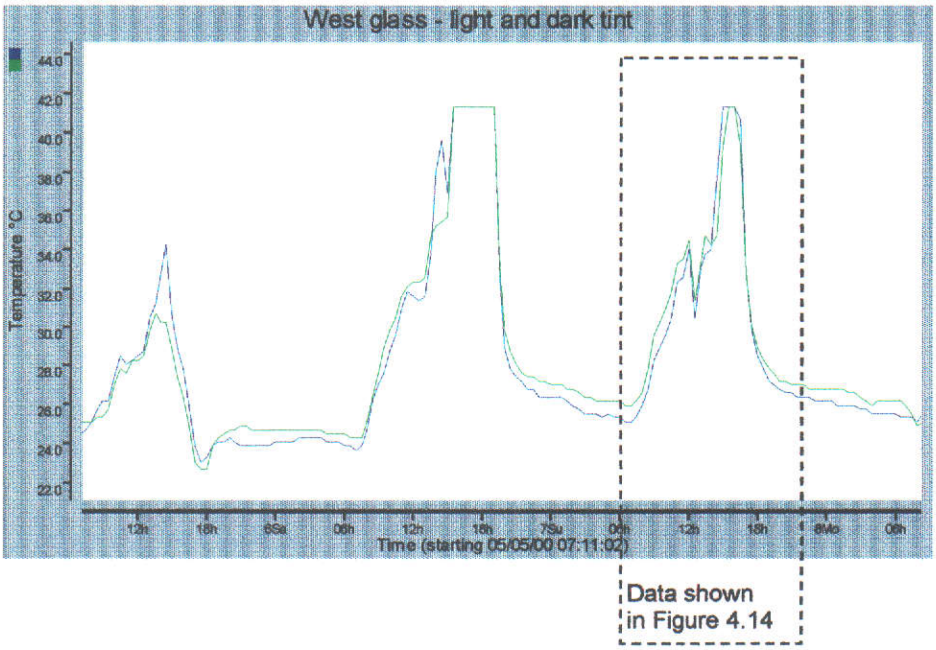


Figure A10.6. W-facing EST_{Glass} of UMNO for impact of transitional space (2 days)



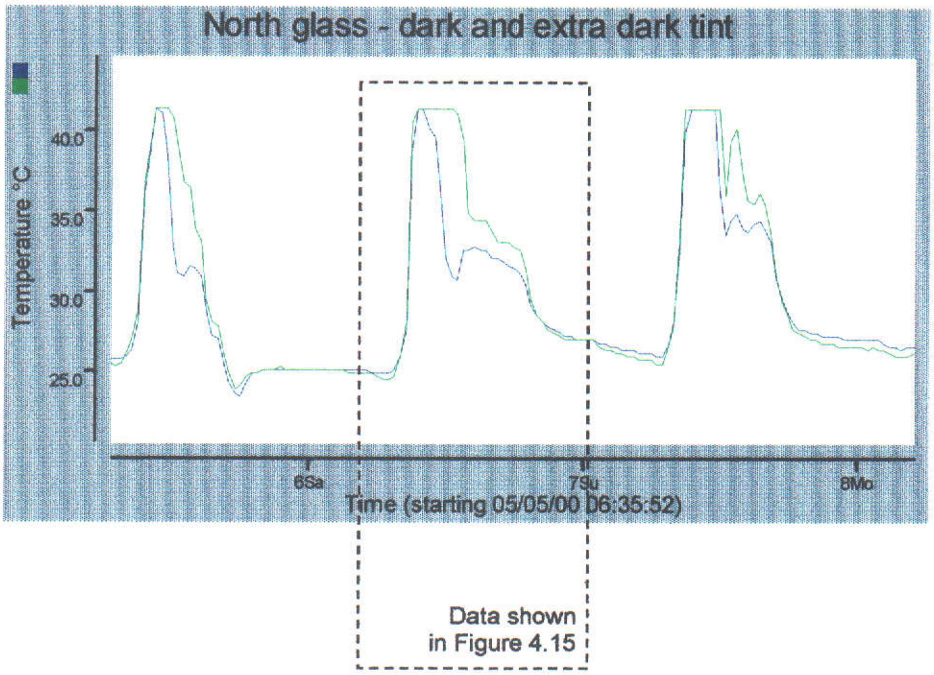
Data shown
in Figure 4.13

Figure A10.7. S-facing EST_{Glass} of MES
for impact of transitional space (3 days)



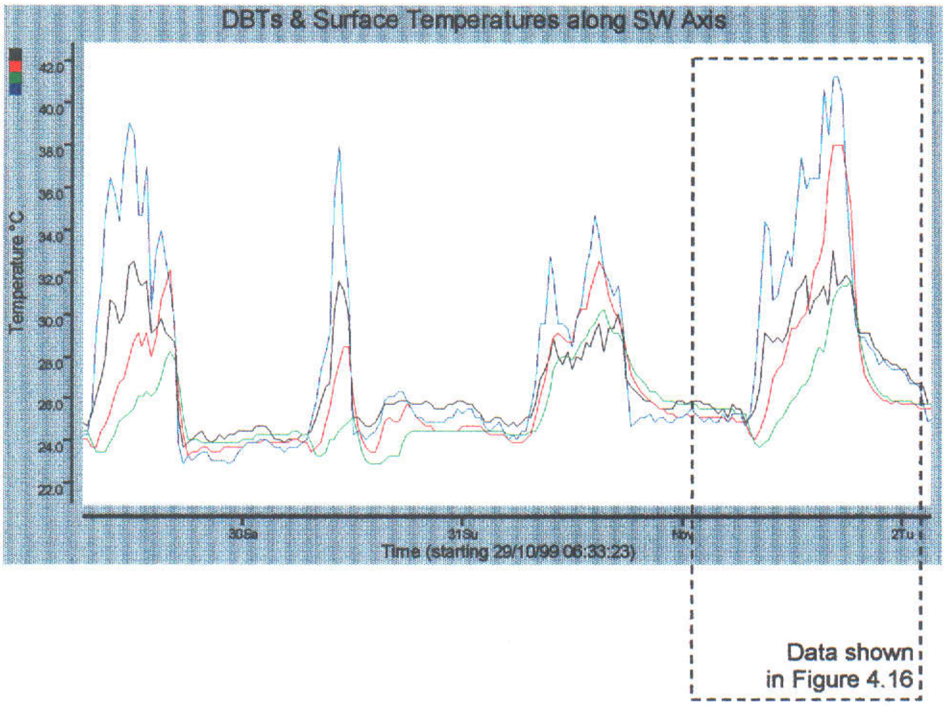
Data shown
in Figure 4.14

Figure A10.8. W-facing EST_{Glass} of MES
for impact of solar tints (3 days)



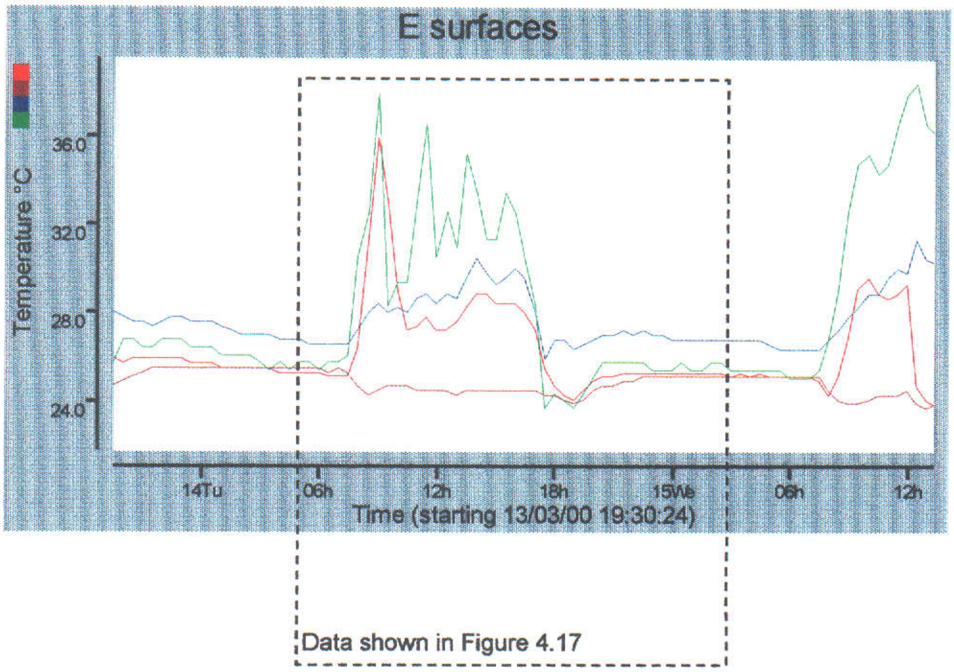
Data shown
in Figure 4.15

Figure A10.9. NE-facing EST_{Glass} of MES
for impact of solar tints (3 days)



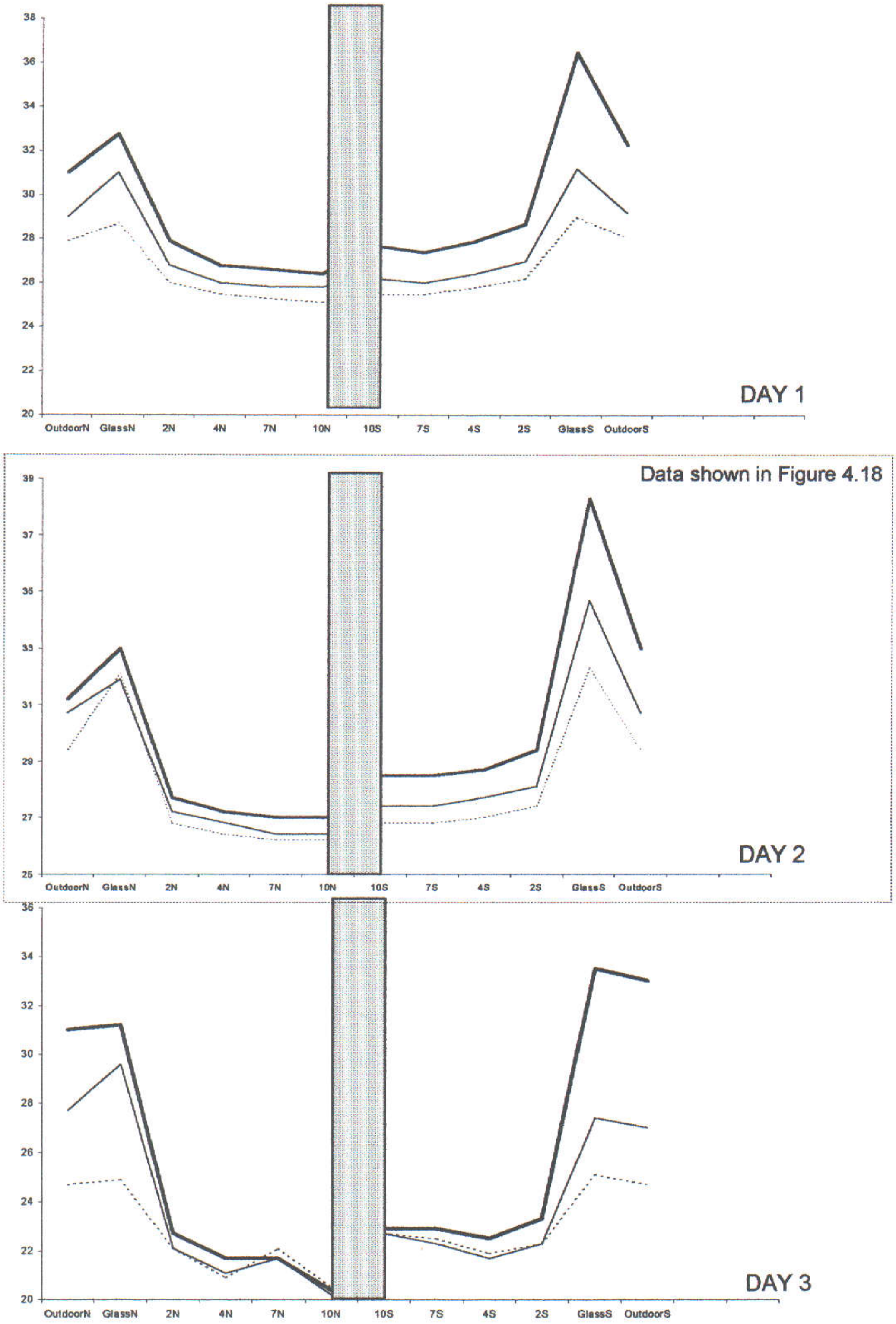
Data shown
in Figure 4.16

Figure A10.10 SW-facing EST at RevH (4 days)



Data shown in Figure 4.17

Figure A10.11. E-facing EST at URA (2 days)



Data shown in Figure 4.18

Figure A10.12 Temperatures along N-S axis of RevH
in passive mode (3 days)

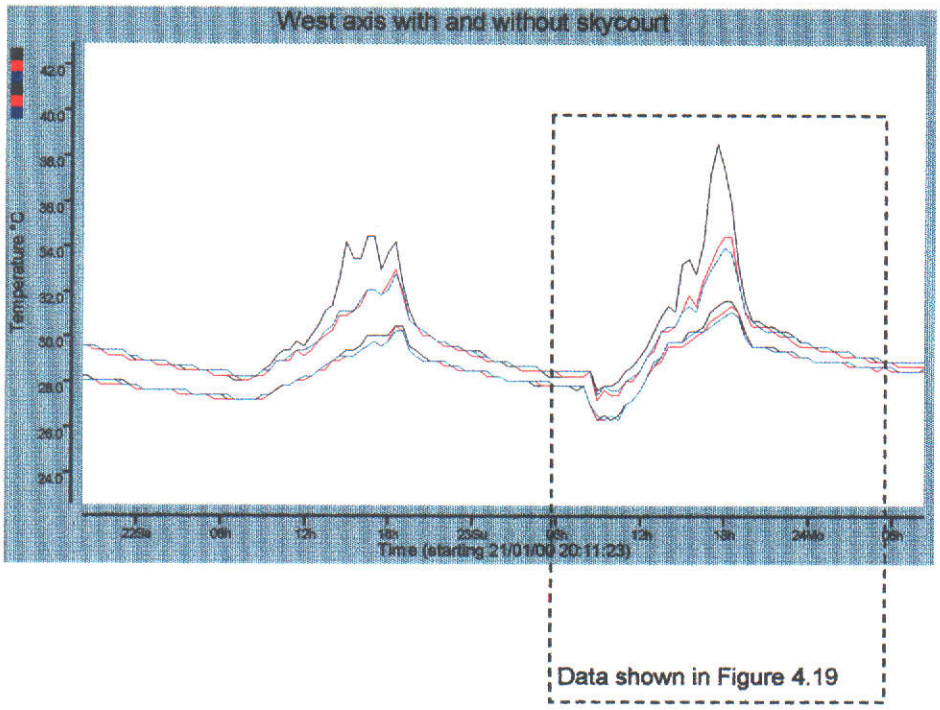


Figure A10.13 IATs from W-facing façade in UMNO
in passive mode (2 days)

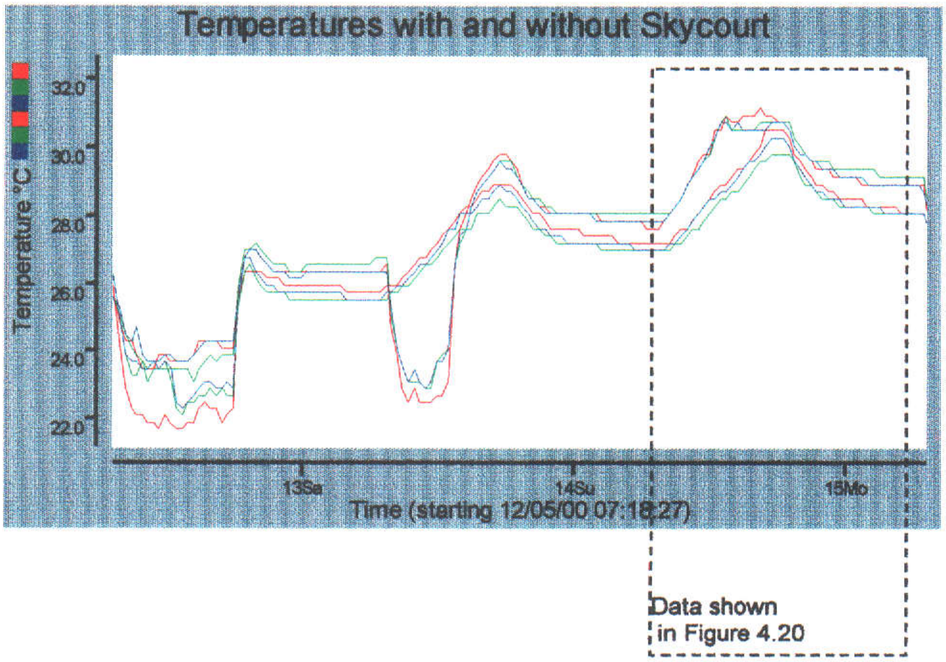


Figure A10.14. IATs from S-facing façade in MES
in passive mode (3 days)

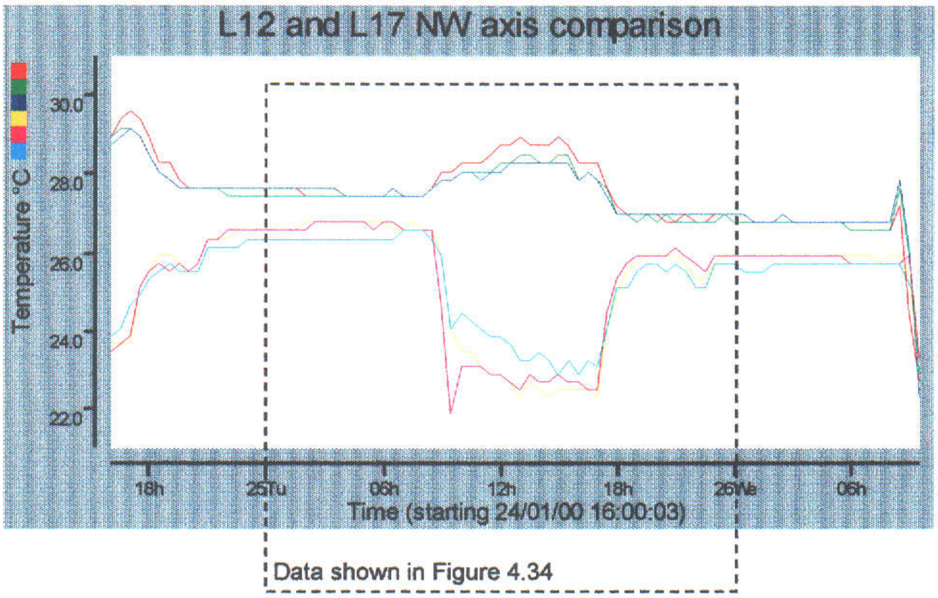


Figure A10.15. IATs for passive and active-run floors in UMNO (2 days)

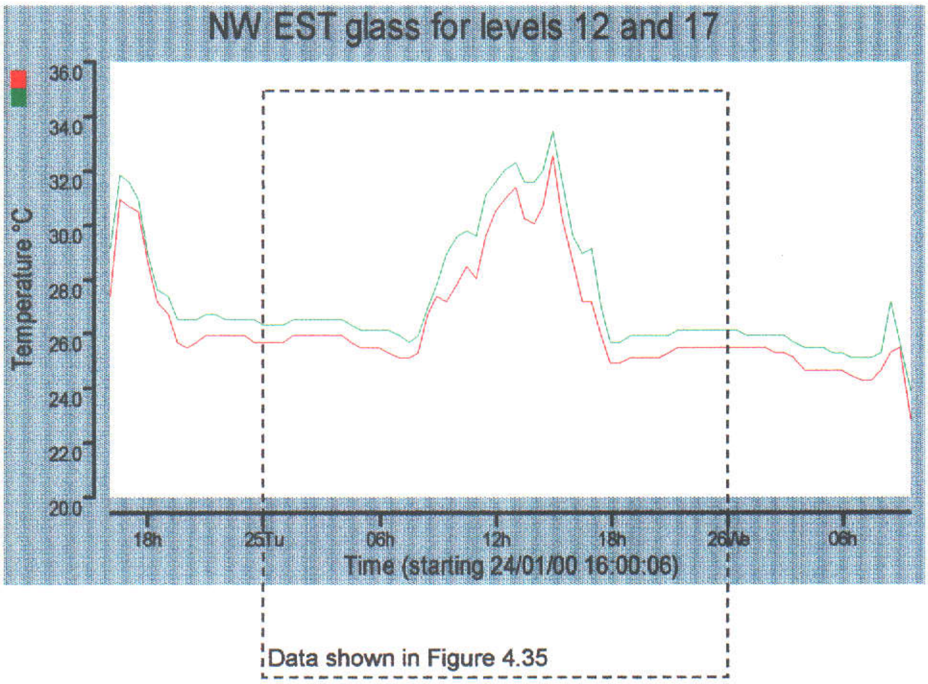


Figure A10.16. EST for passive and active-run floors in UMNO (2 days)

APPENDIX B

Appendix B1. Survey 1 Questionnaire

PART I. Thermal Comfort

A. At this moment, please describe how you feel…

-3	-2	-1	0	1	2	3
cold	**cool**	**slightly cool**	**neutral**	**slightly warm**	**warm**	**hot**

B. At this moment, please rate the humidity…

-3	-2	-1	0	1	2	3
much too dry	**too dry**	**slightly dry**	**just right**	**slightly humid**	**too humid**	**much too humid**

C. At this moment, please rate the air movement around you…

-3	-2	-1	0	1	2	3
much too still	**too still**	**slightly still**	**just right**	**slightly breezy**	**too breezy**	**much too breezy**

D. At this moment, how comfortable do you feel?

6. **very comfortable**
5. **moderately comfortable**
4. **slightly comfortable**
3. **slightly uncomfortable**
2. **moderately uncomfortable**
1. **very uncomfortable**

In general, does your comfort level vary according to...

E.	***time of day***	**1. Yes**	**2. No**
F.	***outdoor weather***	**1. Yes**	**2. No**

Others ____________________

G. If yes to any of the above, please elaborate...

____

____

H. When you feel too cold or too hot, what do you do to make yourself more comfortable?

1. **Change the amount of clothing you have on (eg. put on or remove jacket)**
2. **Change your level of activity (eg. move about to warm up)**
3. **Change the amount of daylight entering through the window**
4. **Have a warm or cool drink**
5. **Others**____

I. Do you generally wear a jacket to work?

1. **Yes** 2. **No**

J. Do you keep a jacket/sweater/coat in the office?

1. Yes 2. No

K. If yes, how often do you wear it?

____

L. On the whole, do you feel your workspace is...

-3	**-2**	**-1**	**0**	**1**	**2**	**3**
cold	**cool**	**slightly cool**	**neutral**	**slightly warm**	**warm**	**hot**

M. How would you rate your overall thermal comfort in your workspace?

6. very comfortable
5. moderately comfortable
4. slightly comfortable
3. slightly uncomfortable
2. moderately uncomfortable
1. very uncomfortable

PART II. LIGHTING

N. At this moment, how would you describe the overall level of light here?

-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Too Dim	**Dim**	**Slightly Dim**	**Just Right**	**Slightly Bright**	**Bright**	**Too Bright**

O. In general, how would you describe the daylight in your work-space....

0	**1**	**2**	**3**	**4**
None at all	**Very dim/ Negligible**	**Soft and diffused**	**Strong and direct**	**Very bright and direct**

P. If you had the choice, how would you change the daylight at your workspace?

1. Decrease it 2. No Change 3. Increase it

Q. Does the daylight you receive affect your thermal comfort?

1. Yes 2. No

R. If yes, please elaborate how and when it affects you?

____

____

S. On the whole, how satisfied are you with the light at your workplace?

6. very satisfied
5. moderately satisfied
4. slightly satisfied
3. slightly dissatisfied
1. moderately dissatisfied
1. very dissatisfied

PART III. PERSONAL CONTROL

Are you able to control any of the following?...

T.	*Open and close blinds*	**1.**	**Yes**	**2.**	**No**
U.	*Adjust the thermostat*	**1.**	**Yes**	**2.**	**No**
V.	*Adjust the level of electrical light*	**1.**	**Yes**	**2.**	**No**

W. If yes to any of the above, how often do you do it?

____

____

X. How satisfied are you with this level of control?

-3	-2	-1	0	1	2	3
Very Dissatisfied	**Dissatisfied**	**Somewhat Dissatisfied**	**Neutral**	**Somewhat Satisfied**	**Satisfied**	**Very Satisfied**

PART IV. BACKGROUND

Y. Gender: **1. Male** **2. Female**

Z. Age: **1. under 20**
2. 20-29
3. 30-39
4. 40-49
5. 50 and above

AA. Job: **1. Professional**
2. Managerial
3. Technical Support (eg. Draftsperson, Technician)
4. Administrative Support (eg. Clerk, Secretary)
5. Others

AB. Race: **1. Chinese**
2. Malay
3. Indian
4. Eurasian
5. Others____________________

PART V. OBSERVATIONS

AC. How far is the subject from the nearest window?

a. **Next to Window**
b. **Second from Window**
c. **Third from Window**
d. **No access to Window**

AD. If next to window, are blinds open or close?

1. Open **2. Close**

Indoor Conditions (at time of interview)

*AE. IAT:*______________________

*AF. RH:*______________________

*AG. Illuminance*_________

AH. Outdoor weather (at time of interview):

1. Clear and sunny
2. Cloudy but bright
3. Cloudy and overcast
4. Rain

AI. Comments

____

AJ. Perception of Transitional Space (where applicable)

____

Date of Survey

____

Time of Survey:

____

Appendix B2. Summary of Statistical Tests for Data from Survey 1

		Gender (2 point nominal)	Age (5 point nominal)	Job (4 point nominal)	Race (4 point nominal)
Thermal Scales	**Thermal Sensation** *at time of interview* (7 point ordinal)	No significance**	No significance***	No significance***	No significance***
	Thermal Sensation *in general* (7 point ordinal)	**Mann-Whitney U test** **Z = -1.966** **p=0.049**	No significance***	No significance***	No significance***
	Thermal Comfort *at time of interview* (6 point ordinal)	No significance**	No significance***	No significance***	No significance***
	Thermal Comfort *in general* (6 point ordinal)	No significance**	No significance***	No significance***	No significance***
	Humidity Level *at time of interview* **(7 point ordinal)**	No significance**	No significance***	No significance***	No significance***
	Air Movement *at time of interview* (7 point ordinal)	No significance**	No significance***	No significance***	No significance***
Visual Scales	**Overall Light Level** *at time of interview* **(7 point ordinal)**	No significance**	No significance***	No significance***	No significance***
	Daylight Level *in general* (5 point ordinal)	No significance**	No significance***	No significance***	No significance***
	Daylight Preference (3 point nominal)	No significance*	No significance*	**χ^2 (8,N=108) = 20.425,p=0.009**	No significance*
	Satisfaction with Overall Light *in general* (6 point ordinal)	No significance**	No significance***	No significance***	No significance***

No significance refers to results with p>0.05
** Chi Square*
*** Mann-Whitney U test*
**** Kruskal-Wallis test*

Table B2.1. Thermal and visual scales against background variables

		Proximity to Envelope[1] (2 point nominal)	**Building** (5 point nominal)
Thermal Scales	**Thermal Sensation** *at time of interview* (7 point ordinal)	No Significance**	**χ^2 (4, N=109) = 29.45 P=0.000*** **
	Thermal Sensation *in general* (7 point ordinal)	No Significance**	**χ^2 (4, N=107) = 20.72 P=0.000*** **
	Thermal Comfort *at time of interview* (6 point ordinal)	No Significance**	No Significance***
	Thermal Comfort *in general* (6 point ordinal)	No Significance**	No Significance***
	Humidity Level *at time of interview* (7 point ordinal)	No Significance**	No Significance***
	Air Movement *at time of interview* (7 point ordinal)	No Significance**	No Significance***
Visual Scales	**Overall Light Level** *at time of interview* (7 point ordinal)	No Significance**	No Significance***
	Daylight Level *in general* (5 point ordinal)	**Mann-Whitney U test Z = -4.3 p=0.000**	No Significance***
	Daylight Preference (3 point nominal)	**χ^2(2, N=108) = 8.156 p=0.02**	**χ^2(8, N=108)= 15.935 p=0.043**
	Satisfaction with Overall Light *in general* (6 point ordinal)	No Significance**	No Significance***

No significance refers to results with p>0.05
** Chi Square*
*** Mann-Whitney U test*
**** Kruskal-Wallis test*

Table B2.2. Thermal and visual scales against building variables

	Overall Light Intensity *at time of interview* (7 point ordinal)	**Daylight Level** *in general* (5 point ordinal)
Thermal Sensation *at time of interview* (7 point ordinal)	No significance*	No significance*
Thermal Sensation *in general* (7 point ordinal)	No significance*	No significance*
Thermal Comfort *at time of interview* (6 point ordinal)	**r_s 0.218, N=85 p=0.045***	No significance*
Thermal Comfort *in general* (6 point ordinal)	No significance*	No significance*

No significance refers to results with p>0.05
**Spearman's Rho*

Table B2.3. Analysis of thermal against visual scales

---

[1] The two groups were based on those who were in the perimeter zone, i.e. less than 6m from envelope and those further in. In terms of the questionnaire results, this meant grouping all subjects into those at location A and the rest.

A three-way breakdown of the population (according to locations A, B and C) had showed no results of significance.

		Satisfaction with Control (7-point ordinal)
Thermal Scales	**Availability of Control** (2 point nominal)	No significance**
	Thermal Sensation *at time of interview* (7 point ordinal)	No significance*
	Thermal Sensation *in general* (7 point ordinal)	No significance*
	Thermal Comfort *at time of interview* (6 point ordinal)	**r_s*= 0.252, N=85, p=0.02**
	Thermal Comfort *in general* (6 point ordinal)	No significance*
	Humidity Level *at time of interview* **(7 point ordinal)**	No significance*
	Air Movement *at time of interview* (7 point ordinal)	**r_s*= 0.292, N=85, p=0.007**
Visual Scales	**Overall Light Level** *at time of interview* **(7 point ordinal)**	No significance*
	Daylight Level *in general* (5 point ordinal)	No significance*
	Daylight Preference (3 point nominal)	No significance***
	Satisfaction with Overall Light *in general* (6 point ordinal)	**r_s*= 0.369, N=84, p=0.001**

No significance refers to results with p>0.05
** Chi Square*
*** Mann-Whitney U test*
**** Kruskal-Wallis test*

Table B2.4. Thermal and visual scales against Satisfaction with Control

Appendix B3. Regressions for Data from Survey 1

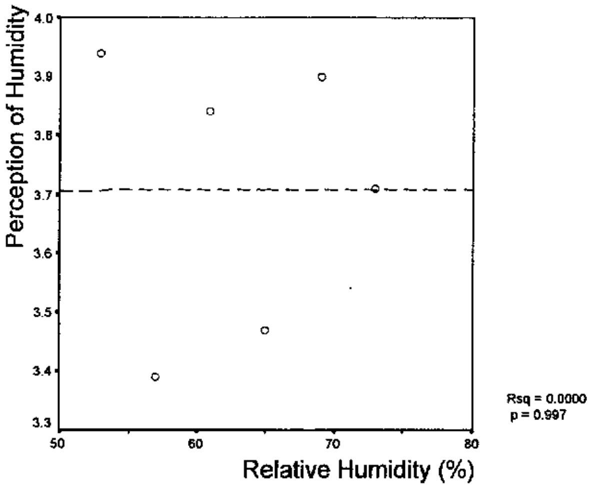


Figure B3.1. Perception of Humidity against RH

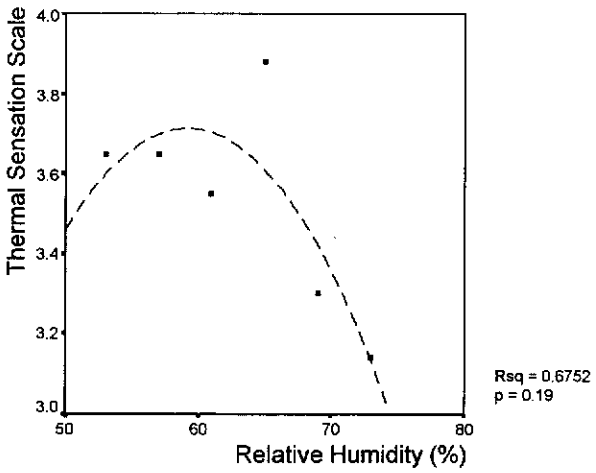
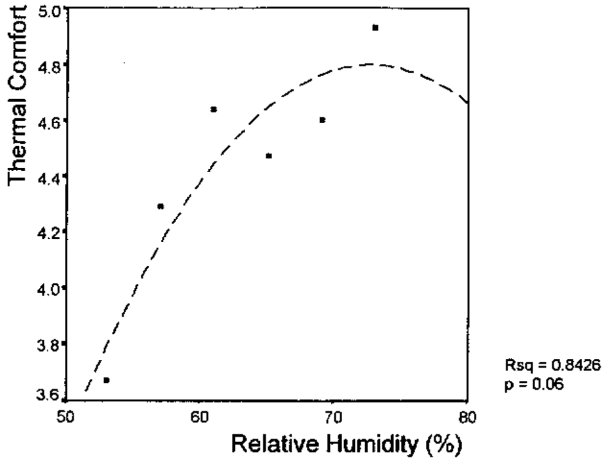


Figure B3.2. Thermal Sensation scale against RH



· Figure B3.3. Thermal Comfort scale against RH

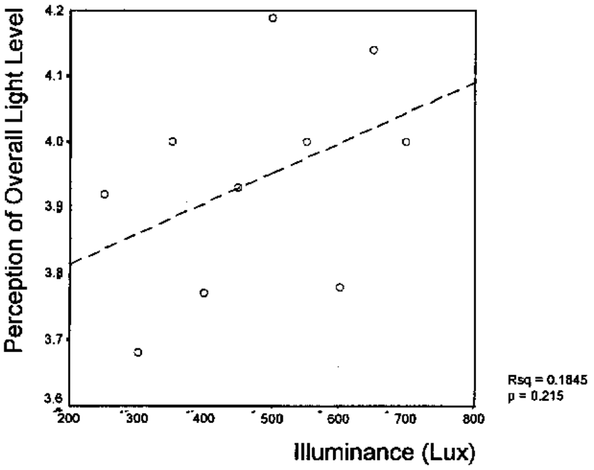


Figure B3.4. Perception of Overall Light against Illuminance

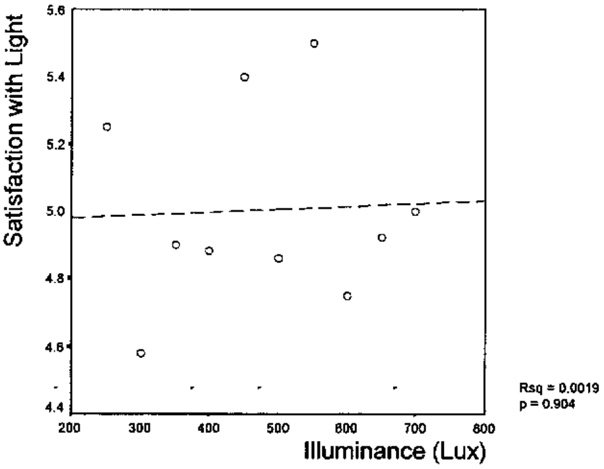


Figure B3.5. Satisfaction with Light against Illuminance

Appendix B4. Survey 2 - Pilot

The list of 15 spaces used in Survey 2 and the two-sort procedure were derived from a pilot survey, involving 10 subjects.

In the first part of the pilot, 5 individuals who worked in office buildings in Singapore were asked to list spaces encountered in such buildings. No limit was placed on how many spaces could be nominated. Over twenty spaces were cited in total. Of these, the 15 most frequently cited were used in the sorting tasks.

A pilot trial of the sorting task was then carried out. The remaining 5 individuals were surveyed.

The procedure, at this point, consisted of a single sort. Each subject was asked to group the spaces on the basis of preference, with as many labels in each mode category as they deemed appropriate.

It was noticed here that most spaces ended up in the active-mode, particularly AC on the question of thermal comfort. Whilst this was indicative of their preference, it said very little about what they were prepared to tolerate. In the dialogue with the subjects, they stated that in an ideal world, with no cost or environmental concerns, this is what they would prefer. It was then decided that a second sort would be introduced, this time with a limit on the number of spaces permitted in each mode, to mimic real-world constraints.

This two-sort procedure was presented to subjects as an academic exercise in which the subject was asked to imagine s/he was a designer who had to make decisions about indoor conditions. During the first sort, subjects were told that it was entirely a matter of their personal preference and no constraints of cost or clients need apply. In the second sort they were told that a limit has been introduced. They had to then move labels from one pile to another to make up the breakdown specified.

The pilot had also shown that subjects were confused by whether choices had to be made with regard to day or nighttime use, particularly in the context of visual modes. All spaces invariably ended up in electrical light (EL) pile, since daylight (DL) is not a meaningful option at night. The verbal instruction introduced in the final survey was that subjects should only consider daytime use of the building.

A second confusion emerged with regard to the use of the label 'Toilet'. Some subjects asked during the pilot if this referred to staff or public toilet. Evidently in some office buildings, there is a delineation of the two. A verbal instruction was therefore issued at the start of each sort that this label referred specifically to staff toilet.

Finally, subjects were instructed that their choice need not reflect that with which they were familiar at their respective place of work. The procedure was to be seen as a hypothetical scenario, not a reflection of conditions they were accustomed to.

Appendix B5. Survey 2 Format

THERMAL SORTING TASK

Verbalisation for Thermal Comfort	***Mode assignment:*** ***1=Active (air conditioning)*** ***2=Mixed (fan-assisted ventilation)*** ***3= Passive (natural ventilation)***	***1 Sort***	***ndSort***
	1.Your Own Workplace/Room/Cubicle		
	2. Meeting Rooms		
	3. Staff Restroom/Lounge		
	4. Cafeteria		
	5. Auditorium		
	6. Main Entrance Foyer/Atrium		
	7. Lift Lobby		
	8. Fire Escape Stairs		
	9. Workplace Toilet		
	10. Store Room		
	11. Staff Kitchen/Pantry		
	12. Photocopy Room		
	13. Gymnasium/Health Centre		
	14. Library		
	15. Day Care Centre		

VISUAL SORTING TASK

Verbalisation for Visual Comfort	***Mode assignment:*** ***1=Active (electrical light)*** ***2=Mixed (electrical + natural light)*** ***3= Passive (natural light)***	***1st Sort***	***2nd Sort***
1 Mainly Natural Light	1.Your Own Workplace/Room/Cubicle		
	2. Meeting Rooms		
	3. Staff Restroom/Lounge		
	4. Cafeteria		
	5. Auditorium		
2. Natural Light combined with Electrical Light	6. Main Entrance Foyer/Atrium		
	7. Lift Lobby		
	8. Fire Escape Stairs		
	9. Workplace Toilet		
	10. Store Room		
3. Mainly Electrical Light	11. Staff Kitchen/ Pantry		
	12. Photocopy Room		
	13. Gymnasium/Health Centre		
	14. Library		
	15. Day Care Centre		

BACKGROUND

A. Gender: **1. Male 2. Female**

B. Age: **1. under 20**
2. 20-29
3. 30-39
4. 40-49
5. 50 and above

C. Job: **1. Professional**
2. Managerial
3. Technical Support (eg. Draftsperson, Technician)
4. Administrative Support (eg. Clerk, Secretary)
5. Others

C. Race: **1. Chinese**
2. Malay
3. Indian
4. Eurasian
5. Others____________________

Appendix B6. Survey 2 Data – Subject Verbalisation

Subject	**MES Subject Verbalisation**	**AC/FA** *DL/ EL+DL*	**FA/NV** *EL+DL/EL*	**AC/NV** *DL/EL*
1	**Comfort, enclosure, activity (work-related), health/hygiene, duration/frequency of use.**	**D2**	**T**	**D1**
2	**Duration/frequency of use, hygiene, activity/functionality, comfort**	**T**	**D2**	**T**
3	**Comfort, duration of use, safety, enclosure/sense of outdoors, health, density of use (no of people/functionality)**	**D1**	**-**	**-**
4	**Comfort, activity/functionality, health/hygiene, duration of use**	**D1**	**T**	**T**
5	**Comfort, activity, image, duration of use, health/hygiene, safety**	**D1**	**D2**	**D1**
6	**Comfort, image/status, duration/frequency of use, enclosure/sense of outdoors**	**D1**	**T**	**T**
7	**Comfort, activity/functionality, duration/frequency of use, health/hygiene, image**	**D1**	**T**	**D1**
8	**Functionality/Activity (work vs. relax), comfort, duration of use, enclosure/outdoor**	**D1**	**T**	**T**
9	**Comfort, functionality/activity (concentration vs. relaxation), health, duration of use, reliability/consistency, enclosure/outdoor**	**D1**	**D2**	**T**
10	**Comfort, activity/functionality, image, hygiene, safety, duration of use**	**T**	**T**	**T**
11	*Outdoor/enclosure (associate with fresh air), frequency/duration of use, choice/control, activity/functionality, thermal comfort*	*D2*	*D2*	*T*
12	*Thermal comfort, enclosure(indoor-outdoor links and transitions), activity (concentration vs. relaxation) image (formal vs. informal)*	*T*	*D2*	*T*
13	*Enclosure, Image (formal vs. informal)*	*T*	*T*	*D1*
14	*Safety, Choice, activity (concentration) enclosure (link to outdoors)*	*T*	*D2*	*T*
15	*Activity (concentration vs. relaxation), choice/reliability, duration/frequency of use, enclosure (link to outdoors)*	*D2*	*D2*	*T*
16	*Duration of use, safety, reliability/consistency, functionality/activity*	*D2*	*D2*	*T*
17	*Consistency/reliability, duration of use, activity (concentration vs. relaxation), image (formal vs. informal)*	*D2*	*T*	*T*
18	*Safety, control/flexibility, enclosure (link to outdoors) duration/frequency of use*	*T*	*T*	*T*
19	*Enclosure (link from outdoor to indoor) , flexibility/reliability, functionality/activity, health (eye strain)*	*T*	*D2*	*T*

Bold text refers to comments made during thermal sorts. Italicised text refers to comments during visual sorts
D = Degree of Comfort. T = Type of Comfort. The number suffix to 'D' refers to which of the modes was deemed to deliver a greater degree of comfort; 1=active, 2=mixed, 3=passive.

Table B6.1. Subject verbalisation for thermal and visual sorts at MES

Subject	**RevH Subject Verbalisation**	**AC/FA** *DL/* *EL+DL*	**FA/NV** *EL+DL/EL*	**AC/NV** *DL/EL*
1	**Comfort (AC), relationship with outdoors (NV), duration/frequency of use**	**T**	**T**	-
2	**Duration/frequency of use, activity/functionality, health/hygiene (gym, toilet)**	**T**	**D2**	-
3	**Comfort (AC), duration of use, health/hygiene (gym), safety (fire escape)**	**T**	**D2**	-
4	**Comfort (AC), activity/functionality, duration of use, image (AC= better) health/hygiene (pantry, gym), relationship to outdoors**	**T**	**D2**	-
5	**Comfort, duration of use, activity, image (AC in atrium/lounge = better), consistency/control (NV= higher chance of discomfort)**	**D1**	**T**	-
6	**Comfort (AC), duration/frequency of use, health/hygiene (cafeteria/pantry), activity/functionality, consistency/control (NV= less control)**	**T**	**D2**	-
7	**Activity/functionality, duration/frequency of use (foyers/lobbies), health/hygiene (day care centre, gym, pantry)**	-	-	-
8	**Activity/functionality, frequency of use, health/hygiene (day care centre), safety (fire escape), image (atrium/lobbies)**	**T**	**D2**	
9	**Comfort (AC), duration/frequency of use, health/hygiene (toilet, cafeteria, photocopy room)**	**T**	**D2**	-
10	**Duration/frequency of use, consistency/control (NV= less control and consistency)**	**T**	**D2**	-
11	**Comfort (AC), duration/frequency of use, activity/functionality, health/hygiene (gym), relationship to outdoors (atrium, lift lobbies)**	**T**	**T**	-
12	**Comfort (AC), activity/functionality, duration/frequency of use, health/hygiene, consistency/control (NV= less control)**	**D1**	**D2**	-
13	*Activity/functionality, relationship to outdoors, duration/frequency of use*	*D2*	*D3*	-
14	*Consistency/control (DL= less reliable), duration/frequency of use, activity/functionality, health (gym, pantry, cafeteria)*	*D2*	*D2*	
15	*Duration/frequency of use, image (EL= "grander"), safety (fire escape), activity/functionality, mood (DL= brighter = concentration)*	*D1*	*D3*	*D1*
16	*Consistency/control (DL= less reliable), activity/functionality, duration/frequency of use*	*D2*	*D2*	-
17	*Safety (atrium, lift lobby), duration of use (pantry), health (day care), privacy (EL = enclosure = privacy), activity/functionality*	*D1*	*T*	
18	*Consistency/control (DL= less control), relationship to outdoors (can be distracting, eg. auditorium)*	*T*	*T*	
19	*Consistency/control (DL= unreliable), duration/frequency of use, image (EL= cozy)*	-	*D2*	-
20	*Activity/functionality, consistency/control (EL= reliable), safety (fire escape), sense of enclosure (DL in atrium/lift lobby)*	*T*	*D2*	*D3*
21	*Relationship to outdoors (atrium), consistency/control, mood (DL= relaxation)*	*T*	*D2*	*T*
22	*Relationship to outdoors (atrium, lobby), activity/functionality, safety (fire escape)*	*T*	*T*	*D3*
23	*Safety, consistency/control (DL = less reliable), duration of use, privacy (absence of windows in toilets, store)*	*T*	*D2*	*D1*
24	*Safety, relationship to outdoors (DL= openness), privacy (store, toilets), activity/functionality, mood (DL= relaxation, EL= concentration)*	*T*	*D2*	*D1*

Bold text refers to comments made during thermal sorts. Italicised text refers to comments during visual sorts
D = Degree of Comfort. T = Type of Comfort. The number suffix to 'D' refers to which of the modes was deemed to deliver a greater degree of comfort; 1=active, 2=mixed, 3=passive.

Table B6.2. Subject verbalisation for thermal and visual sorts at RevH

Subject	**CSC Subject Verbalisation**	**AC/FA** *DL/ EL+DL*	**FA/NV** *EL+DL/EL*	**AC/NV** *DL/EL*
1	*Gym/Health; Openness vs. Enclosure; Aesthetics/Image; Audit/Functionality; Control, Flexibility and Choice.*	*D2*	*D2*	*T*
2	*Reliability; relationship with outdoors (transitional spaces); safety/security; duration of use*	*D2*	*T*	*D3*
3	*Reliability; view; degree of enclosure*	*D2*	*D2*	*D3*
4	*Reliability and consistency; sense of enclosure; view*	*D2*	*D2*	*D1*
5	*Variability and consistency; DL=TC; functionality; privacy, frequency of use; familiarity*	*T*	*T*	*D1*
6	*View; concentration; duration of use*	-	-	-
7	*Variability; duration of use; functionality*	*D2*	*T*	*T*
8	*Variability; consistency; relaxation; frequency of use; privacy; functionality*	*T*	*T*	*T*
9	*Relaxation; control; reliability; views; functionality*	*T*	*T*	*T*
10	*Openness vs. enclosure;*	*T*	*T*	*D1*
11	**Hygiene; duration of use; comfort; functionality; relationship to outside**	**D1**	**T**	**D1**
12	**Density of people; safety; health and hygiene; familiarity; functionality; duration of use; depth into building.**	**T**	**D2**	**T**
13	**Nil**	-	-	-
14	**Comfort; duration of use; functionality**	**T**	**T**	**T**
15	**Health and hygiene; comfort; duration of use; relationship to outside**	**T**	**T**	**T**
16	**Health and hygiene; safety; comfort; density of people; frequency of use.**	**T**	**D2**	**T**
17	**Safety; health and hygiene; comfort; density of people.**	**T**	**T**	**T**
18	**Safety; Health and hygiene; relationship to outdoors; image; comfort; functionality; duration of us; density of people.**	**T**	**T**	**T**
19	**Health and hygiene; functionality, frequency and duration of use, comfort**	**D1**	**T**	**T**
20	**Nil**	-	-	-

Bold text refers to comments made during thermal sorts. Italicised text refers to comments during visual sorts
D = Degree of Comfort. T = Type of Comfort. The number suffix to 'D' refers to which of the modes was deemed to deliver a greater degree of comfort; 1=active, 2=mixed, 3=passive.

Table B6.3. Subject verbalisation for thermal and visual sorts at CSC

Subject	MND Subject Verbalisation	**AC/FA** *DL/ EL+DL*	**FA/NV** *EL+DL/EL*	**AC/NV** *DL/EL*
1	**Duration and frequency of use: functionality;**	**D1**	**D2**	**D1**
2	**Duration and frequency of use; functionality, density of people; comfort.**	**D1**	**D2**	**D1**
3	**Duration and frequency of use; image; functionality.**	**D1**	**T**	**T**
4	**Health and hygiene; frequency and duration of use; comfort; functionality; density of people; enclosure.**	**T**	**T**	**D3**
5	**Safety; comfort; duration of use; image.**	**T**	**T**	**T**
6	**Frequency and duration of use; comfort; transition from outdoor to inside; concentration.**	**D1**	**D2**	**D1**
7	**Image; comfort; frequency and duration of use.**	**D1**	**D2**	**D1**
8	**Safety; health and hygiene; frequency and duration of use; transition from outdoors; functionality.**	**T**	**T**	**D1**
9	**Frequency and duration of use; comfort.**	-	-	-
10	**Openness; frequency and duration of use; comfort.**	**D1**	**D2**	**D1**
11	*Concentration; image; reliability.*	-	-	-
12	*Functionality; consistency and control; view; relaxation vs concentration.*	*T*	*T*	*T*
13	*Health; safety, reliability; density of people; duration of use.*	*D1*	*D2*	*D1*
14	*Reliability; safety; control; frequency of use.*	*T*	*T*	*T*
15	*Relaxation vs concentration; reliability.*	*D2*	*T*	*D3*
16	*Reliability; duration and frequency of use; image.*	*T*	*T*	*T*
17	*Comfort; familiarity; functionality; relationship to outdoors/enclosure; image;*	*D2*	*D2*	*D1*
18	*View; health; duration of use; functionality;*	*T*	*T*	*D1*
19	*Relationship to outdoors; duration of use; mood; functionality*	*D2*	*T*	*D3*
20	*Safety; relaxation, functionality*	-	-	-

Bold text refers to comments made during thermal sorts. Italicised text refers to comments during visual sorts
D = Degree of Comfort. T = Type of Comfort. The number suffix to 'D' refers to which of the modes was deemed to deliver a greater degree of comfort; 1=active, 2=mixed, 3=passive.

Table B6.4. Subject verbalisation for thermal and visual sorts at MND

Appendix B7. Survey 2 Data – Choice of Modes

THERMAL COMFORT N=42			VISUAL COMFORT N=41		
	1st Sort	2nd Sort	1st Sort	2nd Sort	
Workspace					**Workspace**
Active - AC	41(98)	41(98)	1(2)	1(2)	Passive – DL
Mixed - FA	-	-	33(80)	33(80)	Mixed – EL+DL
Passive - NV	1(2)	1(2)	7(8)	7(8)	Active - EL
Meeting Room					**Meeting Room**
Active - AC	42(100)	40(95)	1(2)	1(2)	Passive – DL
Mixed - FA	-	2(5)	31(76)	27(66)	Mixed – EL+DL
Passive - NV	-	-	9(22)	13(32)	Active - EL
Staff Lounge					**Staff Lounge**
Active - AC	36(86)	13(31)	9(22)	21(51)	Passive – DL
Mixed - FA	5(12)	19(45)	21(54)	13(32)	Mixed – EL+DL
Passive - NV	1(2)	10(24)	11(27)	7(17)	Active - EL
Cafeteria					**Cafeteria**
Active - AC	30(71)	5(12)	13(32)	25(61)	Passive – DL
Mixed - FA	7(17)	27(64)	22(54)	12(29)	Mixed – EL+DL
Passive - NV	5(12)	10(24)	6(14)	4(10)	Active - EL
Auditorium					**Auditorium**
Active - AC	42(100)	39(93)	-	-	Passive – DL
Mixed - FA	-	2(5)	5(12)	4(10)	Mixed – EL+DL
Passive - NV	-	1(2)	36(88)	37(90)	Active - EL
Atrium/Entrance Foyer					**Atrium/Entrance Foyer**
Active - AC	32(76)	10(24)	17(41)	28(67)	Passive – DL
Mixed - FA	1(2)	9(22)	21(51)	10(25)	Mixed – EL+DL
Passive - NV	9(22)	23(56)	3(8)	3(8)	Active - EL
Lift Lobby					**Lift Lobby**
Active - AC	32(76)	5(12)	7(18)	17(42)	Passive – DL
Mixed - FA	6(14)	13(31)	18(44)	11(27)	Mixed – EL+DL
Passive - NV	4(10)	24(57)	16(38)	13(31)	Active - EL
Fire Escape Stairs					**Fire Escape Stairs**
Active - AC	2(5)	1(2)	15(37)	22(54)	Passive – DL
Mixed - FA	6(14)	2(5)	16(38)	10(25)	Mixed – EL+DL
Passive - NV	34(81)	39(93)	10(25)	9(21)	Active - EL
Toilet					**Toilet**
Active - AC	12(29)	1(2)	4(10)	14(35)	Passive – DL
Mixed - FA	16(38)	18(43)	18(44)	6(14)	Mixed – EL+DL
Passive - NV	14(33)	23(55)	19(46)	21(51)	Active - EL
Store Room					**Store Room**
Active - AC	15(36)	1(2)	2(5)	5(12)	Passive – DL
Mixed - FA	25(59)	18(43)	7(8)	4(10)	Mixed – EL+DL
Passive - NV	2(5)	23(55)	32(87)	32(78)	Active - EL
Staff Pantry					**Staff Pantry**
Active - AC	15(36)	-	6(14)	22(54)	Passive – DL
Mixed - FA	19(45)	23(55)	18(44)	12(29)	Mixed – EL+DL
Passive - NV	8(19)	19(45)	17(42)	7(17)	Active - EL
Photocopy Room					**Photocopy Room**
Active - AC	37(88)	9(22)	1(3)	8(20)	Passive – DL
Mixed - FA	5(12)	23(55)	11(27)	6(15)	Mixed – EL+DL
Passive - NV	-	10(24)	29(70)	27(65)	Active - EL
Health Club/Gym					**Health Club/Gym**
Active - AC	21(50)	4(10)	11(27)	21(51)	Passive – DL
Mixed - FA	10(24)	16(38)	23(56)	17(41)	Mixed – EL+DL
Passive - NV	11(26)	22(52)	7(17)	3(8)	Active - EL
Library					Library
Active - AC	42(100)	34(83)	2(5)	2(5)	Passive – DL
Mixed - FA	-	5(12)	23(56)	23(56)	Mixed – EL+DL
Passive - NV	-	3(5)	16(39)	16(39)	Active - EL
Day Care Centre					**Day Care Centre**
Active - AC	30(71)	11(26)	9(22)	15(37)	Passive – DL
Mixed - FA	10(24)	25(60)	29(70)	21(51)	Mixed – EL+DL
Passive – NV	2(5)	6(14)	3(8)	5(12)	Active – EL
OVERALL					**OVERALL**
Active – AC	**429 (68)**	**214 (34)**	**98 (16)**	**202 (33)**	**Passive – DL**
Mixed – FA	**110 (17)**	**202 (32)**	**296(48)**	**209 (34)**	**Mixed – EL+DL**
Passive – NV	**91 (15)**	**214 (34)**	**221(36)**	**204 (33)**	**Active – EL**

** Number in parenthesis is percentage against total sample size*

*** AC- Air-conditioning; FA – Fan-assisted; NV – Natural Ventilation DL – Daylight; EL+DL – Electrical and daylight; EL – Electrical light*

Table B7.1. Summary of sorts according to space and modes

Appendix B8. Survey 2 Analysis – MDS Plots

B8.1. Thermal Comfort

B8.1.1. Revenue House

Activity:
A 3-way partition supports the Work, Support and Transit zones. A secondary grouping within the Support group supports the criterion of Health/Hygiene.

Consistency/Control:
The criterion of Consistency/Control emerges on the X-Z elevation. Spaces deemed to require less control at one end and those requiring more control at the other. This could also be related to the question of having a link with outdoors and/or higher tolerance for variability.

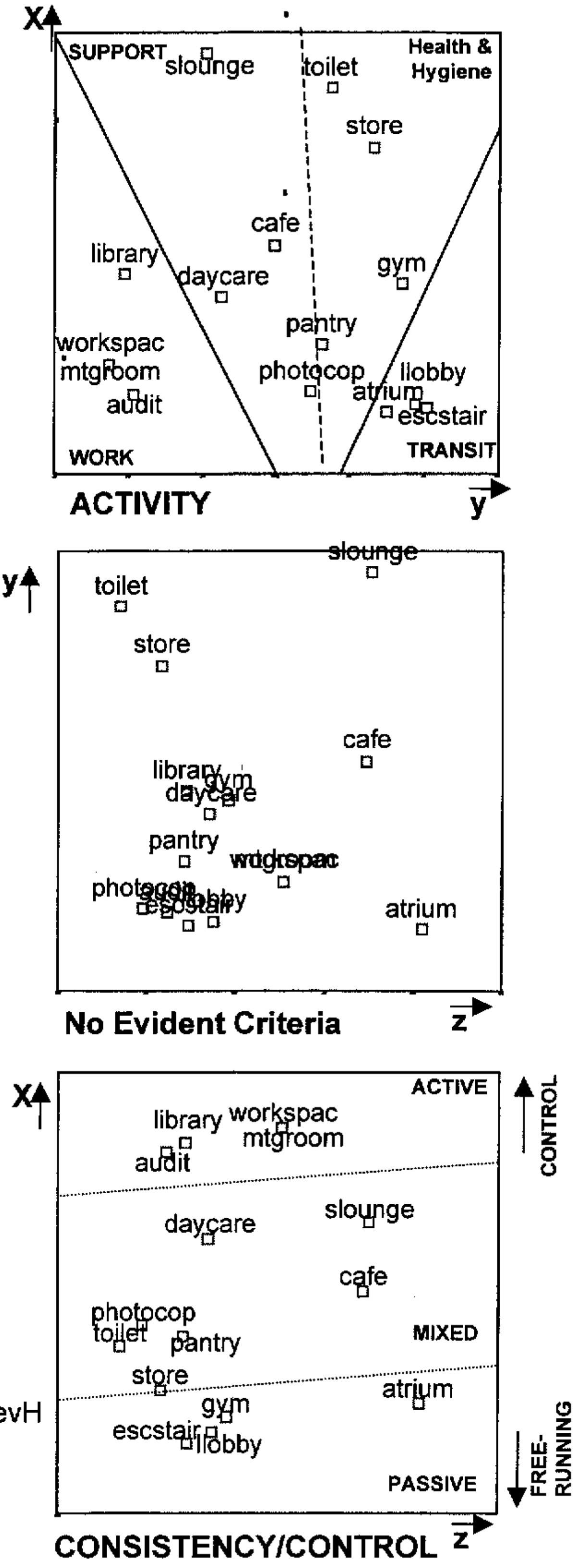


Figure B8.1. MDS Thermal Plots for RevH

B8.1.2. Menara Mesiniaga

Activity:
A 3-way partition supports the Work, Support and Transit zones, including a secondary partition relating to Health/Hygiene.

Toilet in MES emerges in the Transit zone, along with Lift Lobby and Fire-Escape Stairs. This differs from RevH, where it was found to be in the Support zone.

The difference might be explained by the layout of the two buildings. In a typical RevH floor, toilets are accessed from within the Office areas, situated next to spaces such as the Staff Pantry and Storeroom.
In MES, the toilet is in the service core, next to fire escapes and the lift lobby (see Appendix A4)

Privacy:
The Y-Z elevation relates with the criterion of Privacy. This is argued on grounds that the Atrium and Lift Lobby, the most public of spaces, are at the opposite end of the plot from certain staff-only facilities, such as the Pantry, Store and Day Care Centre.
A line can be inserted that reflects the limits of Visitor Access in the building.

Consistency/Control:
The 3-way partition for Active, Mixed and Passive modes fits the plot.

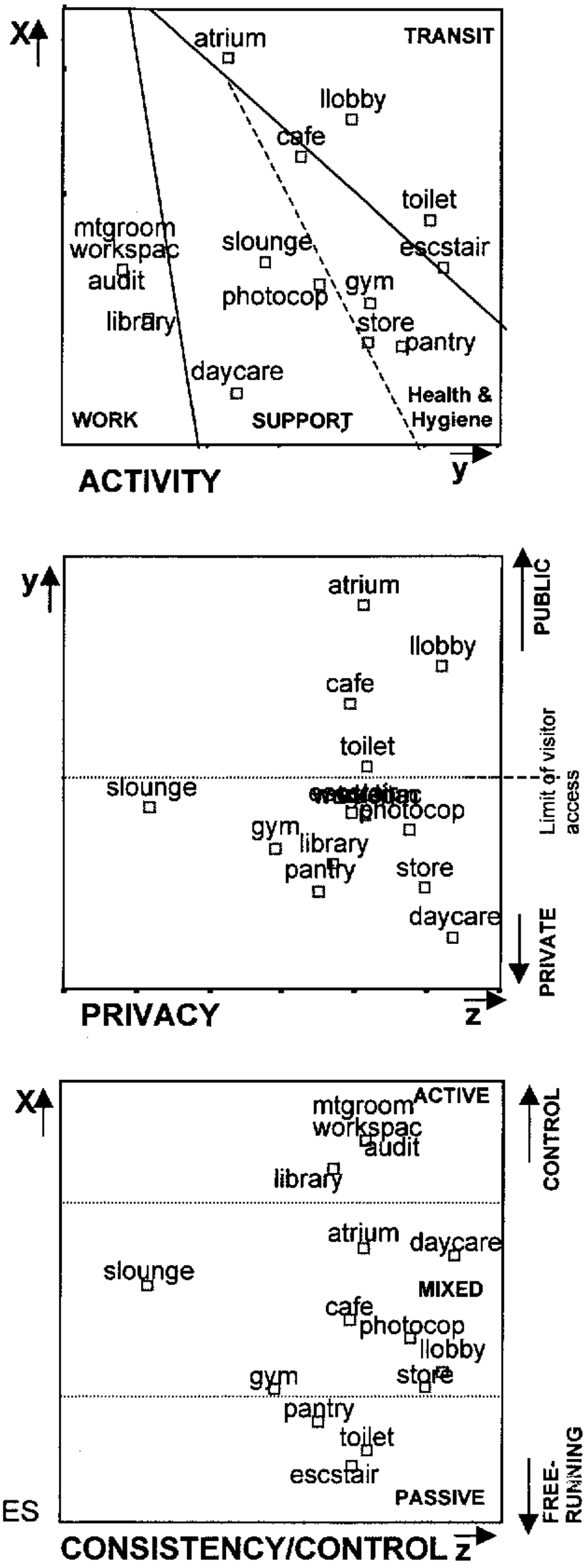


Figure B8.2. MDS Thermal Plots for MES

B8.1.3. Civil Service College

Activity:
The 3-way partition supports Work, Support and Transit zones, including the secondary partition relating to Health/Hygiene.

Unlike the two preceding buildings, the Lift Lobby is no longer in the Transit Zone here. It sits within the Support Zone and Health/Hygiene area.
This ambiguity relating to the Lift Lobby might be explained by the fact that it is used regularly for coffee breaks and meals, as a 'coffee-break' area.

Privacy:
This criterion seems to be supported here.

Consistency/Control:
The 3-way partition for Active, Mixed and Passive modes seems to fit the plot.

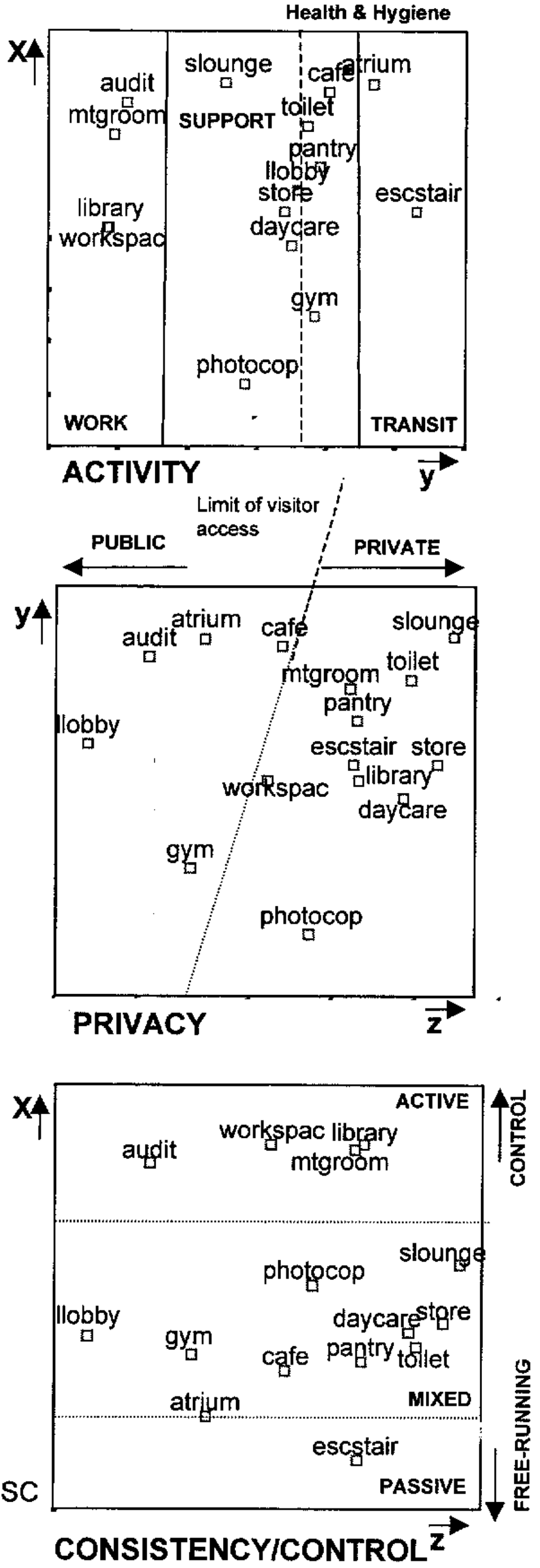


Figure B8.3. MDS Thermal Plots for CSC

B8.1.4. Ministry of National Development

Activity:
The 3 zones of Work, Support and Transit are here, along with the secondary split for Health/Hygiene.

Privacy:
The pattern of Privacy emerges – as before - with the more public Atrium and Lift Lobby found at one end of the plot and the private Pantry, Day Care Centre at the other.

Consistency/Control:
The criterion of Consistency/Control emerges here, similar to earlier plots.

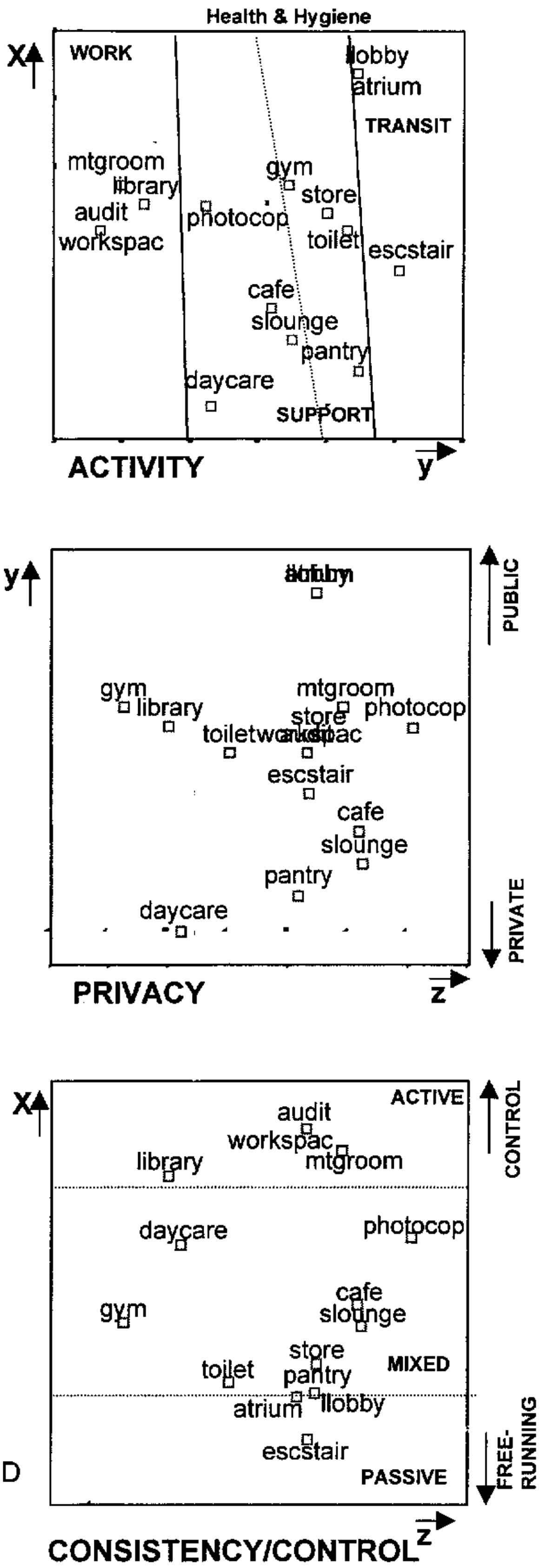


Figure B8.4. MDS Thermal Plots for MND

B8.2. Visual Comfort Sorts

B8.2.1. Revenue House

Activity:
The 3-way partition based on Work, Support and Transit Zones emerges here, but is less clear than with the Thermal Comfort plots.

First, the Work zone includes the Pantry.
Second, the Store, which is commonly a Support space, is in the Transit zone.

It is possible that in the case of Visual Comfort, the criterion of Activity is a really a 2-zone division: Work and Secondary spaces.

Consistency/Control:
The criterion of Consistency/Control is evident but it differs from Thermal Comfort plots in the mix of spaces that constitute the zones.

Mixed-mode zone shows mainly work-related spaces. In the Thermal plots, this area consisted mainly of Support spaces.

The Passive and Active areas show a mix of Support and Transit Spaces. In the Thermal plots, the latter was mainly Work-related, the former mainly Transit.

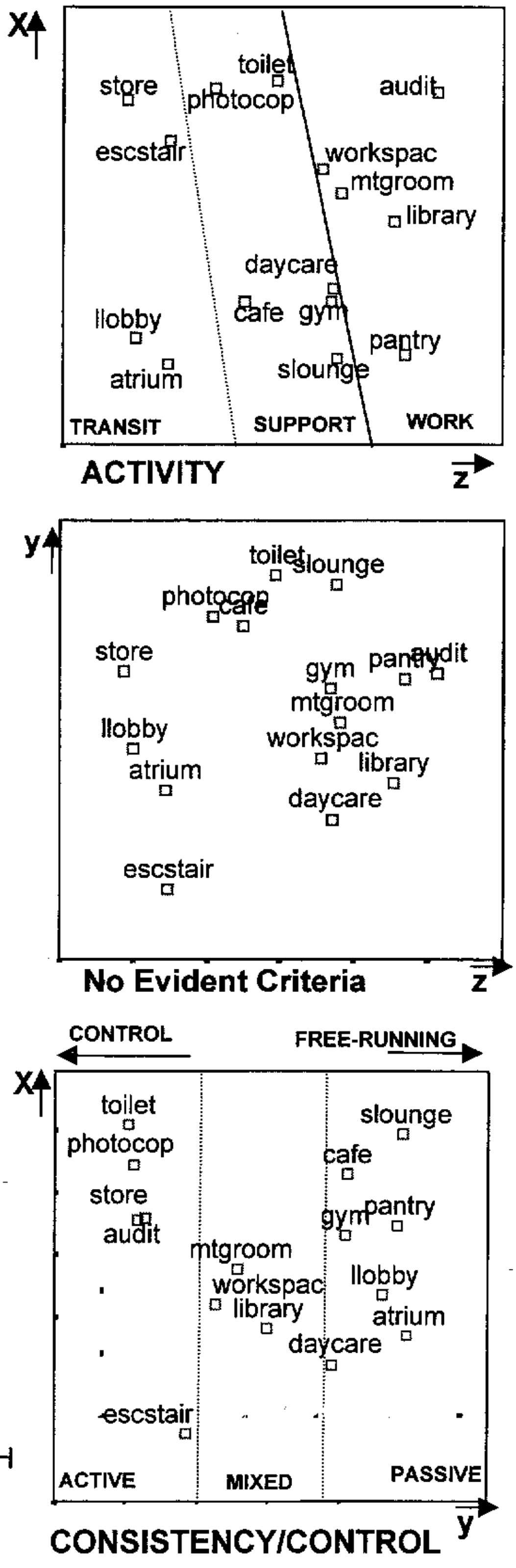
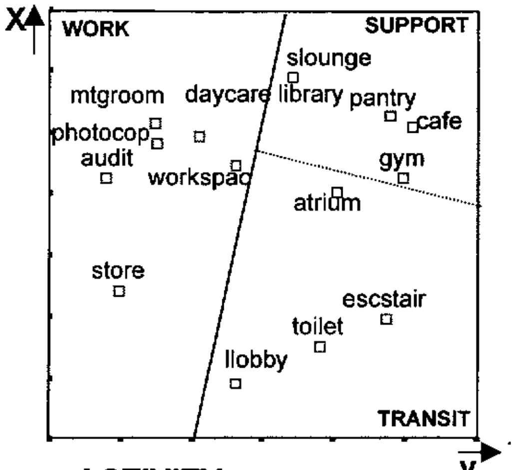


Figure B8.5. MDS Visual Plots for RevH

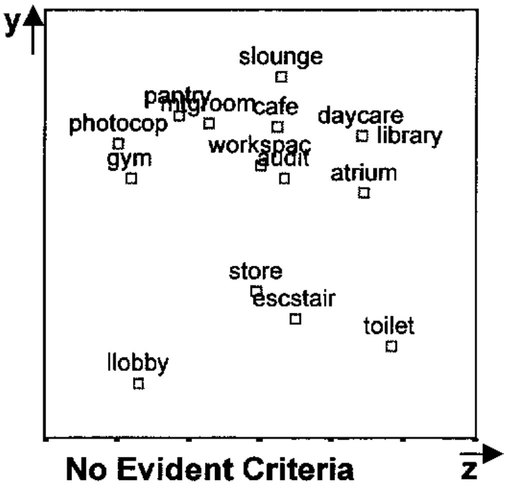
B8.2.2. Menara Mesiniaga

Activity:
The 2-zonal ambiguity found in RevH emerges here.
The Work zone includes Day Care Centre, an anomaly that cannot be explained.

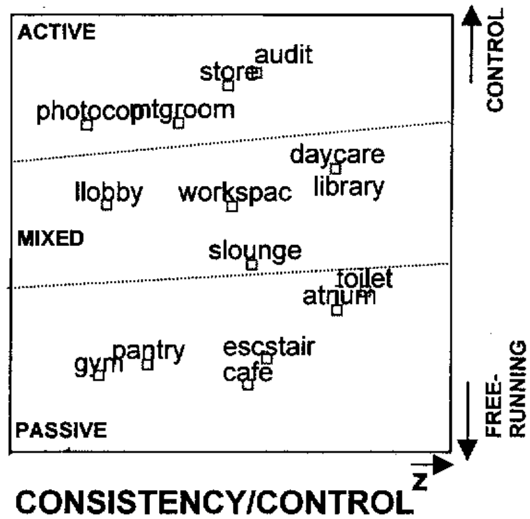
Consistency/Control:
The criterion of Consistency/Control is evident, similar to the RevH plot.



ACTIVITY



No Evident Criteria



CONSISTENCY/CONTROL

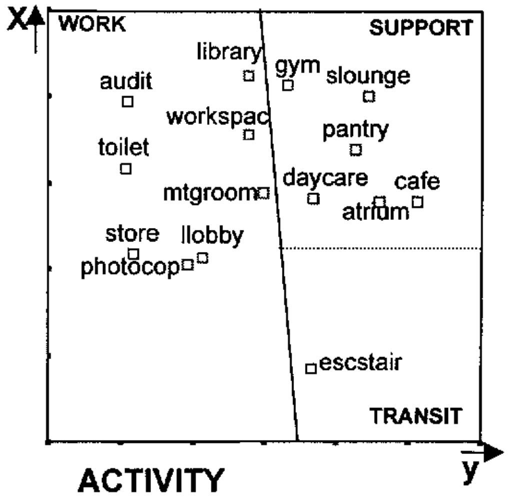
Figure B8.6. MDS Visual Plots for MES

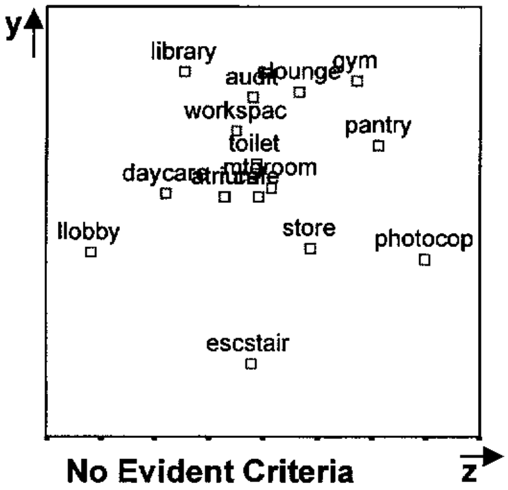
B8.2.3. Civil Service College

Activity:
The blurring of the difference between Support and Transit spaces is evident here, with the Atrium situated in the Support areas. This might be explained by the fact that this space is used for coffee breaks and therefore is designed for a support role.

Inexplicably, the Work zone includes the Lift Lobby.

Consistency/Control:
Consistency/Control is evident and largely similar to preceding plots.





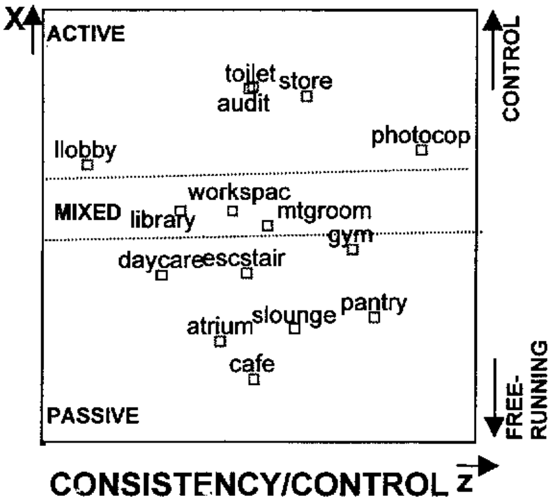
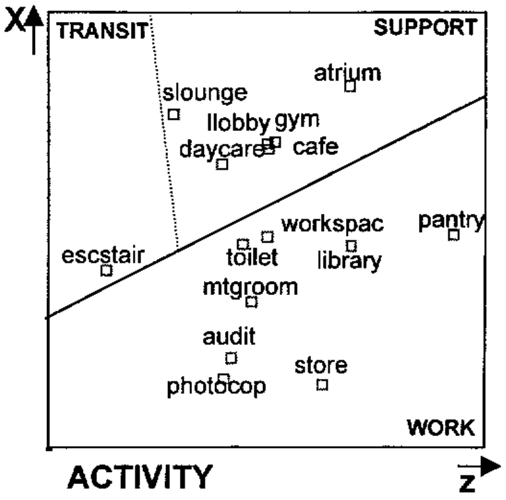


Figure B8.7. MDS Visual Plots for CSC

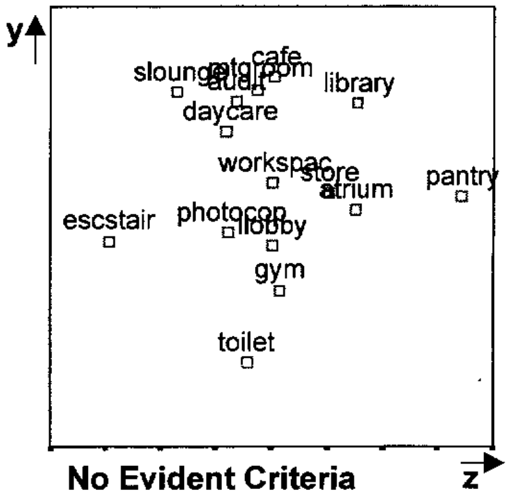
B8.2.4. Ministry of National Development

Activity:
The mixing of Support and Transit spaces is evident here, as with CSC before.

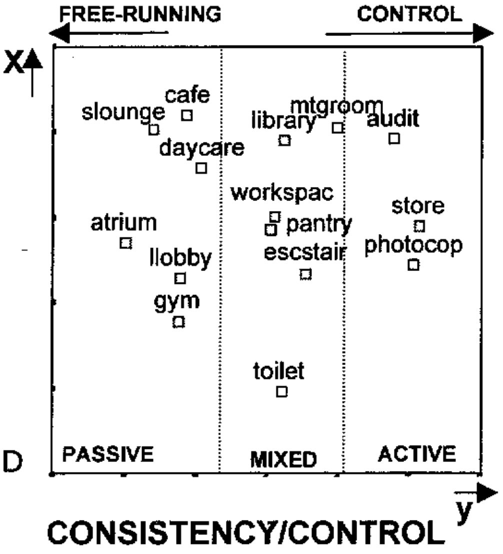
Consistency/Control:
Consistency/Control is evident and similar to preceding plots.



ACTIVITY



No Evident Criteria



CONSISTENCY/CONTROL

Figure B8.8. MDS Visual Plots for MND

Appendix B9. Survey 2 Analysis – MSA Thermal Plot

Coefficient of Contiguity = 0.97

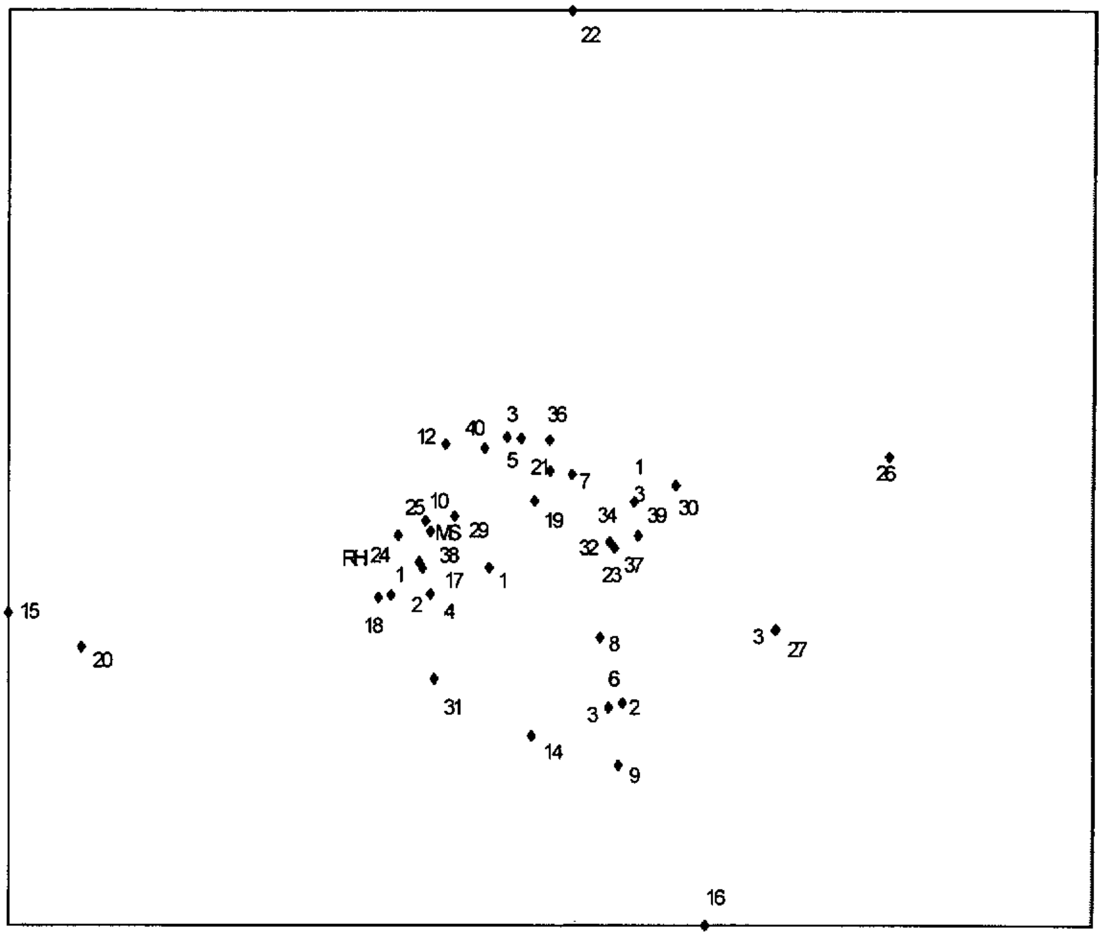
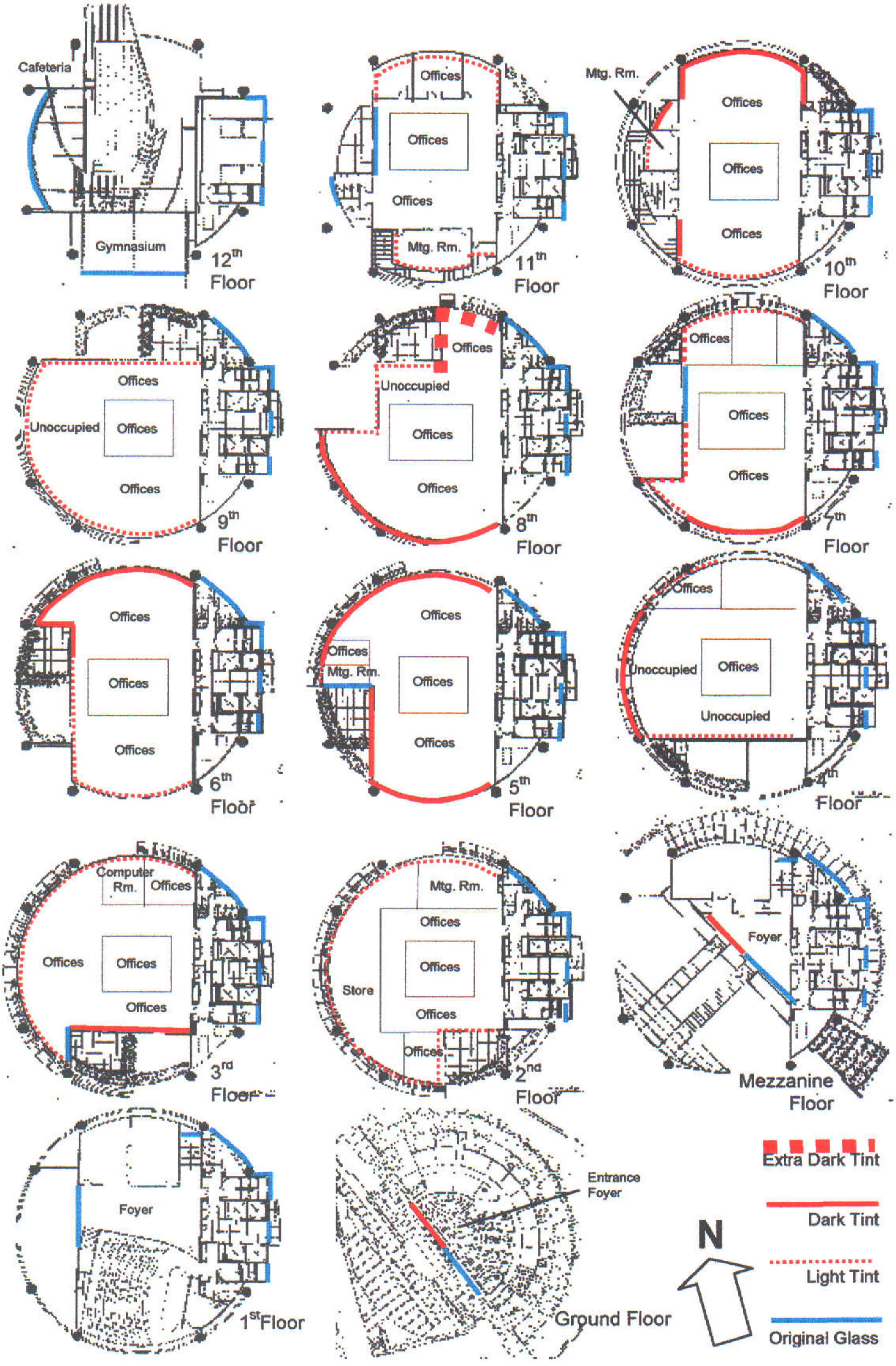


Figure B9.1. MSA plot for thermal sorts

No partitions are possible on the basis of gender, age, race, job or building.

Appendix B10. Summary of MES Solar Tints



APPENDIX C

Appendix C1. Survey 4 Questionnaire

A. Are you staff or visitor? (Atrium and Cafeteria only)

1. Staff **2. Visitor**

B. If visitor, how long have you been in this building? (Atrium and Cafeteria only)

1 just walked in
2. <5 minutes
3. 5-15 minutes
4. 5-30 minutes
5. >30 minutes

C. At this moment, please describe how you feel...

-3	-2	1	0	1	2	3
cold	cool	slightly cool	neutral	slightly warm	warm	hot

D. Is this thermal environment acceptable to you?

1. Unacceptable **2. Acceptable**

E. Please select the option that best represents how you feel at this moment...

I would like to be...

1. Cooler **2. No Change** **3. Warmer**

F. At this moment, how comfortable do you feel in terms of the thermal conditions at your workspace?

1	2	3	4	5	6
very	moderately	slightly	slightly	moderately	very
	UNCOMFORTABLE			COMFORTABLE	

G. In the last half-hour, which activities have you been engaged in?

1. **sitting quietly**
2. **sitting typing**
3. **standing still**
4. **on your feet working**
5. **driving a car**
6. **walking around**

MET Rate
(based on Questions G and H)

H. In the half-hour before that, which of the activities were you engaged in?

1. **sitting quietly**
2. **sitting typing**
3. **standing still**
4. **on your feet working**
5. **driving a car**
6. **walking around**

I. Please indicate if you have consumed any of the following in the last 15 minutes:

1. **Hot drink**
2. **Cold Drink**
3. **Caffeinated drink**
4. **Cigarrete**
5. **Snack or Meal**

J. Record what subject is wearing:

Men		*Women*	
M1	**Short sleeve shirt**	**W1**	**Short sleeve blouse**
M2	**Long sleeve shirt**	**W2**	**Long sleeve blouse**
M3	**Pants**	**W3**	**Pants**
M4	**Tie**	**W4**	**Skirt**
M5	**Outer Jacket**	**W5**	**Outer Jacket**
M6	**Shorts/Bermudas**	**W6**	**Dress**
M7	**Shoes**	**W7**	**Baju Kurung**
M8	**Sandals/Slippers**	**W8**	**Tudung**
		W9	**Shoes**
		W10	**Sandals/Slippers**
		W11	**Stockings/Pantyhose**

CLO Value
(based on Question J.)

BACKGROUND

K. Gender: **1. Male** **2. Female**

L. Age:
1. **under 20**
2. **20-29**
3. **30-39**
4. **40-49**
5. **50 and above**

M. Race:
1. **Chinese**
2. **Malay**
3. **Indian**
4. **Eurasian**
5. **Others**____________________

N. Location (Offices only)
1. **Level 19**
2. **Level 23**
3. **Level 3**

Indoor Conditions

N. Indoor Air Temperature

O. Relative Humidity

P. Air Movement

Date and Time of Survey:

Appendix C2. Clo and Met Calculations for Survey 4

Clothing Insulation
Clo was based on the following list of clothing items and their ascribed insulation values (ASHRAE, 1993; Auliciems and Szokolay, 1997):

Male Clothing Items Clo
1. Short sleeve shirt - 0.19 (0.2, if with tie)
2. Long sleeve shirt - 0.25 (0.26, if with tie)
3. Trousers - 0.26
4. Outer jacket - 0.22
5. Shorts or Bermudas - 0.08
6. Shoes - 0.04 (0.08, if with socks)
7. Sandals/slippers - 0.02

Female Clothing Items Clo
1. Short sleeve blouse - 0.15
2. Long sleeve blouse - 0.20
3. Pants - 0.26
4. Skirt - 0.14
5. Outer jacket - 0.17
6. Dress - 0.33
7. Shoes - 0.04
8. Sandals/slippers - 0.02
9. Stockings/pantyhose - 0.02

Each individual's clothing ensemble, observed during the survey, was added together for its Clo value. A figure of 0.05 was added to the total, so as to allow for underwear.

Metabolic Rate
Each subject was asked which activity or activities, from a list of 6 (ASHRAE, 1993; Auliciems and Szokolay, 1997), s/he had engaged in over the preceding hour. The overall Met rate for the individual was computed by adding up the predominant activities (often the one or two main activities) and averaging the total by the said number of activities. This figure was then multiplied by a factor of 58.2 to convert the unit of Met into W/m^2.

Activity Met
1. Sitting quietly - 1.0
2. Sitting typing - 1.1
3. Standing still - 1.2
4. On your feet working - 1.4
5. Driving a car - 1.5
6. Walking around - 2.6

Appendix C3. Survey 4 Data - Breakdown of Repeat Subjects

	Total *(N=59)*
Gender	
Male - 1	5 (8.5)
Female - 2	50 (84.7)
	4 missing values (6.8)
Age	
under 20 - 1	0 (0)
20-29 - 2	24 (40.6)
30-39 - 3	15 (25.4)
40-49 - 4	12 (20.4)
50 & above - 5	4 (6.8)
	4 missing values (6.8)
Race	
Chinese - 1	49 (83)
Malay - 2	2 (3.4)
Indian - 3	4 (6.8)
Eurasian - 4	0 (0)
Others - 5	0 (0)
	4 missing values (6.8)

Table C3.1. Breakdown of repeat-subjects from offices

Appendix C4. Survey 4 Data – Indoor/Outdoor Conditions and Occupant Feedback

This appendix summarises IAT and occupant response in each space across the three weeks. There are two figures shown for each space. The first shows IAT and outdoor DBT. Also shown here are the space set points, labeled as BAS[1] setting. The second shows response to the four thermal scales, defined here as the percentage of people who expressed dissatisfaction (i.e. felt too warm, uncomfortable, preferred change or voted unacceptable).

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[1] BAS refers to the Building Automation System, which regulates indoor conditions.

C4.1. Offices

The temperature setting at L19 was altered daily in weeks 2 and 3. No adjustments were made to the settings on L3 and L23. The building's manager imposed an upper limit of discomfort on the exercise[2]. As a result, temperatures above 24°C could not be sustained for long.

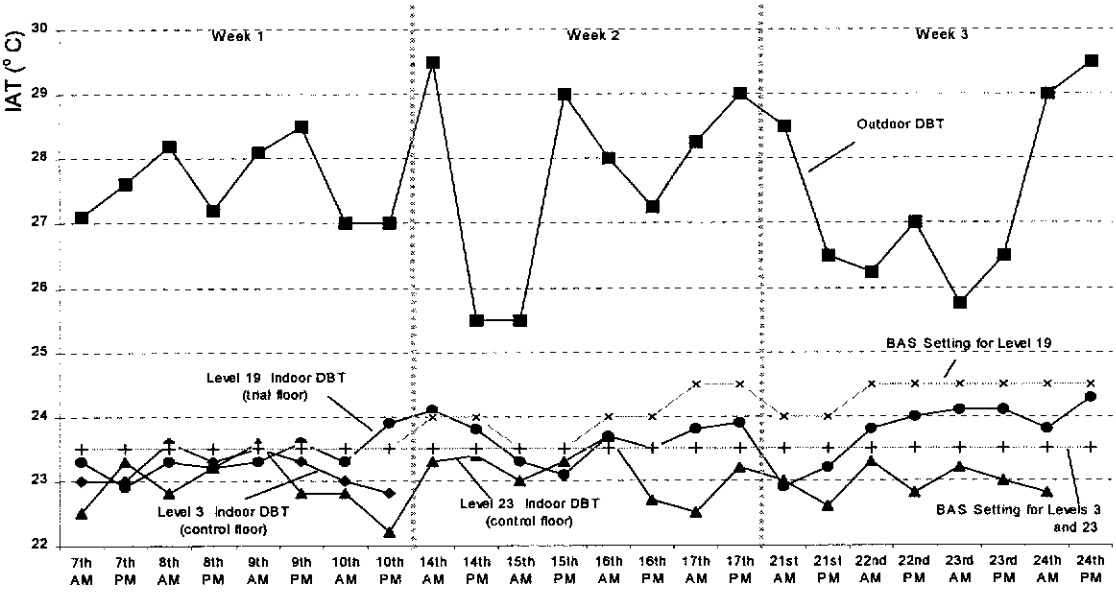

Figure C4.1. Offices IATs

L23 appears to be less predictable and more variable in terms of IAT. There is congruence between temperatures on L19 and its BAS setting.

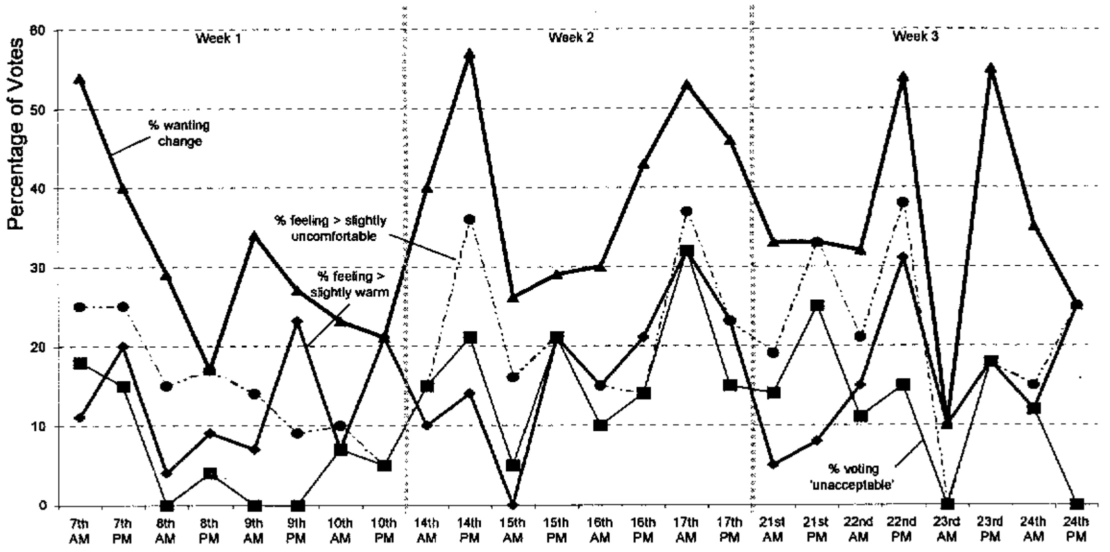

Figure C4.2. Offices occupant response

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[2] A constraint stipulated by the facility manager was that discomfort should not be sustained for 'too long'. This was to mean that conditions, for which more than 10% of those surveyed each day vote 'unacceptable', should not be sustained for more than two consecutive days.

Of the four scales, McIntyre fluctuates the most and Acceptability the least. There is broad congruence in movement across the four scales over the three weeks suggesting they are measuring similar response, albeit with varying sensitivity.

Response on the 1^{st} day shows a high level of dissatisfaction on the McIntyre scale. This does not relate with response on the other scales or with indoor/outdoor conditions. It is speculated that this is due to the Hawthorne Effect, whereby subjects in an experiment respond to the presence of the researcher rather than the condition being tested. On this day respondents may have been expressing an inflated level of dissatisfaction through low preference ratings.

C4.2. Cafeteria

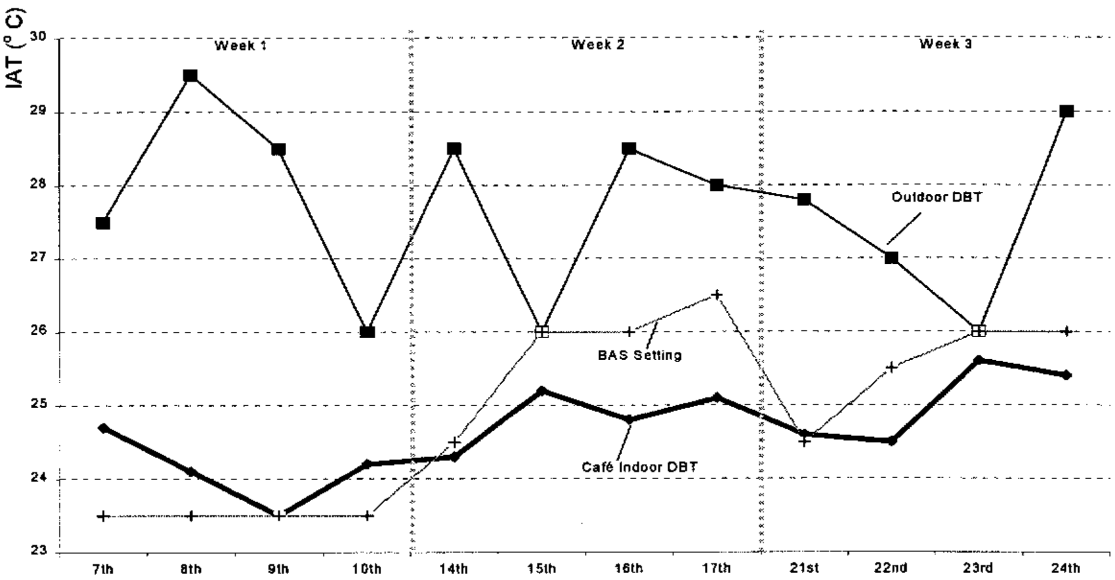

Figure C4.3. Cafeteria IATs

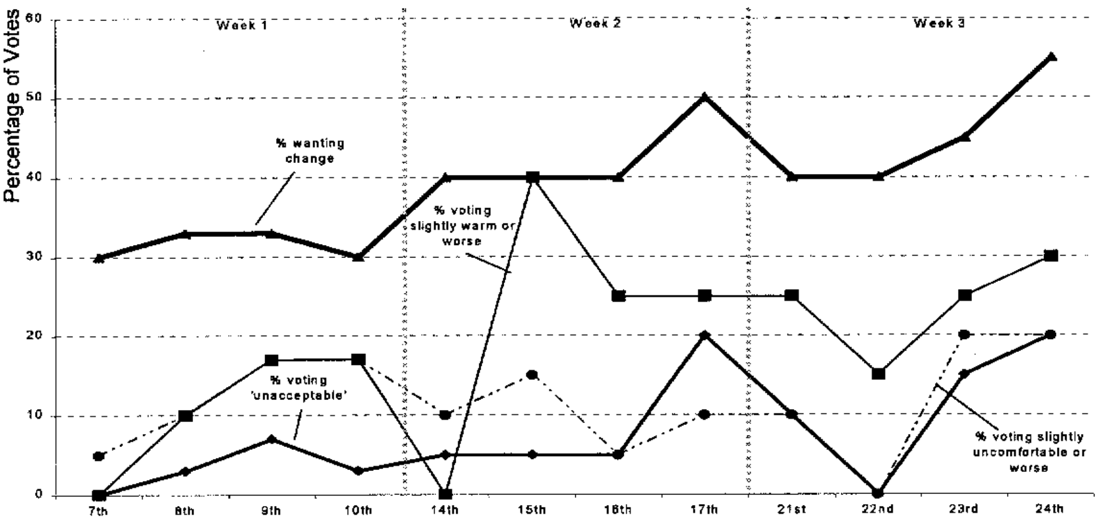

Figure C4.4. Cafeteria occupant response

C4.3. Atrium

The relationship of indoor and outdoor temperatures is most evident in the Atrium.

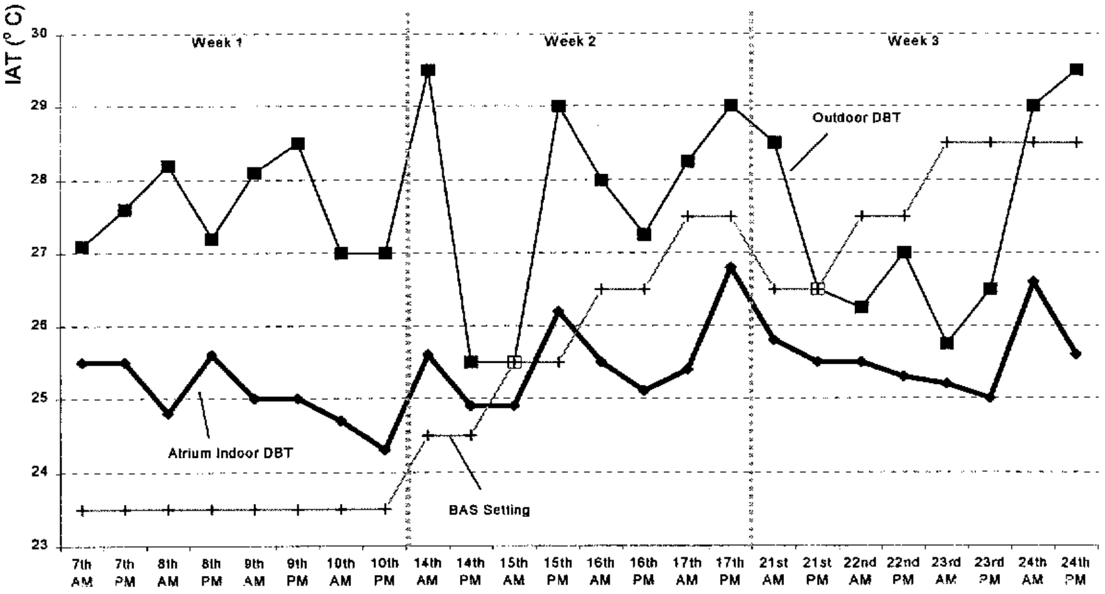

Figure C4.5. Atrium IATs

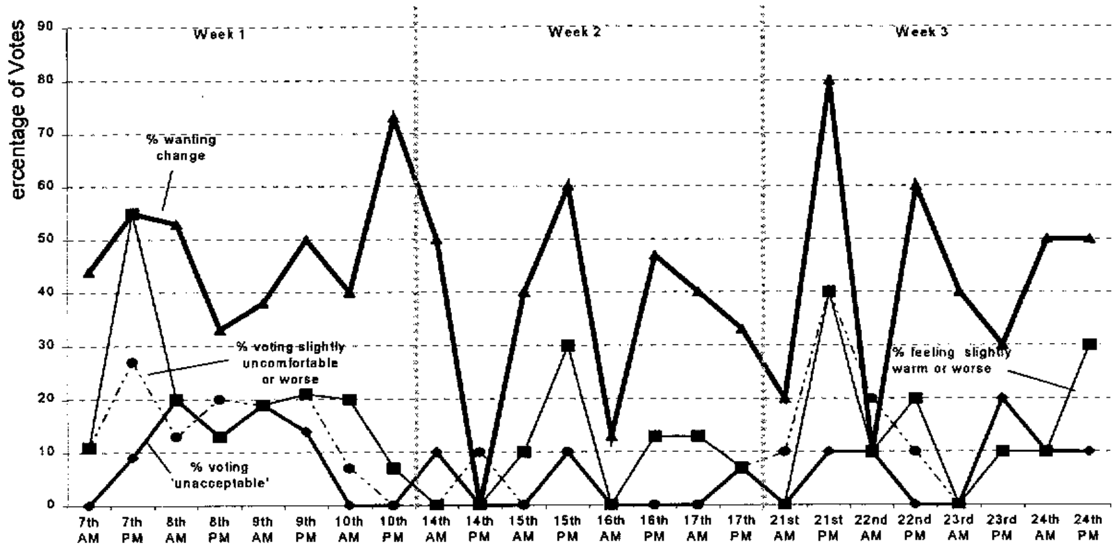

Figure C4.6. Atrium occupant response

Appendix C5. Summary of Statistical Tests for Data from Survey 4

	Offices n=59	Cafeteria n=270	Atrium/ Entrance Foyer n= 290
Gender	No significance		
Thermal Sensation 1		No significance	No significance
Thermal Comfort 2		No significance	**Mann-Whitney U test, z=-2.1, p=0.04**
Preference 3		No significance	No significance
Acceptability 4		No significance	No significance
Age			
Thermal Sensation 1		No significance	No significance
Thermal Comfort 2		No significance	**χ^2 (4, N=290) =11.189, p=0.025**
Preference 3		No significance	No significance
Acceptability 4		No significance	No significance
Staff or Visitor			
Thermal Sensation 1		No significance	No significance
Thermal Comfort 2		No significance	**Mann-Whitney U value=2798, z=-2.2, p=0.03**
Preference 3		**χ^2 (2, N= 270) =6.794, p=0.03**	**χ^2 (2, N=290) =14.83, p=0.001**
Acceptability 4		No significance	No significance
Race			
Thermal Sensation 1		No significance	**χ^2 (2, N=290)=10.54, p=0.005**
Thermal Comfort 2		No significance	No significance
Preference 3		No significance	No significance
Acceptability 4		No significance	No significance
Time of Survey (AM/ PM)			
Thermal Sensation 1		Not Applicable*	No significance
Thermal Comfort 2			**Mann-Whitney U test, z=-2.86, p=0.004**
Preference 3			No significance
Acceptability 4			No significance
Consumption			
Thermal Sensation 1		No significance	No significance
Thermal Comfort 2		No significance	No significance
Preference 3		No significance	No significance
Acceptability 4		No significance	No significance
Time since last exposure to conditions outside the building			
Thermal Sensation 1		No significance	No significance
Thermal Comfort 2		No significance	No significance
Preference 3		No significance	No significance
Acceptability 4		No significance	No significance

No significance refers to results with $p>0.05$

** Occupants in the Cafeteria are surveyed during lunch hour from Noon to 2PM. No distinction of AM/PM is possible.*

Table C5.1. Summary of Tests on Background and Building Variables for Cafeteria and Atrium

Appendix C6. Regressions for Data from Survey 4

C6.1. SET* plots

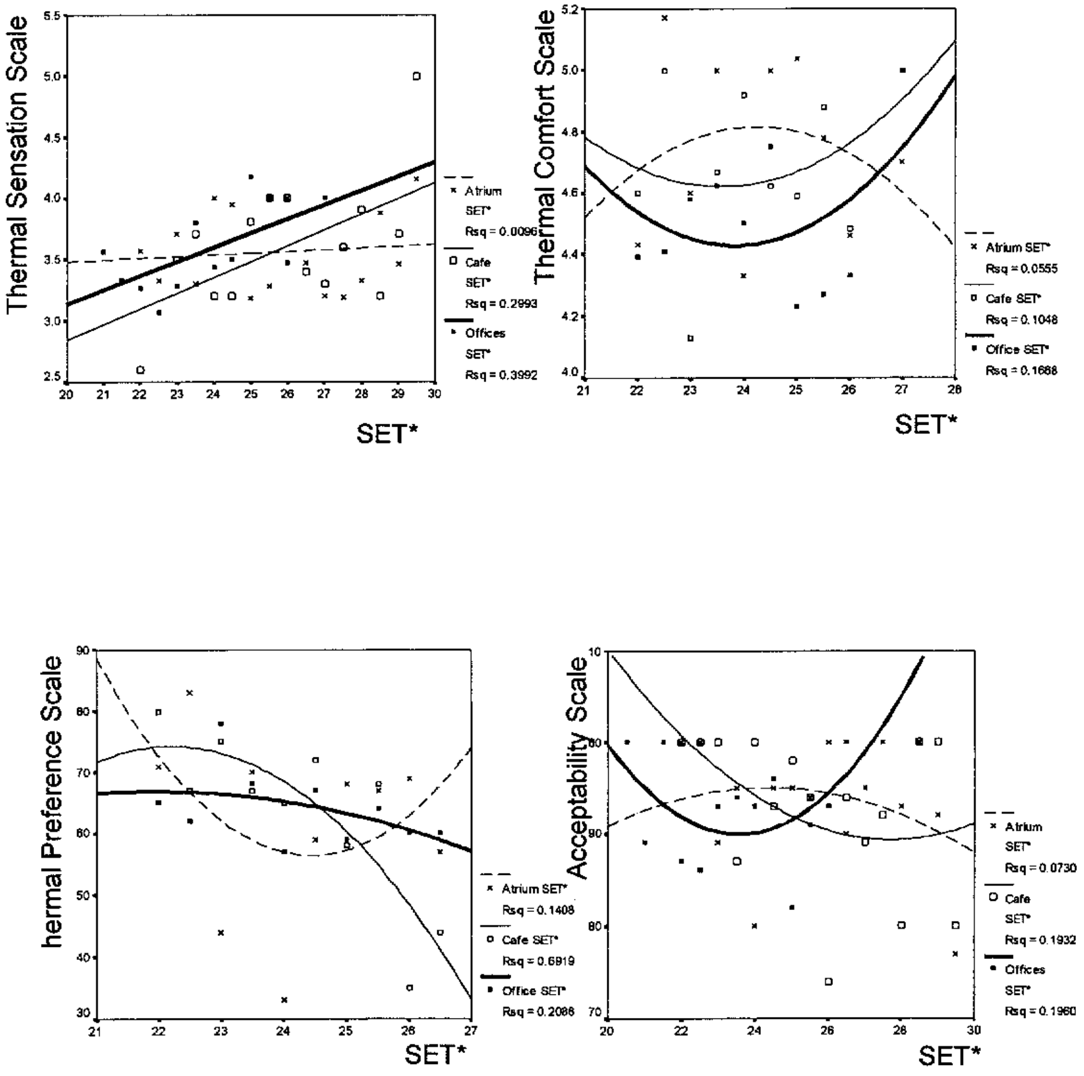

Figure C6.1. SET* plots

C6.2. Acceptability Plots

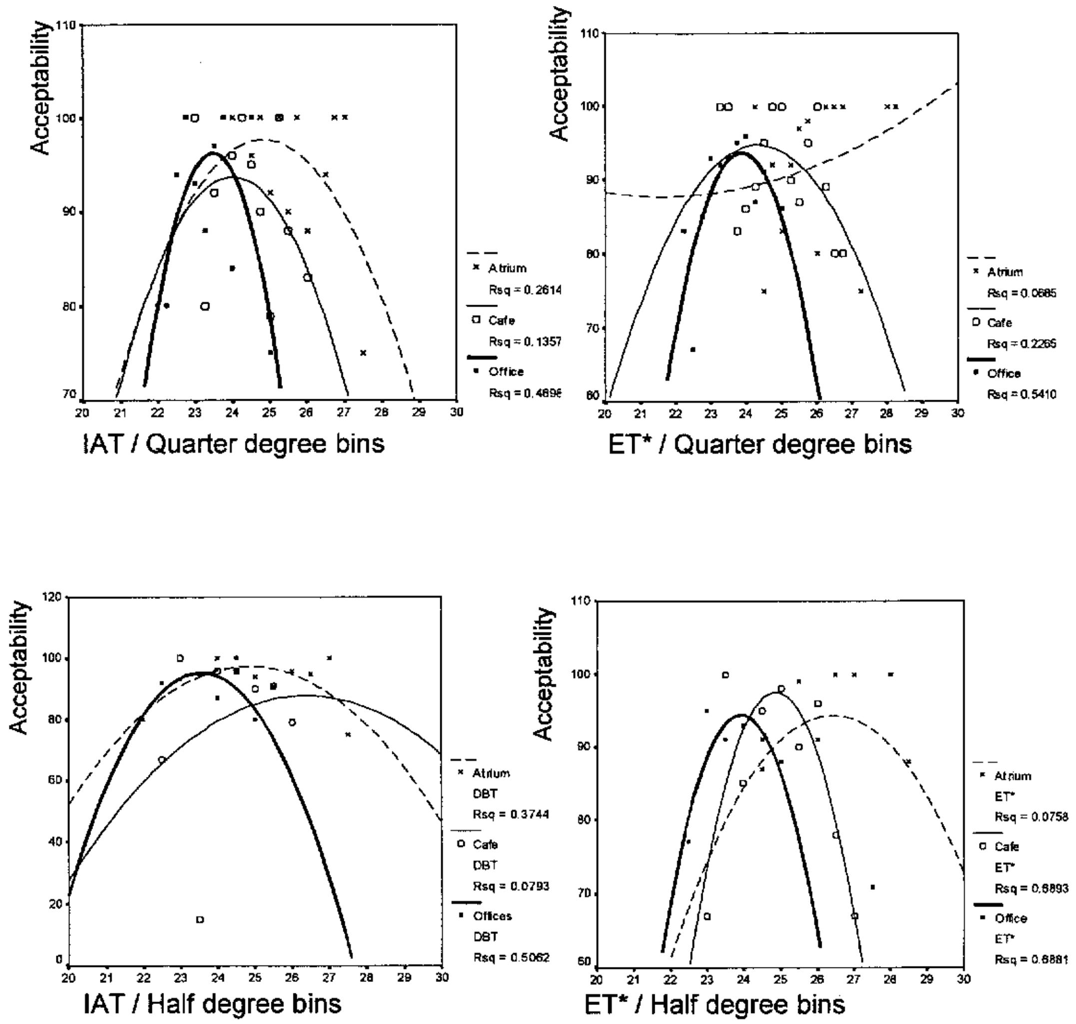

Figure C6.2. Acceptability plots

C6.3. Thermal Comfort Plots at Quarter Degree Bins

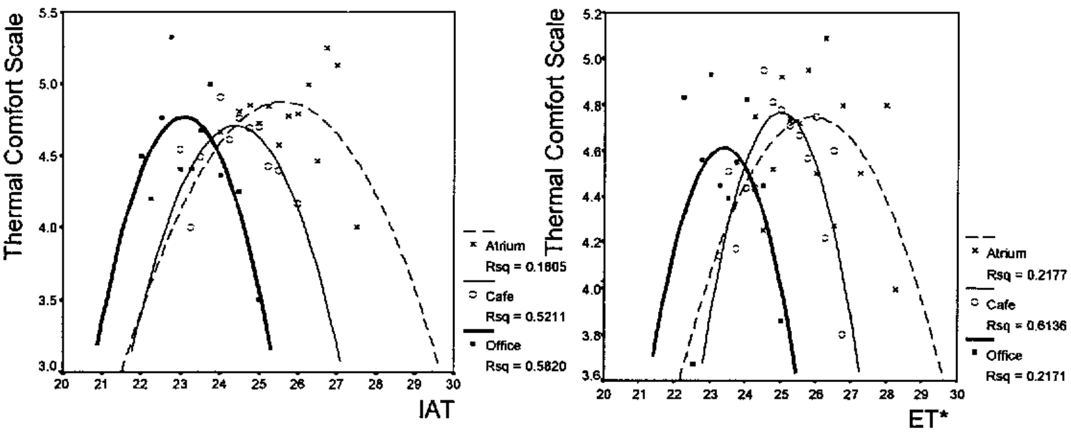

Figure C6.3. Thermal comfort plots

C6.4. Thermal Preference Plots at Quarter Degree Bins

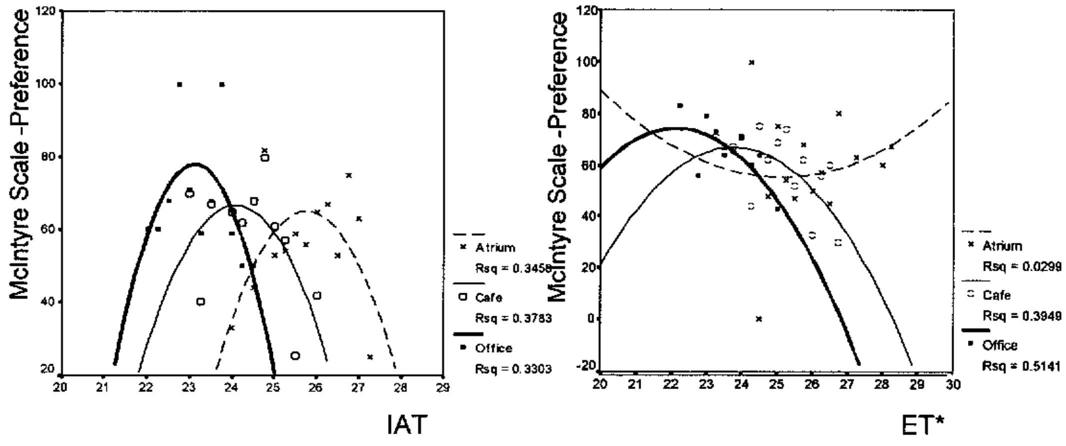

Figure C6.4. Thermal Preference plots at quarter degree bins

C6.5. Thermal Preference Plots at Half Degree Bins

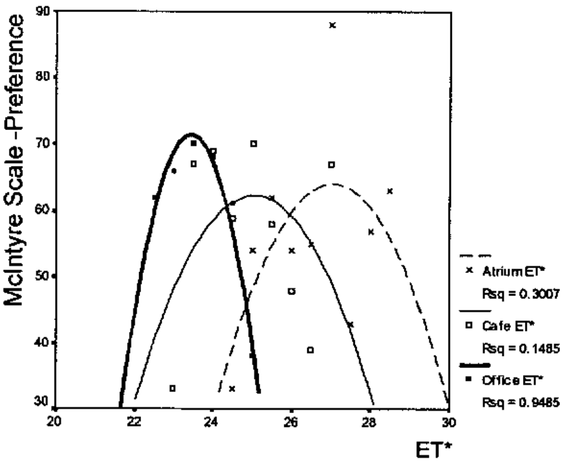

Figure C6.5. Thermal Preference plots at half-degree bins

C6.6. In/Temperature Plots

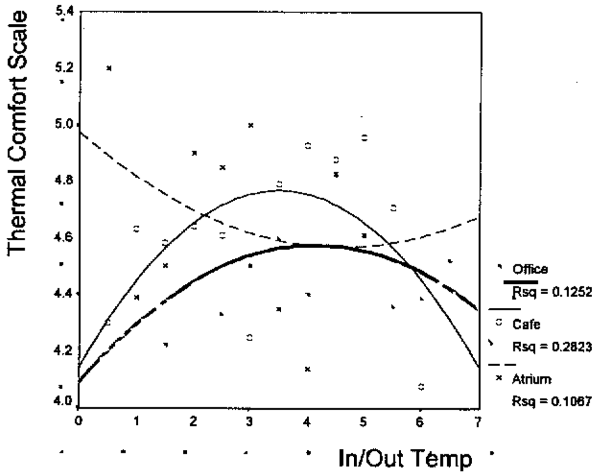

Figure C6.6. In/Out Temperature plots

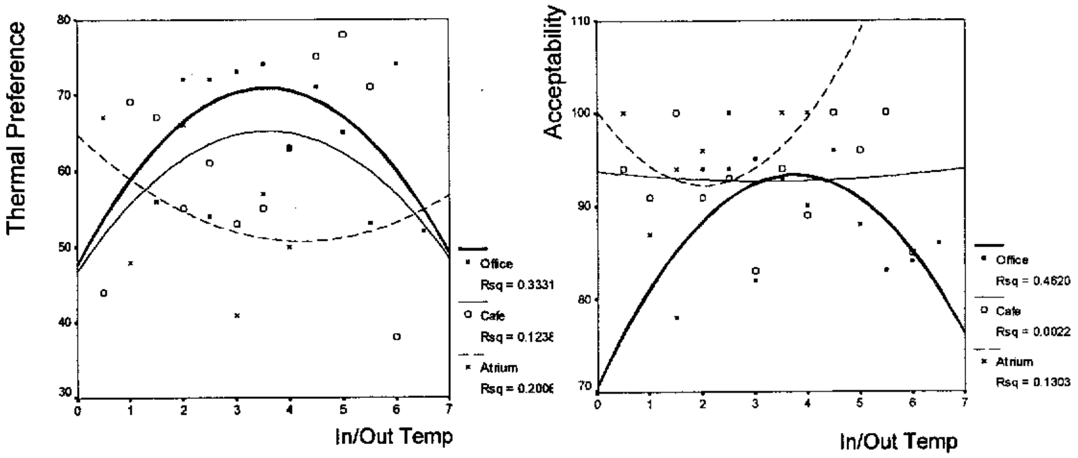

Figure C6.6. In/Out Temperature plots
(continued from preceding page)

Appendix C7. RevH Energy Figures for Years 1999 and 2000

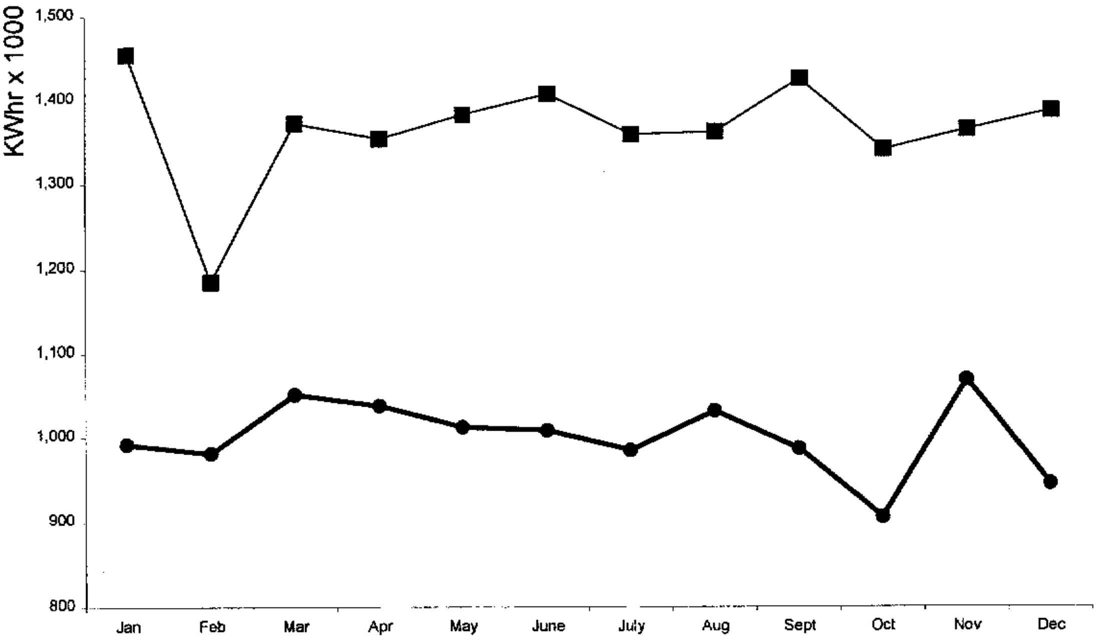

Figure C7.1. RevH energy figure for years 1999 and 2000