DENIS BOURGEOIS

DETAILED OCCUPANCY PREDICTION, OCCUPANCY-SENSING CONTROL AND ADVANCED BEHAVIOURAL MODELLING WITHIN WHOLE-BUILDING ENERGY SIMULATION

Thèse présentée
à la Faculté des études supérieures de l'Université Laval
dans le cadre du programme de doctorat sur mesure en architecture
pour l’obtention du grade de Philosophiæ Doctor (Ph.D.)

FACULTÉ DES ÉTUDES SUPÉRIEURES
UNIVERSITÉ LAVAL
QUÉBEC

JUIN, 2005

Résumé

Cette étude a pour but de combler l'écart entre l'état actuel de la simulation énergétique dans le domaine du bâtiment (i.e. hypothèses et modèles) et la connaissance empirique sur le comportement des usagers en matière de contrôle environnemental. L'application principale issue de cette thèse est un module de simulation autonome qui vise la modélisation à haute résolution et à haute fréquence des interactions personne-milieu: de l'occupation des locaux (i.e. l'affectation individuelle d'un environnement modélisé), du contrôle basé uniquement sur la présence ou l'absence des occupants (e.g. détecteurs de mouvement), jusqu'aux modèles comportementaux plus avancés (e.g. commutation manuelle des appareils d'éclairage, l'utilisation des fenêtres ouvrantes). L'intégration du module au sein du logiciel libre[1] ESP-r, un programme qui permet de simuler l'ensemble des interactions bâtiment-systèmes-environnement, permet d'étudier à quel point les modèles d'interactions personne-milieu, issus des études en milieu réel, peuvent influencer les besoins énergétiques d'un bâtiment donné. Certains traits comportementaux, couramment associés aux modèles de contrôle manuel des systèmes d'éclairage, caractérisent également le comportement individuel au niveau des fenêtres ouvrantes; une conclusion issue d'une étude pilote en milieu réel sur le campus de l'Université Laval (Québec). Cette constatation suggère certains traits communs pouvant décrire le comportement des usagers en matière de contrôle environnemental. Le module développé permet également d'étudier le potentiel écoénergétique de stratégies innovatrices: l'application de stratégies de contrôle reposant sur l'adaptation thermique dans un contexte de climatisation hybride, et basées sur l'opération de fenêtres ouvrantes en tant que commutateurs entre climat naturel et climat artificiel. Les résultats préliminaires suggèrent que pour les climats nordiques ou méridionaux, ces approches permettent effectivement de réduire les besoins en climatisation, mais qu'en contre partie les besoins en chauffage augmentent considérablement en raison de l'utilisation des fenêtres en périodes plus tempérées. L'intérêt de la méthode est ici mis en évidence dans sa capacité à simuler globalement l'ensemble des conséquences énergétiques de l'interaction sociale avec l'environnement bâti.

---

[1] http://www.gnu.org/

Abstract

This study sets out to bridge the gap between building energy simulation and empirical evidence on occupant behaviour. The major output is a self-contained simulation module that aims to control all occupant-related phenomena which can affect energy use in buildings. It provides high resolution and high frequency occupancy prediction (i.e. when occupants as individual agents occupy a modelled environment), occupant-sensing control (i.e. as driven by the mere presence of one or more occupants, such as occupancy-sensing lighting controls), as well as advanced behavioural models (i.e. active personal control, such as manual switching of lights, manual adjustments to window blinds, operable windows, personalized air-conditioning units). The module is integrated within the ESP-r free software[2], a whole-building energy simulation program. Simulation results clearly show that occupants-based phenomena exert a strong influence on simulated energy use, revealing a number of limitations in key assumptions in current energy simulation practice. Key behavioural traits, commonly associated to lighting behavioural patterns, also appear to be associated to personal control of operable windows, as demonstrated in a pilot field study in a Université Laval pavilion in Québec. This may suggest an abstract quality to certain behavioural concepts regarding different environmental controls. The study then focuses on the use of the developed work to investigate the energy saving potential of novel yet untried strategies: adaptive comfort control algorithms in hybrid environments, based on the use of operable windows as switching mechanisms between natural and artificial modes of environmental control. Results suggest that for both heating- and cooling-dominant climates, adaptive comfort control effectively reduces cooling requirements, yet operable window use during cooler conditions appear to increase heating requirements. The usefulness of the original method is here illustrated by providing a more complete view on energy use attributed to occupant behaviour.

---

[2] http://www.gnu.org/

Avant-Propos

This thesis is the culmination of research carried out initially as a Master's student, then as a doctoral candidate following an accelerated passage to the PhD, at l'École d'architecture, Faculté de l'aménagement, de l'architecture et des arts visuels (FAAAV), Université Laval.

As a graduate student, I have been fortunate enough to receive scholarships from the following organizations: le Fonds de recherche sur la nature et les technologies - ministère des Ressources naturelles du Québec, secteur énergie (FRNT); la Fondation de l'Université Laval - Patenaude-JBK, Inc.; and la Fondation Desjardins. I have also received financial support from the CANMET Energy Technology Centre (CETC) University Research Network.

I wish to acknowledge the support of my two supervisors, Associate Professor André Potvin (École d'architecture, FAAAV, Université Laval) and Professor Fariborz Haghighat (Department of Building, Civil and Environmental Engineering, Concordia University). I thank them both for the encouragement and engaging discussions over the course of my graduate studies. I also wish to thank Professor Pierre Côté (École d'architecture, FAAAV, Université Laval) and Dr. Christoph Reinhart of the Institute for Research in Construction (IRC) of the National Research Council of Canada (NRC) for acting as thesis committee members. I am particularly indebted to Dr. Reinhart for his generous involvement over the years. I also wish to thank Professor Ted Kesik of the University of Toronto for acting as my external examiner. Finally, I wish to thank Sophie Baillargeon from the Service de consultation en statistiques et en mathématiques de l'Université Laval for her critical review of the statistical analysis, as well as David Lindelöf of the Laboratoire d'énergie solaire et de physique du bâtiment (LESO-PB) de l'École polytechnique fédérale de Lausanne (EPFL) for helping me in sorting out some of the mathematics of stochastic modelling.

It would have been challenging to complete this thesis without the support of people from CANMET's Energy Technology Centre (CETC): this includes Dr. Ian Beausoleil-Morrison, Jeff Blake and François Dubrous for their vision and leadership, Dr. Kamel Haddad and Julia Purdy for their support, and especially Phylroy Lopez and Alex Ferguson for helping out with the tough parts. I wish to express my gratitude to Professor Joe Clarke of the

University of Strathclyde for providing me with the opportunity to pursue my work alongside fellow researchers at the Energy Systems Research Unit (ESRU), as well as Dr. Iain Macdonald (ESRU) for his precious feedback and hands-on involvement.

I wish to express my gratitude to a number of experts outside Academia, including Mario Gonçalves of Patenaude-JBK Inc., Robert Jutras of the Laboratoire AIR-INS Inc., and Michel Parent of Technosim Inc., for their intellectual contributions over the years.

I wish to thank my fellow colleagues at the PhD, Louis St-Pierre and Hassoun Karam, as well as Maurice Basque and my two brothers, Daniel and Yves, for their input, friendship and support over the years. Finally, a special thanks to my parents as well as Élisabeth and my two children for their love, support and encouragement during my studies.

À Élisabeth, Juliette et Étienne, de par leur
affection et loyauté inconditionnelles, de
m'avoir rappelé quotidiennement durant mes
études supérieures qu'il y avait bien plus
important que la découverte scientifique

Table of content

List of tables

List of figures

1 Introduction

1.1 Indoor climate, energy and the consumer

At the start of the millennium, the Worldwatch Institute published its 2000 edition of the annual *State of the World* report. In the introductory chapter, *Challenges of the New Century*, Worldwatch Institute founder and long-time contributor Lester R. Brown stated that the only feasible alternative to fossil-fuel or carbon-based energy economy is a solar/hydrogen-based one, one that taps the various sources of energy from the sun, such as hydropower, wind power, wood, or direct sunlight (Brown 2000). Based on the last decade's trends in global energy use, the Institute estimated that the use of wind power and solar photovoltaic cells were expanding at 22 percent and 16 percent a year, respectively; overwhelming the annual rate of growth of traditional energy sources, such as coal, natural gas and oil. Brown provides success stories of wind power in Denmark, Navarra in Spain, and Shelswig-Holstein in Germany, and discusses major developments in large growing economies, such as China and India. At the time, Brown ultimately conceded though that the growth in renewable energy production may not be sufficient to curb climate change, and urges for more government incentives and tax restructuring to boost growth in renewables. The tone of the 2000 report, whether found in Brown's words or echoed in the writings of Seth Dunn and Christopher Flavin's *Sizing Up Micropower* (Dunn and Flavin 2000), was cautionary yet enthusiastic. It suggested that, all things being equal, world economies could successfully phase out unsustainable practices in energy production in the near future if policy makers and corporations played their cards right.

The tone of the 2004 edition is somewhat different. Janet L. Sawin, in *Making Better Energy Choices* (Sawin 2004), does provide more encouraging statistics on renewable energy production and energy efficiency, yet goes on to illustrate just how these improvements are now being offset by ever-increasing levels of energy consumption worldwide. Efficiency, apparently, is no longer enough. Government policy may act to influence consumption in many ways, yet ultimately consumers' own decisions may tip the scale either way. Consider the automotive industry. On one hand, it is encouraging to note that consumers often make environmentally-sound choices: US sales of hybrid-electric cars have doubled since 2001 (Mastny 2004), while on the other hand, it is somewhat disconcerting to know that there are now more cars in the US than Americans licensed to drive them (Sawin 2004), and nearly half of all vehicles sold in the US are gas-guzzling sport utility vehicles (SUVs) and light trucks (Sawin 2004).

Consumer trends also influence building energy consumption, namely in regards to indoor climate control. Natural ventilation is a familiar, age-old method of ventilation and cooling, commonly used in homes throughout the world. Despite the wide-spread implementation of mechanical air-conditioning in commercial and institutional buildings, operable windows remain highly-rated components in the working environment (Heschong Mahone Group Inc. 2003, Brager and de Dear 2001, Farley and Veitch 2001) and are even preferred by occupants in many instances to artificial climate control (Rowe 2003, Clements-Croome 1997). At the same time, an ever-increasing percentage of commercial and institutional buildings in Canada – a heating dominant climate - are either partially or fully air-conditioned (CIBEUS 2003). In non-domestic buildings, this growth may have more to do with policy or building professional ideology than consumerism, yet booming world sales in residential air conditioning units are more revealing in this regard (Sawin 2004). In Canada, approximately one third of all housing units were air conditioned in 1997 (SHEU 2000), while this fraction was only one quarter four years earlier (SHEU 1994). The impact of greater air-conditioning use on power demand is well-known. In many countries, peak electricity demands now fall during summer conditions (Santamouris and Asimakopoulos 1996, Baker and Standeven 1994). Over-stressed energy grids, largely due to the greater air-conditioning, produced the largest energy blackout in US and Canadian history in August 2003, affecting 50 million people in eight states and two provinces.

The consumer's *need,* or simply *desire*, to possess control over his or her environment seems deeply rooted. We need only to revisit the writings of Reyner Banham (1969) on the cultural status given to air-conditioning over time in homes, offices or cars, whether to alleviate physiological discomfort or to emblematize social status. Yet this doesn't imply that capital-cost-cutting and energy-saving solutions such as natural ventilation and passive cooling aren't feasible, even preferred by the individual consumer (de Dear and Brager 2001). People might prefer the breezy, natural swings from an open window, while only relying on more narrowly-controlled conditions under extreme periods. This isn't any less consistent to suggest that people prefer daylight while relying on electric lighting when natural conditions no longer suffice. Ultimately, is it reasonable to think that we can still create a single environment that optimizes thermal settings for all people?

In 1998, researchers Brager and de Dear published an extensive literature review on field studies relating to thermal satisfaction in the built environment (Brager and de Dear 1998). In summary, the findings suggest that in centrally-controlled, mechanically-cooled environments, i.e. where thermal conditions are imposed on a building population, occupants either adapt to or tend to expect a narrow range of temperatures, while in naturally-ventilated environments, people tend to adapt to wider temperature swings, suggesting a potential for energy conservation. One clear conclusion emerging from this study seems to be that the *one-size-fits-all* approach to indoor climate management is fast becoming a curious but misguided fad of the last century. The authors later suggest that perhaps the most appropriate goal would be to provide a variety of means for people to control their own environment (Brager and de Dear 2001). This is consistent with the main concept behind personalized environments, provided through task-ambient conditioning (TAC) systems (Arens et al. 1998, Bauman et al. 1997).

As previously stated, occupant control over the indoor environment, whether partial or complete, can significantly affect energy consumption in buildings. From a sustainability perspective, it would be beneficial for building designers and owners, academics, policy makers, etc. to understand and anticipate what can be considered as sustainable occupant interactions with building components and systems, and conversely to avoid built conditions where occupant interaction might cause sustainable penalties, e.g. greater energy expenditure. Acquiring field evidence from the existing building stock of what constitutes a successful design (i.e. in how such a design encourages sustainable building occupant interaction) and subsequently deriving empirical models for predictive purposes is, in principle, a theoretically viable method of providing such knowledge. Practically, this could mean correlating unitary building energy consumption (kWh/m^2 per year) against various occupant control opportunities. To be considered valid, such an approach would have to be undertaken at an unfathomable scale, given the inherent complexity of buildings as systems, and how these systems are influenced by constantly-changing meteorological conditions. A more viable approach would be to carry out a limited number of field studies at a greater resolution in the hope of deriving reliable empirical models describing occupant interactions with their surroundings, and then to simulate the effect of these interactions using building energy simulation programs.

The aim of this thesis is to address current limitations in whole-building energy simulation when dealing with detailed occupancy prediction (i.e. when occupants as individual agents occupy a modelled environment), occupant-sensing control (i.e. as driven by the mere presence of one or more occupants, such as occupancy-sensing lighting controls, demand-controlled ventilation based on metabolic carbon dioxide emissions, power management of equipment during prolonged user absenteeism), as well as advanced behavioural models (i.e. active personal control, such as manual switching of lights, manual adjustments to window blinds, operable windows, personalized air-conditioning units). The following hypotheses are investigated in this thesis:

- Advanced behavioural models and occupancy-sensing control, together with advanced occupant mobility prediction, can be successfully linked to whole-building energy simulation to reliably predict the influence of occupant interactions on energy use at high frequencies (i.e. down to a time scale of minutes) and at high resolutions (i.e. for any given, user-defined number of independent agents), without significantly penalizing simulation run-times.
- The impact on energy use of simulated occupant interactions can be dramatic in certain instances, revealing possible shortcomings of certain modelling assumptions made for building energy ratings and compliance methods.
- Key behavioural model parameters, such as individual or group predispositions towards manual control (which are found to be significant in published behavioural models, e.g. overhead lighting, window blinds) can be considered as universal in nature, and can reliably characterize other interactions (e.g. operable windows). This would support the elaboration of a common approach to modelling occupant interactions in whole-building energy simulation.
- The enhanced functionality can be used to investigate the feasibility (e.g. energy saving potential or penalty) of novel yet untried strategies that strongly rely upon user interactions, such as adaptive comfort control through manual use of operable windows in harsh climates such as Québec.

1.2 Thesis outline

In the first part of this thesis, a simulation module which provides whole-building energy simulation access to advanced occupant-based control models is developed. A review of existing methods in building energy simulation of modelling occupancy, occupant-sensing control and behavioural models is carried out in Chapter 2. An original sub-hourly occupant-based control module (SHOCC) is introduced in Chapter 3, followed by an example application in Chapter 4.

In the second part of this thesis, a behavioural model describing manual control of operable windows is proposed. A review of current knowledge on hybrid ventilation is presented in Chapter 5, followed by a state-of-the-art review on thermal adaptation and adaptive comfort control in Chapter 6. A description and results analysis of a pilot study on operable window use are presented and discussed in Chapter 7. The integration of a new operable window model in SHOCC is presented, followed by an example application of adaptive comfort control, in Chapter 8.

Chapter 9 summarizes the results of this thesis.

2 Modelling occupants and behaviour in building energy simulation

The first part of this chapter briefly introduces building energy simulation and presents the ESP-r system as the whole-building energy simulation program of choice for the purpose of this thesis. The second part of this chapter presents the current state-of-the-art of modelling occupant-related influences (e.g. metabolic heat injections, personal use of appliances such plug loads or lighting systems) in building energy simulation. This is followed by a review of more advanced occupancy prediction and behavioural models found in the literature that may or may not have been integrated within building energy simulation. The influence of a few of these models on building energy simulation results is presented, and the underlying challenges of integrating future models are discussed.

2.1 Building energy simulation

For decades, building performance software tools have been developed to simulate the complex interactions between building fabric and services, weather and of course, human activities within buildings. They are useful in building research by providing greater insight in the underlying physics of a problem, such as understanding why building components fail (e.g. mould growth and wood rot from water retention in building envelopes). They are relied upon to estimate future energy trends in the building stock at regional or national scales (Parent 2002). They provide assistance to building designers in risk management by forecasting the behaviour of intended designs (e.g. condensation assessment of a curtain wall design), and in estimating the cost effectiveness of individual components (e.g. heat recovery). They are increasingly used for code compliance purposes (ASHRAE 90.1 2001, MNECB 1997), or building rating systems (LEED v.2.1 2002). Well-written historical backgrounds and current perspectives on the use of building energy software tools are found in Clarke (2001), Beausoleil-Morrison (2000) and Hand (1998).

Under the US Department of Energy (DOE), the Office of Energy Efficiency and Renewable Energy (EERE) harbours the Building Energy Software Tools Directory[3]; an

---

[3] www.eere.energy.gov/buildings/tools_directory

online gateway providing access to hundreds to publicly available computer tools for a wide variety of uses. These tools are sometimes classified by looking at the underlying computational approach and the nature of the targeted issue which merits investigation. Clarke and Maver (1991), as reported in Hand (1998), suggest four generations:

- *1st generation*: Handbook oriented computer implementations, analytical in formulation, and biased towards simplicity. Piecemeal in their approach, providing indicative results within constrained solution domains.
- *2nd generation*: Characterised by the introduction of the dynamics of fabric response, but decoupled in relation to the treatment of air movement, systems and control. Early implementations often limited in scope or resolution as a result of the expensive computational requirements for their time.
- *3rd generation*: Characterised by treating the entire building as a coupled field problem and employing a mix of numerical and analytical techniques. Demand considerable expertise and resources to go beyond simple problems. Modelling integrity is enhanced but is often used to derive information to be incorporated in simplified techniques.
- *4th generation*: Characterised by full computer-aided building design integration and advanced numerical methods which allow integrated performance assessments across analysis domains.

Third and fourth generations are commonly referred to as *simulation*, while the first and second generations are referred to as *simplified methods* because of their constrained treatment of the underlying physics (Hand 1998). Within the scope of this thesis, only simulation is considered.

Although the influence of occupant interactions may be treated independently of building model resolution (e.g. a room, a building), potentially influencing the choice of which software tool to use, this thesis will focus solely on ESP-r, an open source, free software system equipped to model heat, air, moisture and electrical power flows at user determined resolution.

2.1.1 The ESP-r System

The ESP-r system (ESRU 2002) is an integrated modelling tool for the simulation of the thermal, visual and acoustic performance of buildings and the assessment of the energy use associated with the environmental control systems and constructional materials. Within

ESP-r, a building comprises a collection of interacting technical domains, each solved by exploiting the specific nature of the underlying physical and mathematical theories (Clarke and Tang 2004). A few notable, typically coupled, domains include natural illuminance prediction, building thermal processes, intra-room airflow, and electrical demand and embedded power systems. Clarke (2001) describes the approaches taken to solve the governing equations, while preserving domain interaction. Figure 1 illustrates the complex energy flow paths considered in ESP-r.

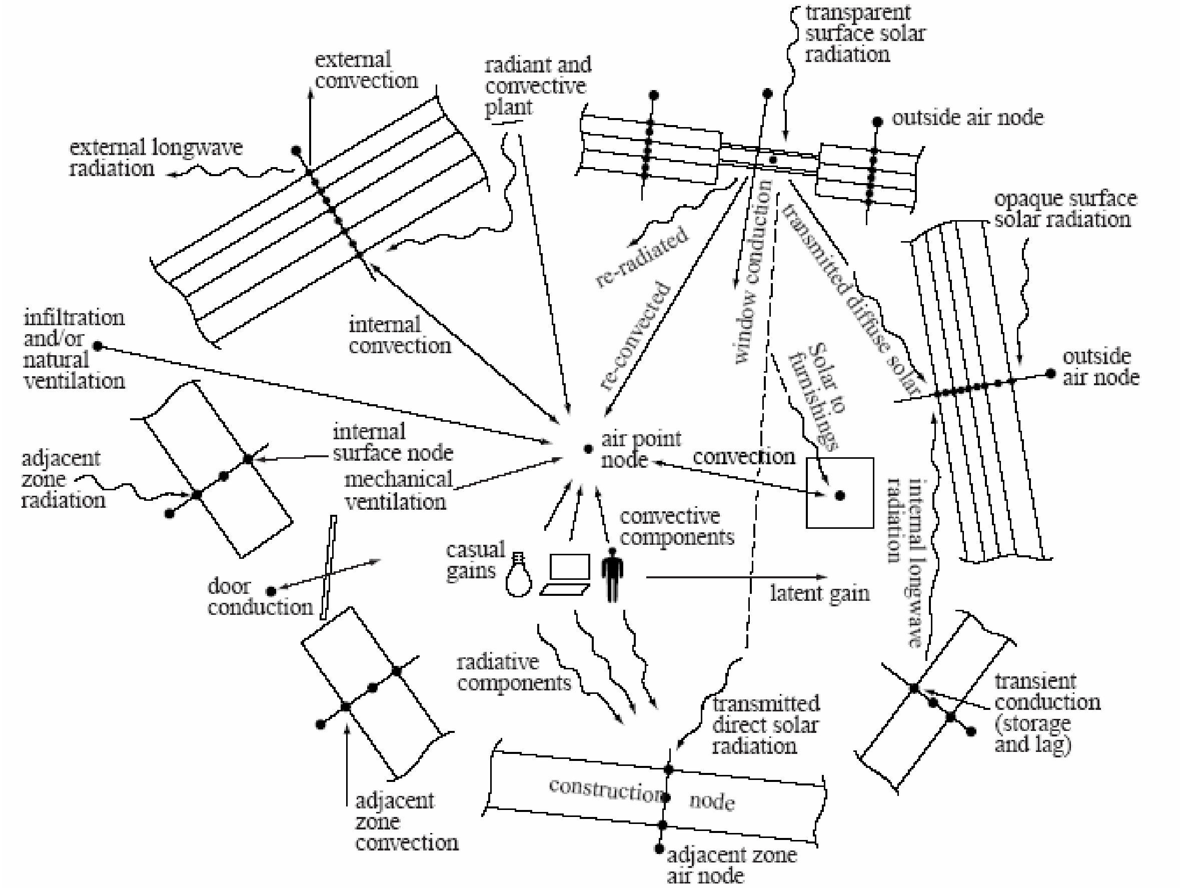

Figure 1 Building energy flowpaths, taken from Clarke (2001)

ESP-r is often referred to as a whole-building energy simulation program, fully capable of quantifying the overall energy use in a building. It is also used for more focused studies, such as multi-dimensional heat conduction in wall assemblies or interzonal airflow through computational fluid dynamics (CFD). A wealth of information on ESP-r can be found on the University of Strathclyde's Energy Systems Research Unit[4].

Within the scope of this thesis, occupant interactions will be considered in relation to ESP-r, independently of model resolution. Importance is rather given to domain integration (e.g. how technical domains such as lighting, thermal, airflow, CFD, affect one another; each of which can be affected by the state of a single occupant-controlled component). For instance, manual control of indoor window blinds, computed during the solar calculations in ESP-r, will influence the sensed illuminance in the daylighting calculations, which can in turn affect the lighting load on the electrical network and how power is used from embedded renewable components, if such systems are defined. The transmitted solar loads, a function of the blind/glazing interactions, in addition to the heat output of lighting systems, will equally affect a zone's heating, ventilation and air-conditioning (HVAC) energy use. Finally, the updated temperature of blind slats may affect the airflow patterns calculated within ESP-r's CFD domain. And so on. The following section provides a background review of how occupancy and related controls are commonly modelled in existing energy simulation programs. It then reviews a number of advanced behavioural models which, although published, are for the most part unavailable in whole-building energy simulation. The purpose is to identify current limitations as an introduction to the design of a more robust method of integrating occupant interactions within whole-building energy simulation.

2.2 Current approaches in modelling occupants

An exhaustive review of *all* existing approaches to modelling occupants, their mobility and the potential influence they exert (e.g. control over equipment, lights, blinds, windows) in energy simulation is beyond the scope of this thesis. The most widespread approaches in energy simulation programs are nonetheless presented.

---

[4] www.esru.strath.ac.uk

2.2.1 Diversity profiles

A widely-used technique in energy simulation is to model metabolic heat rejected from occupants (i.e. latent, as well as sensible radiant and convective heat), as well as heat rejected from occupant-controlled equipment (i.e. receptacle loads) and lighting systems through diversity factors, a solution passed down from the earlier generation of hourly simulation programs. Diversity factors are numbers between zero and one, and are used as multipliers of some user-defined maximum load. Depending on the approach, the latter is either defined as a maximum rate (e.g. in watts in ESP-r) or integrated heat injections over the course of a defined period of time (e.g. in watt-hours). Load variability, due to absenteeism, behaviour and power management features of IT equipment, is ordinarily defined by associating different sets of 24-hour diversity factors, or diversity profiles, for different day types (e.g. weekdays, weekends, holidays, etc). Many energy standards and codes either provide, or refer to, typical diversity profiles for performance-based compliance demonstrations (ASHRAE 90.1 2001, MNECB 1997). As an example, Figure 2 illustrates a common diversity profile used to define occupancy in office environments, taken from the standard database of the Canadian DOE-2.1E-based (Winkelmann et al. 1993) energy compliance software *EE4 CBIP* (EE4 2000).

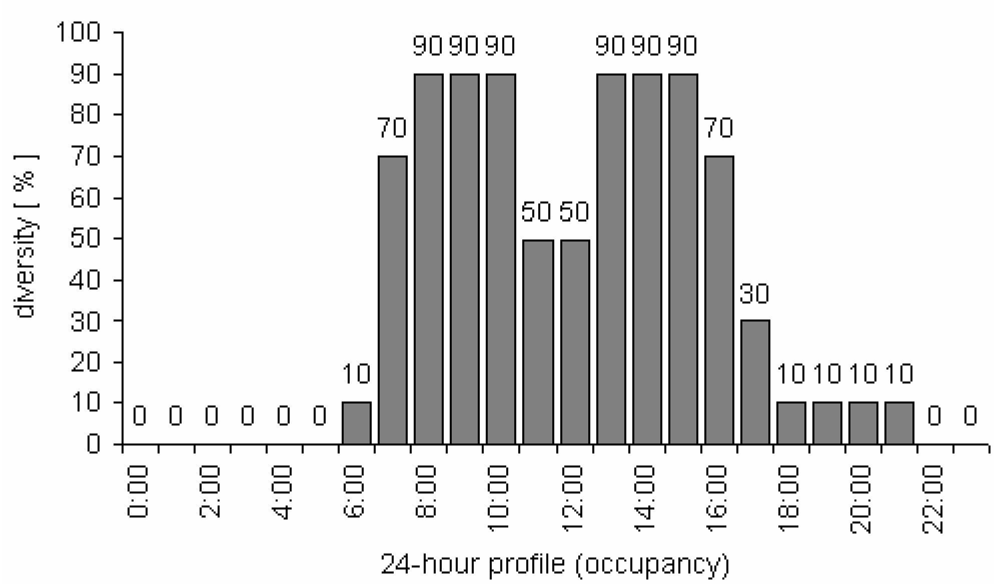

Figure 2 24-hour diversity profile for typical occupancy loads in office environments, taken from EE4 standard database.

The corresponding 24-hour diversity profile for overhead electric lighting loads in office environments is provided in Figure 3. Here, an electric lighting base load of 5% occurs during unoccupied hours, while main periods of occupancy are mainly characterized by lighting use of 90%. It can also be seen that overhead lighting use remains at 90% of nominal values from 8:00 to 17:00, despite the lower occupancy loads during lunch. This pattern in lighting use is typical of large core zones in deep office environments.

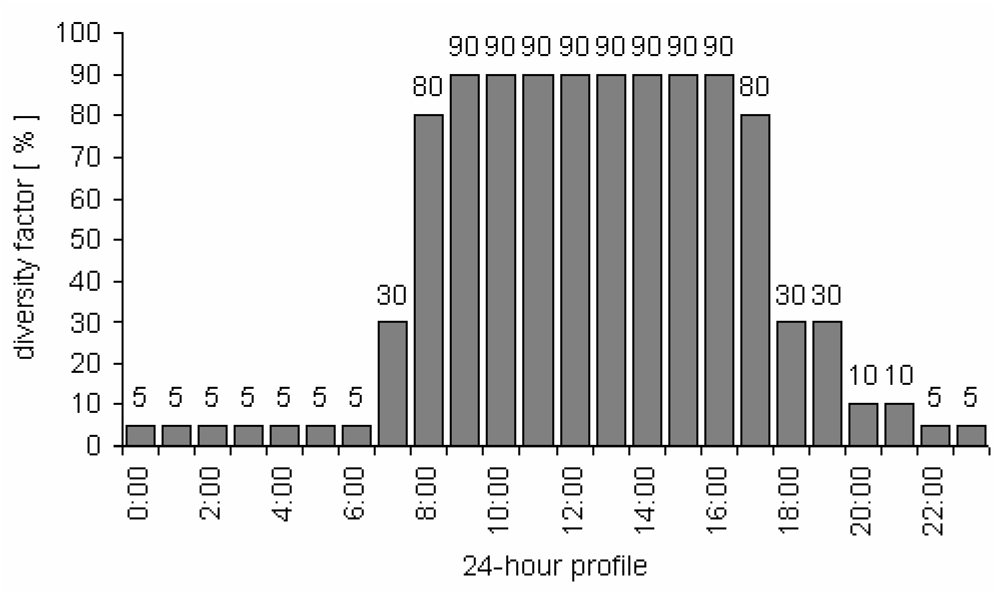

Figure 3 24-hour diversity profile for typical overhead electric lighting loads in office environments, taken from EE4 standard database.

Abushakra et al. (2004) provide an overview of existing methods for deriving diversity profiles. Recent developments in this area include findings from the ASHRAE Research Project 1093 (Abushakra et al. 2001). The goal of this project was to compile a library of schedules and diversity factors based on measured electricity use data for energy simulations and peak cooling load calculations in office buildings. This research project derived multiple sets of diversity factors from measured lighting and receptacle loads in 32 office buildings (Claridge et al. 2004). Occupancy was not monitored under RP-1093, yet another study from Claridge et al. (2001) established a strong correlation between observed occupancy levels and lighting loads, suggesting that valid occupancy diversity profiles may be derived from lighting diversity profiles using linear regression.

Diversity profiles are often adequate as average input data models for large, deep core zones containing multiple spaces. If lighting and office equipment use in a given building is considered predictable for a given set of day-types, e.g. if their use is independent of weather patterns, then the technique can be considered valid. One significant shortcoming of the RP-1093 diversity profiles, or of any other similarly-derived data, is that they are derived independently of meteorological data. This may be a valid assumption when considering core zones, but hardly so for perimeter spaces: for a given occupancy pattern and daylight illuminances, two differently-oriented perimeter zones will clearly possess very distinct lighting loads if manual and/or automated control are available. Correlating occupancy from these lighting profiles would lead to obvious errors.

Yet as many North American buildings have very low envelope-to-floor area ratios, these errors are considered by some to be minor and applying diversity profiles, including those for occupancy, derived from monitored core zone lighting use may be considered acceptable. In cases where greater envelope-to-floor area ratios are found, or even in some cases where there are no core zones at all, the use of general diversity profiles becomes difficult to justify. This would certainly be the case for building designs aiming at high daylight autonomy levels and/or offering outside views to most occupants, such as prescribed by certain daylighting design guides (DGCCB 2002), required by related standards (DIN 5034 1999), or recommended by green building rating systems like LEED (2002).

Other studies have shown that the use of hourly diversity profiles can lead to considerable errors when applying control strategies that are quite sensible to short-term variations in occupancy. This consideration fuelled the original Lightswitch model (Newsham et al. 1995). Based on field data, it predicts arrival, departure and temporary absence probabilities of individual occupants in office environments at 5-minute intervals. The short time-step accuracy of Lightswitch provides more realistic estimates of electric lighting use resulting from occupancy-sensing controls. Newsham et al. suggest carrying out multiple runs of Lightswitch to produce averaged lighting diversity profiles for DOE-2.1E (Winkelmann et al. 1993). Degelman (1999) also suggested that fixed lighting profiles generate misleading information when occupancy-sensing lighting controls are used, and put forth a Monte Carlo approach to space occupancy prediction based on survey statistics. Keith (1997) demonstrated how average profiles lead to overestimations of electrical energy savings and demand reduction through occupancy-sensing controls, which in turn lead to underestimations of heating loads for various U.S. locations. Keith proposed an on-line, field-based tool modifying standard DOE-2.1E weekly profiles by introducing *peakdays*, thereby enhancing monthly peak demand estimations without increasing simulated energy use[5].

The aforementioned studies focus on improving occupancy prediction to better assess the energy savings from occupancy sensors, but fail to address the lingering misconception in energy simulation that, in Newsham's words, *occupants are fixed metabolic heat generators passively experiencing the indoor environment* (Newsham 1994). Occupants instead respond to various, often sudden environmental changes, triggering in the case of lighting abrupt manual adjustments in window blind settings and artificial light use, which in turn affects electrical energy use and demand. This reiterates the necessity of introducing valid short-term behavioural models to predict occupant perception and response to environmental stimuli.

2.2.2 Behavioural models of personal environmental control

The following literature review on personal environmental control modelling is non-exhaustive in its scope in the sense that it does not cover all possible actions taken by building occupants to suit their preferences. It nonetheless provides insightful background information on two major topics of study on personal environmental control: manual operable window control and manual lighting control. Within the scope of this thesis, lighting control is considered henceforth to include window blind and overhead lighting control. First, a review of operable window control models is presented followed by a review of a publicly-available suite of manual lighting control models: the Lightswitch2002 algorithm (Reinhart 2004).

---

[5] www.resodance.com/pod/

2.2.2.1 Past research on operable window use

Warren and Parkins (1984) review previous studies of window opening patterns in homes in the UK. In all previous studies, the percentage of opened windows is strongly correlated to outdoor air temperature, and slightly to wind speed. Similar studies conducted in a school (Nicol and Humphreys 1972) and an office building (Pallot 1962), again both in the UK, showed similar strong correlations, as well as an additional weaker dependence with the number of hours of sunshine. Warren and Parkins analysed five naturally-ventilated office buildings with small cellular offices in Garston, UK during a 13-week period and found again a similar relationship, where outside air temperature accounted for 76% of the observed variance, the effect of sunshine for an additional 8%, and wind speed, 4%. They differentiated between small openings and large openings, the state of the former showing little dependence upon weather, while the latter being mainly a function of the above-mentioned independent variables, leading to two separate regression equations. They also observed a façade-orientation and sky-condition dependencies, as well as daily cycles. Occupant questionnaires showed a strong relationship between an occupant’s desire of opening windows and the desire for fresh air, especially in winter. Another interesting observation concerns the frequency of exercised control: windows, when opened, were often left that way until the room was vacated.

A similar study on the impact of occupant opening windows in homes on the southern Japanese island of Kyushu, was carried out by Iwashita and Akasaka. (1997). It was observed at the time that although air-conditioning was becoming increasingly popular, many still insisted on using natural ventilation. One interesting observation was that even when high concentrations of particulate matter were found in outside air (i.e. ash from a nearby volcano), 23% still insisted on opening windows; possible evidence of population clustering among window users (i.e. those who insist on mechanical ventilation; those who switch ventilation modes, depending upon circumstance, those who don’t care for natural ventilation at all, etc.).

Fritsch et al. (1990) investigated personal use of operable windows in four offices at the *Laboratoire d'énergie solaire et de physique du bâtiment* (LESO), *École polytechnique fédérale de Lausanne*. The opening angles of each office window were measured every half hour, mainly during winter conditions (1983-1985). Monitored meteorological variables included outdoor and indoor air temperature, wind speed and vertical solar radiation impinging on the window. Data analysis ruled out wind speed and solar radiation as statistically significant driving variables, while indoor air temperature was discarded as it remained relatively constant (e.g. between 19°C and 23°C) during heating periods. The intercorrelation between window opening angle and outdoor air temperature (i.e. the only remaining independent variable in their study) is strong in winter conditions (i.e. with measured outdoor air temperatures between -6.0°C and 22.0°C), with a noticeable increase in window angle beyond 15°C. Although open window observations were much more frequent in summer (i.e. with measured outdoor air temperatures between 7.0°C and 29.0°C), and at greater angles of opening, there no longer appears to be any dependency of opening angle on outdoor air temperature. Simple autocorrelation analysis showed that windows are usually left in one position for long periods of time, while a differentiated autocorrelation analysis did not show any dependence of any greater order. In other words, they found that the probability of finding a window in a certain position did depend on its preceding position yet not on any others. The authors chose discrete Markov chains as the basis of a suitable predictable model. A Markovian process has no memory; the next state will depend only on the present state and no others. Such an approach does have the benefit of capturing all the particularities of an investigated room (e.g. size, inhabitant behaviour, etc.), yet it requires a unique set of observations for every office. Not only is this a costly endeavour, it is virtually impossible to carry out for planned (i.e. simulated) environments. In response to these limitations, the authors suggest developing multiple Markovian matrices in the future, representing a larger number of cases, yet the literature does not reveal any such follow-up. Apart from a strong winter dependency of opening angle on outdoor air temperature, the conclusions do not describe any significant relationship which can be useful in a simulation context. Despite this, the study remains to this day one of the most detailed and thoroughly-analyzed investigations on window opening behaviour.

Raja et al. (2001) carried a more recent study, using occupant questionnaires, on the use of traditional controls in ten naturally-ventilated and five air-conditioned buildings in the UK. Of all available controls, windows had the biggest effect on indoor climate, with the operation of fans following closely behind. The relationship is strongest with instantaneous indoor and outdoor air temperatures. However, no regression equation relating occupant behaviour and window openings was formulated at the time. As a follow-up, Nicol (2001), and then Nicol and Humphreys (2004), did a more extensive survey of the use of controls - windows, lighting, window blinds, heaters and fans - by occupants of mainly naturally ventilated buildings. The surveys were conducted in the UK, Pakistan and throughout Europe.

In cases where a dependent variable assumes a continuum of values, conventional regression analysis is appropriate to link the observed outcome to the values of certain *driving* or *explanatory* variables. Here, the use of controls is instead binary in nature (i.e. windows are either opened or closed, blinds either retracted or lowered, etc.) rather than being part of any continuum. The author appropriately links the use of controls to either outdoor or indoor globe temperature using *binomial logit regression*; a form of *generalized linear modelling* (Borooah 2001, Crown 1998, Liao 1994, Aldrich and Nelson 1984). The resulting function provides the *probability* of a particular event occurring, as described in Equation 1, where *a* and *b* are statistically-derived constants and *x* is the independent variable (e.g. temperature).

$$p = e^{(a+bx)} \Big/ \left(1 + e^{(a+bx)}\right) \tag{1}$$

A more detailed presentation and discussion of the results are found in Nicol and Humphreys (2004).

Table 1 presents the values of the constants *a* and *b* for Pakistan, UK and Europe, while Figure 4 gives the predicted relationship between outdoor air temperature and the proportion of open windows. Although the latter investigations are not as detailed as the Fritsch et al. (1990) study in its analysis and treatment of time-series data, it is much more transversal – versus longitudinal – and as such, offers greater insight on overall trends in operable window use.

Table 1 Values of the constants a and b (±standard error) in Equation 1, taken from (Nicol and Humphreys 2004)

	Outdoor temperature °C		**Indoor globe temperature °C**	
	Intercept a	**Slope b**	**Intercept a**	**Slope b**
Pakistan	-3.73±.06	0.118±.004	-5.14±.19	0.149±.005
UK	-2.65±.11	0.169±.009	-13.55±.65	0.531±.027
Europe	-2.31±.16	0.104±.010	-10.69±.52	0.379±.020

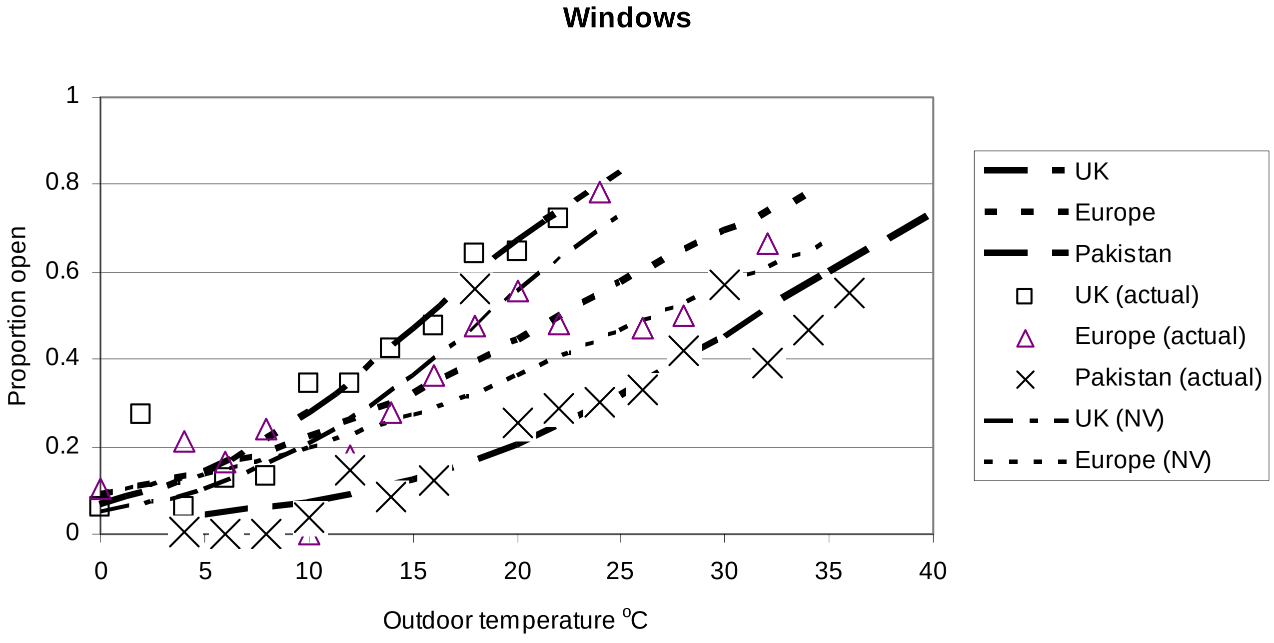

Figure 4 Proportion of open windows as a function of outdoor air temperature (taken from Nicol and Humphreys 2004)

2.2.2.2 Application of window models in energy simulation

Although the aforementioned studies provide great insight into what drives personal control of operable windows, it is necessary to consider how these models can be applied in energy simulation. The aforementioned user surveys carried out by Warren and Parkins (1984) clearly indicated that the use of windows is not only influenced by sensed thermal conditions but also as a response to perceived indoor air quality (IAQ), draughts, rain, outdoor noise levels, etc. Similar complex relationships have been noted in more recent studies: Rowe and Wilke (1995) evidenced that perceived IAQ is not only influenced by well-established variables, such as perceived levels of pollutants and thermal conditions, but also by a larger set of indoor environmental criteria, such as perceived levels of personal control, the quality of daylighting, etc. However, reliable values of key driving variables, such as rain or acoustic nuisances, are difficult to obtain, while others, such as draught levels, can only be simulated and therefore are subject to great uncertainty. Although it is reasonable to establish that behavioural models predicting the likelihood of opening of window can be largely based on indoor/outdoor air temperatures, it appears preferable to consider the influence of other variables as random variations. As the uncertainty in simulated indoor air temperature (i.e. a state variable) is far more significant than that of outdoor air temperature (i.e. simulation input), the latter is generally preferred as the main driving variable in published models (Nicol and Humphreys 2004, Fritsch et al. 1990). This does not rule out indoor air temperature as an independent variable, only that its reliability should be carefully considered.

2.2.2.2.1 Dynamic application of Nicol and Humphreys' model in energy simulation

The following focuses on the practical application of the aforementioned Nicol and Humphreys' (2004) operable window control model in energy simulation. Derived by logistic regression from a large international database of occupant response surveys and measurements of physical conditions in buildings, the model gives the probability of a window being open as a function of outdoor air temperature. Its mathematical expression has been provided earlier in Equation 1, with empirical coefficients related to regional settings provided in

Table 1.

Nicol and Humphreys' model provides the fraction of open windows as a function of outdoor air temperature, rather than *when* and *how long* a window is open: it is not possible to predict through Nicol and Humphreys' model what the average *delay* before an arriving occupant opens a window, or what the average *delay* before an occupant eventually closes an open window. Nicol and Humphreys' relationship could be theoretically coupled to probability density functions based on empirical evidence of the aforementioned delays. Such information can only be derived from high frequency time series data over long periods (e.g. observations every 5 minutes), and unfortunately, no such information appears to have been collected in the past. This implies that Nicol and Humphreys' model, as it stands, cannot describe detailed time-dependent occupant behaviour with regards to operable window use. Instead, it provides various *snapshots* of what can be witnessed in the field at any given moment. Implicitly, it is unable to describe what has occurred before or what can occur next in a given office.

In a simulation context, if one compares the outcome of a truly random process (e.g. producing a random draw of real numbers between 0 and 1) against the output of Nicol and Humphreys' model at a given time step (e.g. T1), based on outdoor air temperature, one would get a good approximation of how many windows in a given building sample are likely to be open. If one repeats the process a second time (e.g. T2) based on different conditions, one again would get a good approximation of how many windows in a given building sample are likely to be open. The problem would be that there wouldn't be any relationship between the previous (i.e. at T1) and current (i.e. at T2) state of *individual* windows. In other words, without stipulating what happens once an *individual* window is open (e.g. does it stay open for one hour? a half-day? a whole-day?), then the previous state of individual windows must ignored every time the stochastic process is initiated.

Without such stipulations, unexpected outcomes may occur in a simulation context: for instance, certain windows could stay open for weeks while others could alternately open and close at every single time step. To avoid such intuitive inconsistencies, one inevitably must stipulate what happens *once* an individual window is open, while possibly still relying on Nicol and Humphreys' model to predict *when* windows initially open, at least until empirical evidence of the aforementioned *delays* is eventually made available. Without such evidence, one cannot rule out whether stipulated average *delays* could last one hour or one day, all individual outcomes being theoretically possible using Nicol and Humphreys' model. This analysis provides some insight on possible challenges in applying empirical behavioural models to dynamic energy simulation. In particular, it illustrates that additional assumptions or stipulations may be required to adequately integrate published empirical models in dynamic energy simulation applications.

2.2.2.3 The Lightswitch2002 algorithm: personal control of lighting

Based on field evidence gathered within the scope of his doctoral studies (Reinhart 2001) and from previously published surveys in Canada, Japan, the UK and the United States (Reinhart and Voss 2003), Reinhart (2004) derived the Lightswitch2002 algorithm to predict personal control of electric lighting systems and blinds. Key concepts include population clustering into *active* versus *passive* users (Love 1998), stochastic functionality, and dynamic responses to short term changes in luminous conditions and occupancy patterns. By stochastic, it is meant that whenever a user is confronted with a control decision, e.g. to switch on the lighting or not, a stochastic process is initiated to determine the outcome of the decision. By dynamic, it is meant that instead of looking at an average day in a year or month, user occupancy, indoor illuminances and the resulting status of electric lighting systems and blinds are considered at regular time steps (e.g. 5 minutes) throughout the year. Occupant responses are adapted to various lighting control options, from manual switching to various combinations of dimming and occupancy-sensing technology. It has been developed in the same spirit as the original Lightswitch model (Newsham et al. 1995), briefly presented in section 2.2.1. Its designation underlines that the algorithm is expected to evolve over time along with future advances in the field.

The algorithm stands out from other published developments in the area in the sense that the independent models that make up Lightswitch2002 are used in a complementary way for dynamic simulation purposes. For instance, one model is used to predict whether an occupant switches his or her lights on or not upon arrival, while a complementary model is used to predict whether the same occupant switches lights off or not upon departure, dynamically setting up lighting boundary conditions for the following day. This overall organizing principle makes Lightswitch2002 a suitable choice for dynamic energy simulation purposes, in part by minimizing the need for model assumptions, as discussed in the preceding section. Nonetheless, a number of assumptions are required to set at what point during a simulation, and under which conditions, should the Lightswitch2002 functions be accessed, as presented in Reinhart (2004).

2.2.2.3.1 Underlying assumptions

Even though occupants behave differently, they use their lighting and blind controls consciously and consistently. Stated otherwise, although behaviour in regards to lighting control can be described in part as a stochastic process, it is not completely arbitrary; certain behavioural traits appear to be stable among certain population groups.

Manual lighting control mainly coincides with an occupant's arrival at or departure from the work place. Some individuals always activate their lighting throughout the whole working day independently of prevailing daylight levels (referred to as *passive* users). Others only switch on their electric lighting when indoor illuminance levels due to daylight are low (referred to as *active* users). For the latter user type, the probability of switching on electric lighting is correlated to minimum indoor illuminance levels at the work plane upon arrival (Love 1998, Hunt 1979).

Instantaneous adjustments to electric lighting levels (i.e. other than those chosen upon arrival) are related to minimum work plane illuminances. The probability of switching on lights rises from 0.5% to 2% per 5-minute time step for minimum work plane illuminances below some 250 lux; approximately the value at which subjects in a laboratory study tended to reset their electric lighting levels that were slowly falling over time (Newsham et al. 2002).

The length of absence from the work place strongly correlates with the probability that electric lighting is manually switched off. It has been found that the presence of automated lighting controls influences the behaviour of some people (Pigg et al. 1996). People in private offices with occupancy control were found to be less likely to turn off their lights upon temporary departure than people without sensors. Similarly, probabilities of switching off lights were found to be lower for a dimmed, purely indirect lighting system that for an undimmed system.

As with lighting, manual blind control mainly occurs upon arrival, when either an *active* user retracts blinds upon arrival (Lindsay and Littlefair 1993, Inoue et al. 1988) or a *passive* user lowers blinds for the day (Rubin et al. 1978). Retracted blinds are lowered if direct glare exceeds 50W/m². An automated blind control algorithm is also available; its target is to optimize natural illuminance at the workstations while avoiding excess direct glare.

2.2.2.3.2 Limitations

The model in its present state has some notable limitations; generally a result of a lack of quantitative field data, as taken from (Reinhart 2004).

- The scenario that a user returns to the workplace after a temporary absence and switches off lighting is not covered.
- The model assumes that users keep blinds either fully opened or closed. In reality, some occupants only lower their blinds to a point at which direct glare is avoided.
- The model also ignores any thermally driven mechanisms which might trigger a closing of the blinds to avoid overheating.
- Anecdotal evidence suggests that office occupants in densely populated urban settings use their blinds to block the view from the outside to satisfy their privacy needs (Foster and Oreszczyn 2001). Such privacy needs are not modelled.
- The seating orientation of an occupant determines his or her field of view and should therefore influence the use of lighting and blinds. Due to the absence of conclusive data, the current model considers only horizontal work plane illuminances, i.e. the orientation of the occupant is ignored.
- The frequency with which blind and lighting controls are used depends on the actual location of the control with respect to the occupant’s work place. Occupants are less likely to interrupt their work and use a switch near the entrance than to use a control within easy reach of their work place (Bordass et al. 1994).

2.2.2.3.3 Significance of the model on simulated lighting use

As suggested earlier, and despite the aforementioned limitations, the Lightswitch2002 algorithm remains one of the most advanced and complete applications predicting user response to lighting systems. By coupling the algorithm to advanced lighting simulation programs such as DAYSIM[6] (Reinhart 2001), a Radiance-based application (Ward Larson and Shakespeare 1998, Ward 1994), Reinhart puts forth a powerful tool to quantify the switching and energy characteristics of various lighting controls and identify under what circumstances these controls lead to energy savings and how big these savings are. This can

---

[6] www.daysim.com

inform design professionals on how robust a lighting concept in a particular building is towards *unexpected* usage.

Reinhart (2004) investigated the impact of four different behavioural patterns (e.g. *active* versus *passive* blind users, in combination with *active* versus *passive* light users) on five different lighting systems for a south-facing daylit office. These four user behavioural types mimic the individual spread between different occupants that has been found in monitored buildings. The combination of these user-specific energy demands with frequency distributions for the different users offers some guidance as to how much energy savings can be expected from a particular control strategy in a particular building. Reinhart illustrated that, depending on the user type, annual electric lighting energy use for manually controlled lighting and blind systems may vary between 10 and 39kWh/m² per year. Reinhart also showed that depending on how reliably occupants switch off a dimmed lighting system, mean electric lighting energy savings due to a daylight-linked photocell control range from 60% to zero. This wide range in results clearly demonstrates the significance of behavioural types on lighting energy use, and ultimately on the feasibility of automated lighting controls. Yet what is the frequency distribution of the four investigated user types in real buildings? According to Reinhart, there is no reliable data to meaningfully answer this question. Assigning equal frequencies to all four user types is not supported by the few mentioned field studies, which instead suggest that *active/passive* clustering is asymmetrical amongst different buildings (Reinhart and Voss 2003). Although the uncertainty in user profile distributions is sobering for the lighting efficiency enthusiast, the evidence at least provides field researchers with a sounder basis to design future monitoring campaigns, i.e. what should be monitored in the future.

2.3 Discussion

The preceding analysis of the Lightswitch2002 algorithm, as well as the previous review of operable window models, provides some insight on the requirements for integrating advanced behavioural models in dynamic simulation applications. Specifically, it illustrates how assumptions are often required to render individual behavioural models applicable under dynamically-changing situations. For instance, the Nicol and Humphreys' (2004) model describing manual control of operable windows requires an assumption on how long windows are kept open once in use. It also illustrates just how important certain key data inputs such as occupant mobility (e.g. arrival, departure) and personal predisposition (e.g. active/passive users) are to behavioural models like the Lighstwitch2002 algorithm (Reinhart 2004). Such information is usually not available in whole-building energy simulation programs, which suggests that additional data models and functionality are required.

The addition of new occupant-related data models in whole-building building energy simulation warrants some thought regarding certain challenges. In ESP-r for instance, each control function provides its own definitions for describing occupancy, whether by specifying arrival and departure times in Hunt's algorithm or by setting a temporal window when control is enabled, e.g. 8:00 to 17:00. Bookkeeping arises then as a major challenge with regards to occupancy-related input and control in ESP-r, or in any other advanced simulation package for that matter. Considerable effort can be required to harmonize casual gain definitions and control parameters to ensure, for instance, that metabolic heat from occupants is indeed injected simultaneously when personal computers are operated, and when lights are turned on, and when windows are opened, etc. The potential for incorrect data specification increases with the number of zones, occupants, nested domains and enabled control laws. Clearly, a more robust solution is desired.

This preceding examination into lighting behavioural models is insightful regarding mixed-mode approaches to climate control. It provides a wider perspective on user behaviour in general, providing potential key concepts which may be helpful when considering specific behavioural patterns. For instance, the field evidence supports the concept of grouping building populations into at least two clusters: those who consciously adjust settings on a frequent basis, versus those who consistently remain indifferent to natural environments and instead choose constant settings. Such binomial population clustering, as well as their frequency distribution, are found to be significant parameters in energy use estimation. As binomial clustering is found to be as significant in lighting as in blind control, should similar clustering not be expected for other personal environmental controls, such as task-ambient conditioning systems (TACs), ceiling fans, and operable windows? Past field studies on personal use of operable windows have not targeted this question explicitly, and so only through future investigations can this be evidenced. If such clustering is true however, then this needs to be addressed carefully when considering the use of previously-published operable window behavioural models within energy simulation. For instance, if one out of four occupants in a given mixed-mode building are assumed to be *passive* window users (i.e. who never open windows at all), then the probability of having opened windows amongst *active* users necessarily increases, at least based on the output of Nicol and Humphreys's model (2004). This likelihood has not been thoroughly accounted for in past studies. Another issue has to do with the increased likelihood of personal control coinciding with an occupant's arrival or departure, and to a lesser degree with intermediate absenteeism. Apart from anecdotal evidence from Warren and Parkins (1984), previously-published models do not consider the significance of these events.

2.4 Summary

The first part of this chapter presented building energy simulation software with a special focus on ESP-r, a whole-building energy simulation program. This included how existing programs, including ESP-r, simulate occupant interactions, from diversity factors to control functions. Diversity factors were shown to be valid only if limited to long-term influences considered independently of prevailing meteorological data, while existing control functions were shown to rely on static thresholds as triggering mechanisms; a hypothesis which has often been proven invalid. The few advanced behavioural models that have been successfully integrated within simulation programs have shown to exert a significant influence on simulation results. The overarching limitation of previously reviewed models concerns the simultaneous application of various occupant-based models in a whole-building simulation: the risk of incorrect data specification increases along with the number of individuals, nested controls and coupled domains increase.

3 Advanced occupancy-based control within whole-building energy simulation

The preceding chapter discussed the benefits of coupling advanced behavioural models, such as the Lightswitch2002 algorithm, with Radiance-based lighting simulation methods, such as DAYSIM. This coupling provides short term, dynamic and stochastic variations in simulated lighting conditions, subsequently affecting simulated lighting energy use. As shown, the Lightswitch2002 algorithm simulates user behaviour with regards to two distinct, albeit related, environmental devices: window blinds and lighting fixtures; both affecting user-sensed illuminance. Fortunately, window blind properties (e.g. slat angle, reflectance), artificial lighting features (e.g. distribution) as well as related lighting controls (e.g. photocell dimming control) can all be accurately modelled within single-domain applications (e.g. Radiance-based lighting simulation programs). This chapter presents SHOCC (sub-hourly occupancy control): a new self-contained, whole-building energy simulation module that is concerned with all building occupant related events.

3.1 Sub-hourly occupancy control (SHOCC)

SHOCC (Sub-Hourly Occupancy Control) is a self-contained simulation module that targets all occupancy-related phenomena in whole-building energy simulation. Its design is based on a critique of existing occupancy-related models reviewed in the preceding chapter. SHOCC's design goes beyond a number of concepts traditionally used in whole-building energy simulation when dealing with occupancy-related definitions, such as diversity factors and profiles. It instead focuses on suitable techniques to facilitate data management and exchange between various technical domains within whole-building energy simulation. Many of its underlying concepts are inspired from the Lightswitch2002/DAYSIM coupling, although it largely operates in abstraction to any given behavioural model. The following present SHOCC's key concepts and underlying assumptions.

3.1.1 SHOCC: underlying concepts and assumptions

3.1.1.1 Granularity and expandability

SHOCC's design goes beyond the traditional concept of merely modelling the state of clustered objects rather than the individual objects themselves. For instance, rather than tracking lumped heat injections from a group of occupants or a set of PCs, SHOCC instead tracks individual instances of occupants and occupant-controlled objects, the state of which depends on personal mobility and control. As discussed later on, such granularity has not been shown to produce any significant computational penalties, given the current capabilities of modern day personal computers. Coded in ANSI C (Kernighan and Ritchie 1988), SHOCC makes use of dynamic memory management and as such, the number of individual instances (e.g. occupants, lights, PCs, etc.) in SHOCC is virtually boundless and only practically limited to a computer's physical memory. SHOCC is fully expandable, and can be as detailed as it needs to be for any given energy simulation.

3.1.1.2 Abstraction

Most of the functionality needed for tracking occupant-controlled objects, whether through simple control laws or advanced behavioural algorithms, is common to most models. For instance, knowing the current number of individuals within a space at any given time and how long it's been since the last occupant left are both useful for any occupant-based control model, whether it is for lighting, ventilation, or IT equipment use. SHOCC is largely conceived in abstraction of specific behavioural models, yet is designed with expansion in mind so as to accommodate model-specific concepts in the future. It is hoped that this eases future development through code reusability.

3.1.1.3 Self-containment

Rather than burdening current whole building energy simulation programs with the additional required functionality, which can spread over many technical domains, SHOCC is instead designed as a self-contained simulation module that is concerned with all building occupant related events in a building. As such, SHOCC can be integrated within different whole building energy simulation programs with very few changes in either application. This modular approach facilitates future code maintenance and upgrades.

3.1.1.4 Encapsulation

SHOCC adopts an encapsulated, object-based approach in its representation of the entities of interest, as illustrated in Figure 5. Using population, lighting and IT equipment as examples, the self-contained structures on the left would represent a few instances of related information packets, such as psycho-social traits or physiological attributes for individuals, or power features for lighting and equipment. These packets are in turn encapsulated as to constitute an individual or a lighting fixture or a personal computer, as illustrated by the central figure. Finally, individuals, lighting fixtures and computers are grouped into clusters to facilitate data sharing and common functionality, such as scheduling and control, as indicated on the right. An example of appropriate clustering scheme for population would be differentiating students from teachers within classrooms. Another would be to differentiate overhead- from task-lighting. SHOCC objects populate SHOCC spaces, which together constitute building thermal zones within a SHOCC project.

3.1.1.5 Modularity

For every instance of encapsulation, a routine library is provided to probe and update specific bits of information within the self-contained data structures through a high-level interface; a common technique in object-oriented programming based on encapsulation and internal methods. SHOCC library function calls can be as intuitive as, in the case of population, "is anyone currently in?" or "how long ago has this individual left?" The high-level libraries constitute the basic building blocks of advanced controls in SHOCC, such as occupancy-sensing controls, advanced power management (APM) profiles (Roberson et al. 2002), and even advanced behavioural models. The Lightswitch2002 algorithms, for instance, are enabled in SHOCC as one out of many self-contained control libraries.

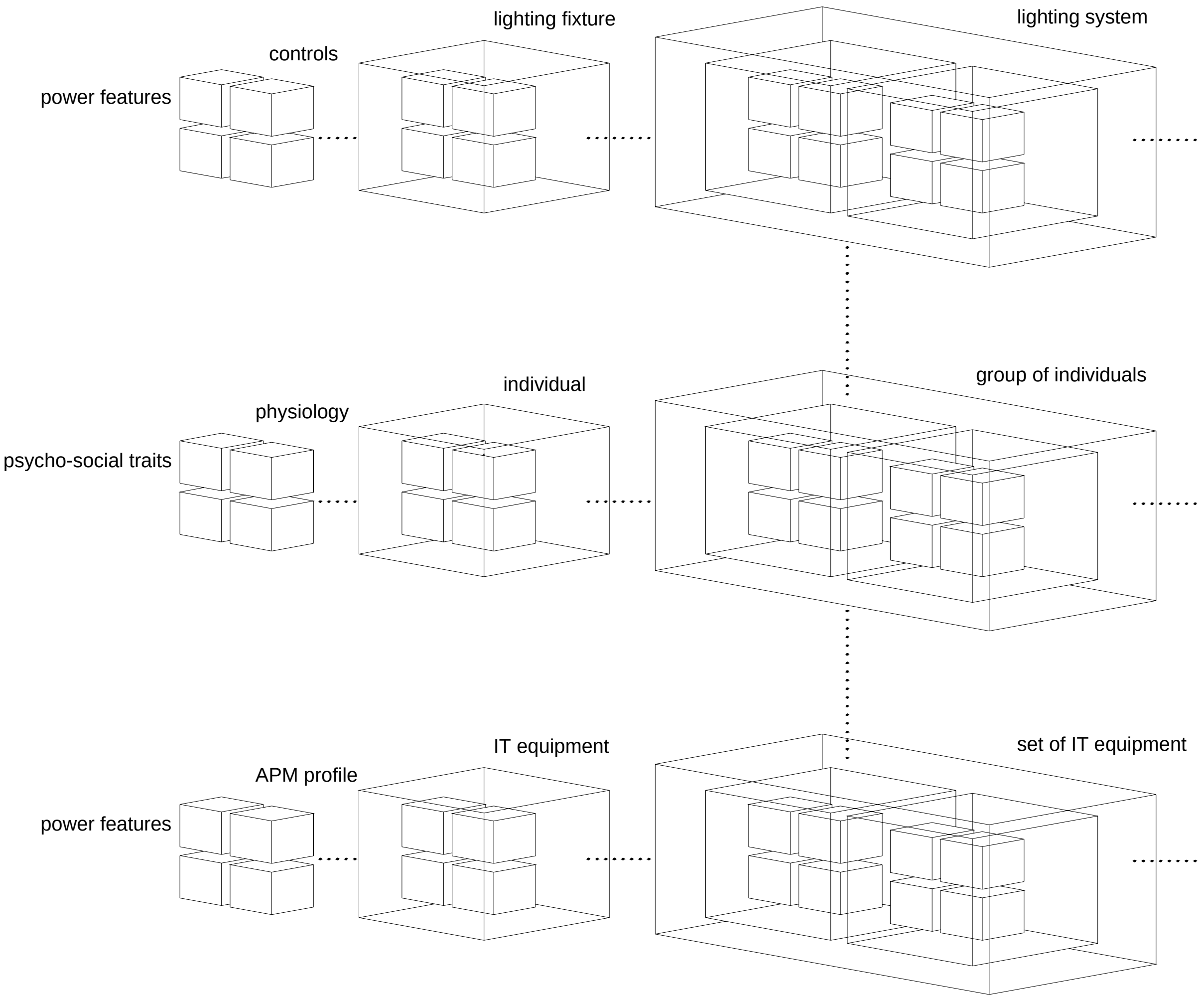

Figure 5 Example of SHOCC data encapsulation

This modular approach also facilitates future code maintenance. For instance, as our understanding of occupant response and behaviour towards lighting systems progresses over time, changes can be brought to the Lightswitch2002 algorithms without ever changing SHOCC lighting system definitions, functionality or interfacing. Conversely, lighting systems can be redefined in SHOCC, without ever changing the Lightswitch2002 algorithms. To make this code maintenance as trouble-free as possible in the future, rules must be set in how access to various entities is provided. For instance, as illustrated by the dotted connections in Figure 5, various groups of people may control a room's lighting system, without ever having access to the technical aspects of a lighting system or fixture, such as photocell-controlled dimming parameters.

3.1.2 Predicting population mobility in SHOCC

Although there are a few published techniques that could be used to predict individual, short-term occupancies (Wang et al. 2005, Nassar and Nada 2003), the population predictor used in the Lightswitch2002 algorithm, an adapted version of Newsham et al.'s original Lightswitch model (Newsham et al. 1995), is considered as the sole method of predicting individual occupancies in SHOCC within the scope of this thesis. The model requires as input mean arrival and departure times, as well as the duration of meals and mid-shift breaks. By assuming a Gaussian distribution of random variations in arrival and departure times over a given time interval (e.g. ±15 minutes), the predictor assigns realistic variations in daily events. For instance, if the mean arrival time on Mondays is assumed to be 8:30, then an occupant may just as easily arrive at 8:23 on one day and arrive at 8:37 on the following day, and in very rare cases at 8:15 or 8:45 (assuming a ±15 minute interval). As SHOCC can take into account more than one group occupant, individual occupancies are computed based on common group scheduling data. For instance, two group occupants sharing the same scheduling data will arrive at slightly different times on each day, with temporary absenteeism adjusted accordingly.

3.1.3 Defining personal control in SHOCC

SHOCC features allow differentiation between groups in a given space, as well as individual occupants within groups, when it comes to attributing control over specific entities. This is mainly achieved through keyword input. For instance, control over individual "computers" in a school lab can automatically be attributed to *every* single "student" arriving in the lab at different instances during the day, as illustrated in Figure 6(a). This way, plug loads in the lab will vary according to short term changes in individual occupancies. Similarly, control over "lights" can be attributed to *any* "student" occupying the lab, as indicated in Figure 6(b). This *any/every* differentiation mechanism is used in SHOCC in abstraction of controlled entities.

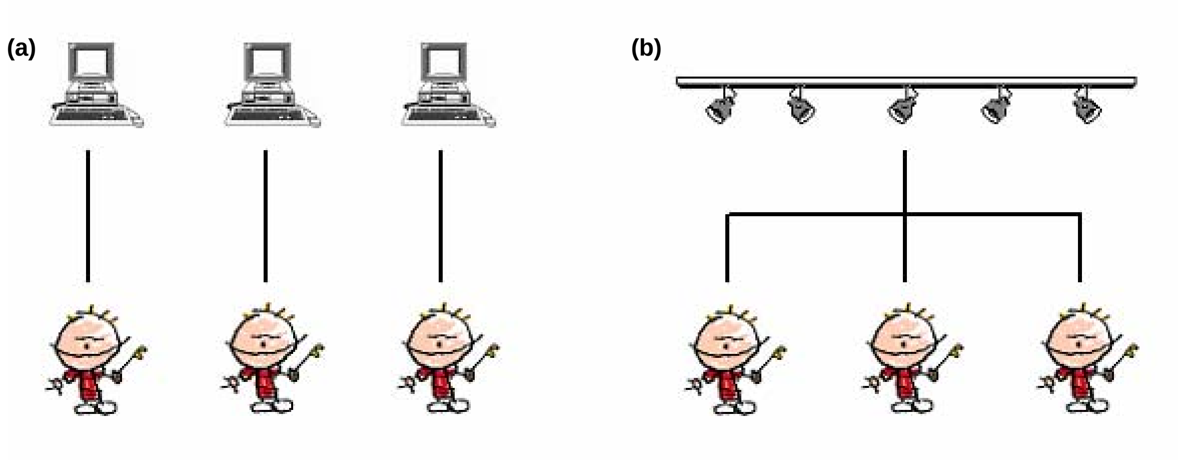

Figure 6 Control attribution in SHOCC: (a) *every* "student" controlling individual "computers"; (b) any "student" controlling "lights"

3.1.3.1 Occupancy-sensing control

In some cases, the mere presence – or absence - of occupants can drive the use of certain devices. Examples include occupancy-sensing lighting controls, demand-controlled ventilation based on metabolic carbon dioxide emissions, and the automatic powering-off of PCs when left unattended, e.g. by severing feed to display monitors based on factory-set advanced power management (APM) profiles. In the case of personal computers, determining the short term heat output may be difficult. First, the literature does not reveal any reliable field-based statistics on user behaviour, e.g. the probability of office workers consciously switching-off their computers when leaving for the day. Second, there does not appear to be any straightforward way to determine their instantaneous electrical load and related heat output when in use. For instance, the total energy expenditure and related heat output of a photocopy machine will directly depend on the number of copied items over a given time frame. Even a small laptop will give off variable rates of heat depending on its use (e.g. gaming versus word-processing). Until more reliable information in this regard is made available, the postulate in SHOCC is that equipment units are considered to be in use if any designated *controllers* (i.e. occupants) are present, and corollary to this is that they start powering down once *controllers* leave. In addition, the time-dependent energy expenditure of equipment is solely based on averaged data published in engineering handbooks (ASHRAE 2001) as well as common factory-set APM profiles (Roberson et al.

2002). Both postulates are somewhat simplistic, as it is quite possible that people may indeed be at their workstations while their PCs are off, or powering down, or that APM profiles are disabled thereby leaving PCs on during prolonged periods.

3.1.3.2 Enabling advanced behavioural models

The preceding section presents how SHOCC computes *unit* status and output at simulation run-time for entities that do not have any associated field-based behavioural model, e.g. personal computers. Additional control options are available in SHOCC for advanced behavioural models, such as the Lightswitch2002 algorithm[7]. To ensure code portability, behavioural models such as the Lightswitch2002 algorithm are deprived of any direct SHOCC data access; instead the functions can only process data sent as arguments by SHOCC and subsequently return one or more *replies* (e.g. blinds *lowered/retracted*).

As reviewed earlier (see 2.2.2.3), personal control over lights and blinds has been shown to differ whether users are considered *active* versus *passive* controllers. The working hypothesis in SHOCC is that any *active* controller has supervisory control over units (e.g. blinds) when concurrently sharing control with any number of *passive* controllers. This way, personal control resulting from the social interactions of many is collapsed to the behaviour of the dominant controller. This produces three possibilities of *active*/*passive* cohabitation to consider: *active* controllers only; *passive* controllers only; and the *asynchronous cohabitation* of both *active* and *passive* controllers. The outcome may differ depending on occupancy patterns. The frequency distribution of active/passive users within a group is inputted as a simple probability. For instance, if the probability of group occupants being active light users is inputted as 75%, then for every four occupants within a group, three will be labelled as *active*, and the fourth as *passive*.

SHOCC requires similar assumptions when considering multiple entities that can affect a single independent variable for a given behavioural model. In the case of lighting control, the original Lightswitch2002 algorithm predicts several distinct behavioural patterns given different combinations of lighting controls (e.g. manual on/off, dimmed, occupancy-

---

[7] The Lightswitch2002 algorithm also covers automated blind control which aims at optimizing daylight availability while avoiding direct glare. This is not developed in the current SHOCC version

sensing, etc.), user types (e.g. active/passive) and occupancy events (e.g. arrival, temporary absenteeism, departure, etc.). For instance, an office environment can easily be equipped with task lights in addition to overhead lighting. Both lights provide artificial illuminance (e.g. sensed at the desk-level), an independent variable to the Lightswitch2002 algorithm. This produces two difficulties. First, the literature does not provide much insight on behavioural patterns (e.g. manual on/off switching) dealing with more than one artificial light source. Just as with equipment and blinds, it is necessary to compensate this lack of information from field studies by providing a simple mechanism to resolve arising conflicts of cohabitating lighting systems. The postulate in SHOCC is that for similarly described systems (e.g. manual on/off control), simple input precedence is used to process control in order. The second difficulty with cohabitating systems is a potentially-conflicting feedback loop whereby the outputs of at least two automated systems interact with one another. For instance, two separate lighting systems furbished with photocell-controlled dimming technology, yet with different lighting setpoints, will process the same signal (e.g. sensed illuminance) differently, likely leading to the higher-set system reaching its designed output, while the other powers off or falls to minimal settings. Obviously, such a mismatch should be labelled as *poor* lighting design, although it would be rarely encountered in real life, even be considered a freak occurrence. Nonetheless, just as it is possible to make mistakes within the design process, it should be possible to model the same mistakes in a virtual environment. This principle should be embraced rather than rejected, and so by design SHOCC does not impose any limitations in this regard.

Rules must nonetheless be set to sequentially process various cohabitating systems, in this case lighting: SHOCC first processes lighting controls that do not consider sensed illuminance, either by photocells or by the controlling dominant occupant. This includes manual off-switching behaviour when leaving, as well as occupancy-sensing control (i.e. power off or power up). These controls are processed first as their resulting output remains fixed for the current time step. Next, SHOCC processes occupancy-sensing control (i.e. power-up) with dimming capabilities. The logic here is that these systems will automatically power up once someone arrives/returns regardless if additional illuminance is actually required. SHOCC then processes dimmed systems which are already on, based on the resulting illuminance. At the exception of manual off-switching when leaving, only automated controls have been considered up to this point, since their signal processing (e.g. occupancy-sensing, photocell-sensed illuminance) and subsequent actuation (e.g. on/off switching, dimming, etc.) is executed in a fraction of the time it takes an occupant to process the resulting desk-level illuminance. At this point, any manual on-switching behaviour is processed, finally followed by subsequent corrections from any dimmed systems which remain on; an automated response to manual settings. A more detailed presentation of SHOCC data flow, with examples, is presented in Appendix A.

3.1.4 Coupling SHOCC and whole building energy simulation

The preceding sections mainly dealt with the internal concepts and organizational principles of SHOCC, e.g. how occupant mobility is predicted. This section describes how SHOCC is coupled to whole building energy simulation, namely ESP-r.

3.1.4.1 ESP-r time flow

The basic run-time operation of ESP-r is described in Figure 7a. At every time step (*time t*, then *time t+dt*, then *time t+2dt*, and so on), the ESP-r simulator sequentially updates boundary conditions for each technical domain, computes new domain solutions, and moves on to solve the next domain equations, often sending the preceding solutions as boundary conditions for the next set of domain equations to solve. This process is repeated until the end of the simulation. In the figure, only a few domains of note are illustrated, with the dark areas in each domain symbolizing the parts of the code which can be considered as occupancy-related. Pertaining to lighting control, the status of each transparent surface (i.e. blinds open/drawn) is determined during the solar calculations; which becomes input for natural illuminance calculations, required to set lighting output during casual gain computations. Data is passed from one domain to another by directly accessing global data structures, as illustrated by the connection between solar and lighting domains.

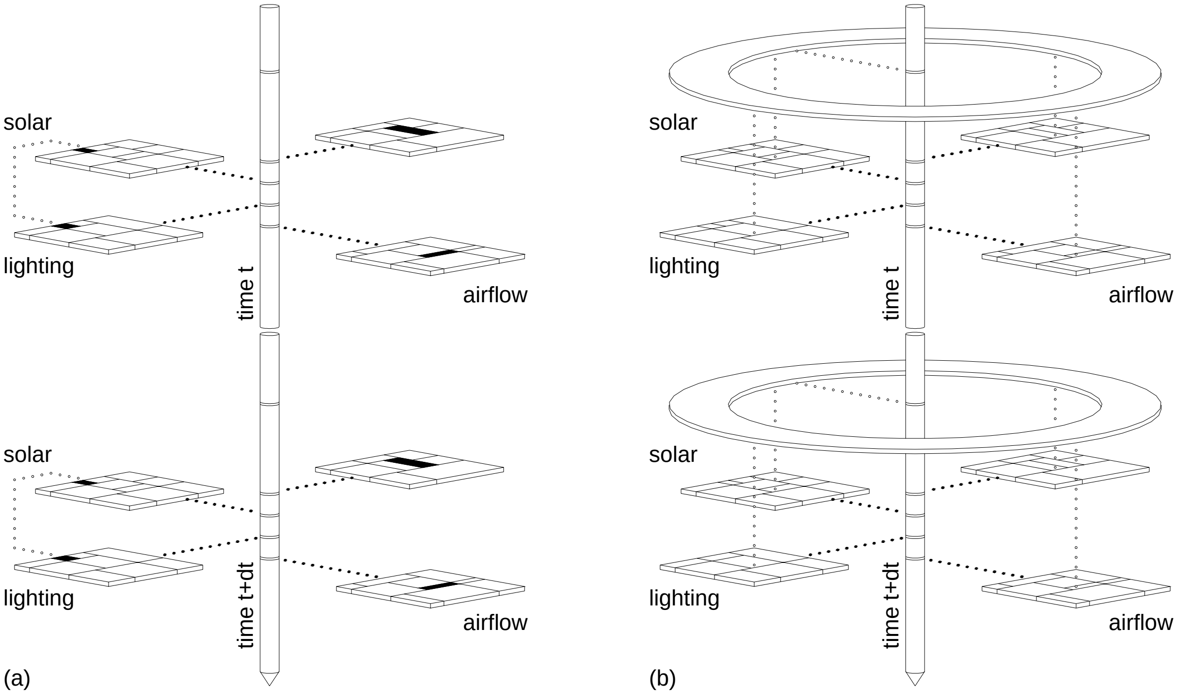

Figure 7 ESP-r simulator's sequential run-time access to technical domains; and b - same process but with SHOCC enabled

3.1.4.2 Linking SHOCC

ESP-r and SHOCC can be largely considered as parallel applications which share only the same number of thermal zones as well as a number of matching ID strings, providing a means of linking paired ESP-r and SHOCC entities. For instance, dynamically adding the heat output of SHOCC lighting systems over ESP-r-calculated heat injections, is done by defining matching ID strings to designate the same lumped heat injection (or casual gain, e.g. "Lights").

At the early stages of a design, it is typical to rely on basic definitions when running ESP-r, such as diversity factors. As the design evolves, and more information become available, one has the option of overriding basic definitions by enabling more complex calculation methods. This option is already available in ESP-r for advanced lighting control (overriding user-defined casual gains) and multizone airflow networks (overriding user-defined infiltration rates). SHOCC operates in a similar way, updating specific boundary conditions within targeted technical domains once SHOCC input is provided in a project model.

SHOCC itself does not control its own flow of time (e.g. over the course of an annual simulation); rather it requires as input, and at every simulation time step, both *current* and *past current* times, the latter being the current time at the preceding time step. These inputs are computed by the parent program (e.g. ESP-r). The difference between *past* and *current* time determines the temporal interval used to increment or decrement past and future events, such as the time remaining before an occupant leaves, or before an occupant is expected to arrive. More on ESP-r's use of past and current time in its numerical solutions is provided in (Clarke 2001); suffice to state at this point that both *times* are updated and made available at any given moment during simulation within ESP-r.

ESP-r follows a logical sequence of technical domain processing/solving, starting with solar processes. It is within each technical domain that SHOCC can be called to reset the state of an occupant-based parameter. First, the ESP-r simulator calls SHOCC directly to update the status of its own internal representations of occupants, e.g. daily arrivals and departures, short-term mobility at every time step, etc. Then SHOCC is called to update and retrieve only specific bits of information useful to a given technical domain. For instance, SHOCC is called during the casual gain calculations a first time to update the status of its own internal representations of IT equipment and lighting systems, and then called a second time to send back the summed heat injections and/or electrical loads of these systems for ESP-r's own computations. Data exchange between technical domains, at least data associated to occupants, is no longer done directly as in Figure 7a, but rather via SHOCC. The advantage of the latter approach is that data pertaining to occupants, e.g. mobility, behavioural control, etc., are no longer spread throughout ESP-r's technical domains, minimizing the aforementioned risk of incorrect data specification. As SHOCC is fully expandable, this approach offers a high degree of resolution for populating a building model without this being cumbersome for energy simulation programs. Technical details of SHOCC's integration within ESP-r are provided in Appendix B.

3.2 Discussion

This chapter introduces SHOCC (Sub-Hourly Occupancy Control): a self-contained simulation module that targets all occupancy-based control within whole-building energy simulation. Its underlying concepts and assumptions are discussed in detail. The chapter also describes the approaches used to integrate detailed population prediction models within SHOCC, and how various control options can be used to describe a wide variety of real-world situations. The chapter ends with a description of the dynamic coupling of SHOCC and ESP-r.

It may be questionable whether simulation users can afford the extra computational time associated to such high-resolution, high frequency processes. Yet in relation to whole-building energy simulation processes, SHOCC computations appear to be minor. ESP-r's advanced daylighting calculations and thermal processes will likely overwhelm additional SHOCC computations. The following chapter describes an ESP-r model of a single office used to demonstrate SHOCC capabilities. On an IBM ThinkPad equipped with 1.4GHz Intel Pentium M processor and 768MB of RAM, an annual *unSHOCC'ed* simulation takes 2 minutes 39.8 seconds to complete, based on the output of the UNIX *time* utility. Once *SHOCC'ed* with a single occupant controlling a laptop computer and window blinds, the simulation requires an additional 2.9 seconds to complete; a computational penalty of less than 2%.

3.3 Summary

A new occupancy-based simulation module is introduced and its underlying concepts and assumptions are discussed. Its use of an advanced population predictor as well as advanced behavioural models is described, as well as its coupling with a whole-building energy simulation program.

4 The total energy impact of manual and automated lighting control

Based on the developmental work described in the preceding chapter, namely the development of SHOCC, the addition of detailed population prediction, occupancy-sensing control and advanced behavioural modelling as well as the coupling of SHOCC and ESP-r, this chapter presents a series of example applications focusing on the total energy impact of manual and automated lighting control.

4.1 Purpose of the investigation

The influence of user behaviour on whole-building energy use is illustrated through limited ESP-r/SHOCC/Lightswitch2002-coupled simulations. This demonstration is useful is several ways, namely by:

1. Demonstrating the usefulness of SHOCC;
2. Pursuing Reinhart's initial investigation on the influence of user behaviour on electric lighting use (Reinhart 2004) by assessing whole-building energy use, including heating and cooling requirements; and
3. Establishing a more accurate estimate of internal loads (e.g. metabolic heat, IT equipment, lighting) pertaining to peripheral zones, i.e. environments where operable window use and adaptive comfort control can occur. This will be established later in the thesis as being a key parameter when assessing the energy impact of other behavioural patterns, such as operable window use and adaptive comfort control.

4.2 Scope of the investigation

The chosen test case is a single occupancy perimeter office. Three control options are investigated:

- *Constant* – continual overhead lighting use during occupied hours, without blinds;
- *Manual* – occupant-controlled ON/OFF light switching, with manual control over blinds; and
- *Automated* – occupant-controlled ON/OFF light switching with ideal dimming and occupancy-sensing OFF switching, with manual control over blinds.

The first option is chosen as a basic reference, evocative of lighting use in core zones, yet commonly used in practice for perimeter zones as well. The second option relies on the Lightswitch2002 behavioural models for manual light switching and blind control. As discussed in Reinhart (2004), *manual* control is considered by the Illuminating Engineering Society of North America (IESNA) as "the most common practice and should function as a reference system, relative to which energy savings of *automated* lighting controls should be expressed" (IESNA 2000). Depending on which reference system is chosen, *constant* or *manual*, estimated energy savings from *automated* control may differ.

All simulations are carried out using a 5-minute time-step; a suitable frequency to capture short-term occupancy patterns and dynamic responses to luminous conditions. All three control options are investigated for two locations: Québec City, Canada (heating dominant) and Rome, Italy (cooling dominant). The Québec climate file used for the demonstration can de downloaded from the CANMET Energy Technology Centre's (CETC) Buildings Group's Hot3000 web site[8], while the Rome climate file is included in the ESP-r package, which can be downloaded at the University of Strathclyde's Energy Systems Research Unit (ESRU) web site[9].

4.3 Model description

The office's south facing wall (3m x 3m) is in contact with the outdoor environment, while interior partitions, ceiling and floor are considered to be in an adiabatic state with similar indoor conditions. A cross-section of the office is provided in Figure 8. Although access to outside views in office environments is rarely regulated, and specifically not in Canada, the south facing wall integrates a wood-framed, insulated double glazing unit (DGU), with size and placement (e.g. height from floor, width, etc.) matching the prescriptive requirements of the German standard DIN 5035 (1990). This is an attempt to fix the window's geometry within the scope of this study, regardless of office lighting/climate-control energy use. The DGU is provided with a spectrally-selective low-e coating on the interior face of the outer pane. Variations in blind position, i.e. drawn or retracted, are simulated in ESP-r by alternately choosing paired optical data sets, illustrated in Figure 9a and Figure 9b. The

---

[8] www.buildingsgroup.nrcan.gc.ca/software/hot3000_e.html

DGU's visual transmittance (VT) is 69% when blinds are retracted, and drops to 15% when blinds are drawn.

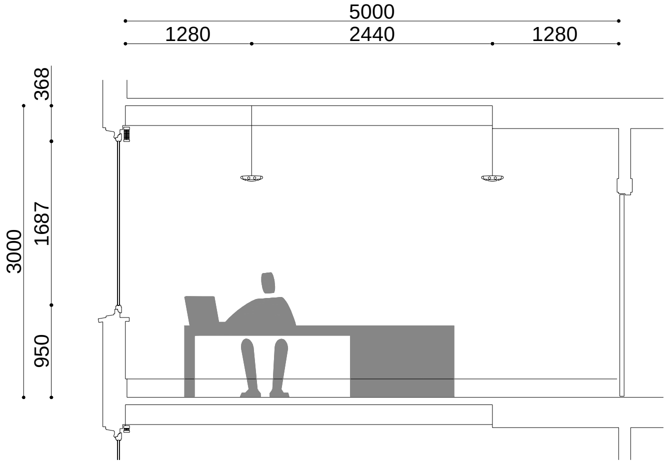

Figure 8 Cross-section of modelled test office (dimensions in mm)

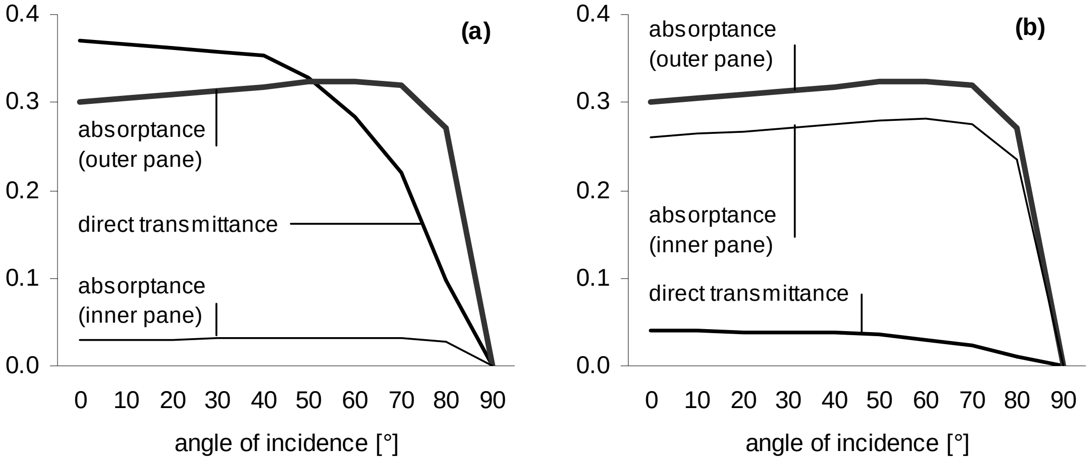

Figure 9a Direct solar transmittances and pane absorptances for the chosen double-glazing unit (DGU), when blinds are retracted; and b when blinds are drawn.

Preliminary simulations show that by lowering blinds, absorbed solar heat gain in the office only drops slightly given the initial solar performance of the glazing assembly and the limited secondary heat rejection capabilities of interior blinds. The increase in artificial

---

[9] www.esru.strath.ac.uk

lighting use, due to the drop in the DGU's VT when blinds are drawn, is found to be a much more significant factor in total energy expenditure than solar absorption patterns in the office. For this reason, *manual* light control and blind control are considered to go hand in hand within the scope of this demonstration. All multilayered constructions, as detailed in Table 2, conform to prescriptive requirements of the Model National Energy Code of Canada for Buildings (MNECB 1997) and the Regulation Respecting Energy Conservation in New Buildings in Québec (RRECNB 1992).

In all simulated cases, a SHOCC individual occupies the space on weekdays, typically arriving at 08:30 and then leaving at 17:00, with lunch and morning/afternoon breaks splitting the time spent in the office cell into four equal shifts. Stochastic variations in daily occupancy patterns, based on the Lightswitch2002 occupancy predictor, add realism to the simulation as presented in the preceding chapter. In cases where *manual* control is enabled using the Lightswitch2002 algorithm, it is assumed that the individual indeed considers daylight and adjusts blind and lighting settings accordingly (i.e. *active* lighting and blind control).

Table 2 Multilayered construction of exterior and interior assemblies

Assembly	material description	thickness
outside wall	wood siding air mineral fibre insulation gypsum plasterboard mineral fibre insulation gypsum plasterboard air off-white gypsum plasterboard	19 mm 19 mm 38 mm 13 mm 75 mm 13 mm 19 mm 13 mm
inside walls	off-white gypsum plasterboard mineral fibre insulation[10] off-white gypsum plasterboard	13 mm 75 mm 13 mm
floor-to-ceiling	rubber tile light mix concrete Plywood air white gypsum plasterboard	03 mm 50 mm 16 mm 19 mm 13 mm

---

[10] Insulation filling 38x89@406mm wood stud cavity; thickness adjusted to account for thermal bridging.

As presented in the preceding chapter, the individual's presence produces metabolic heat injections in the office, and also triggers the use of a laptop computer, which in turn injects additional convective and radiant heat in the office. When left unused, the laptop powers down to factory-set rates. As scheduling is the same in all simulated cases, annual heat injections from the individual and the laptop would remain equally constant. This produces an average annual metabolic heat injection of 128.4 kWh in the sensible range, and an average annual injection of 72.0 kWh for the laptop.

The study specifically targets loads directly influencing the luminous and thermal conditions within the office. This includes energy required for operational tasks, e.g. overhead lighting and the laptop, as well as heating and cooling requirements. Space heating is provided locally through a hot-water baseboard heating system, while cooling is provided through a local AC unit. All other loads, such as the energy required for primary air conditioning, hot water heating, IT servers, elevators, etc., are not simulated. Primary air is nonetheless delivered at a constant 21°C at a rate of 10 L/s (weekdays, from 7:00 am to 8:00 pm), which is indicative of a dedicated outdoor air delivery approach. Background infiltration is set at a constant 0.25 L/s per m² of building envelope area. Overhead lighting is provided through fluorescent fixtures, with a nominal lighting density of 15 W/m². Desk-level natural illuminance is computed using ESP-r's Radiance-based daylight coefficient method (Janak and Macdonald 1999, Janak 1997).

4.4 Results

Annual estimated electrical energy use for lighting, as well as cooling and heating requirements, are presented in Figure 10 for Rome, and in Figure 11 for Quebec.

4.4.1 Lighting

As *constant* lighting output is predefined independently of any meteorological boundary conditions, e.g. natural illuminance available in the room, annual lighting use is set equal for both climates, representing 38.1 kWh/m² per year. Once SHOCC enables *manual* control over lights and blinds by accessing the Lightswitch2002 behavioural models, annual lighting use is reduced significantly, down to 8.1 kWh/m² per year in Rome and 8.6

kWh/m² per year in Québec. This represents less than 23% of the initial estimate in lighting use. If *automated* lighting control is added to *manual* control, then lighting energy use is further reduced to 0.8 kWh/m² is Rome and 2.0 kWh/m² in Québec. In both *manual* and *automated* control options, lighting use is less in Rome given the greater daylight availability. If energy savings from automated lighting controls are to be expressed as relative to some previously-defined reference case, as suggested by IESNA guidelines, then results in both figures clearly underline just how significant the selection of the reference case may be in this instance, as both *manual* control and *constant* lighting use are often considered as valid choices in simulation practice.

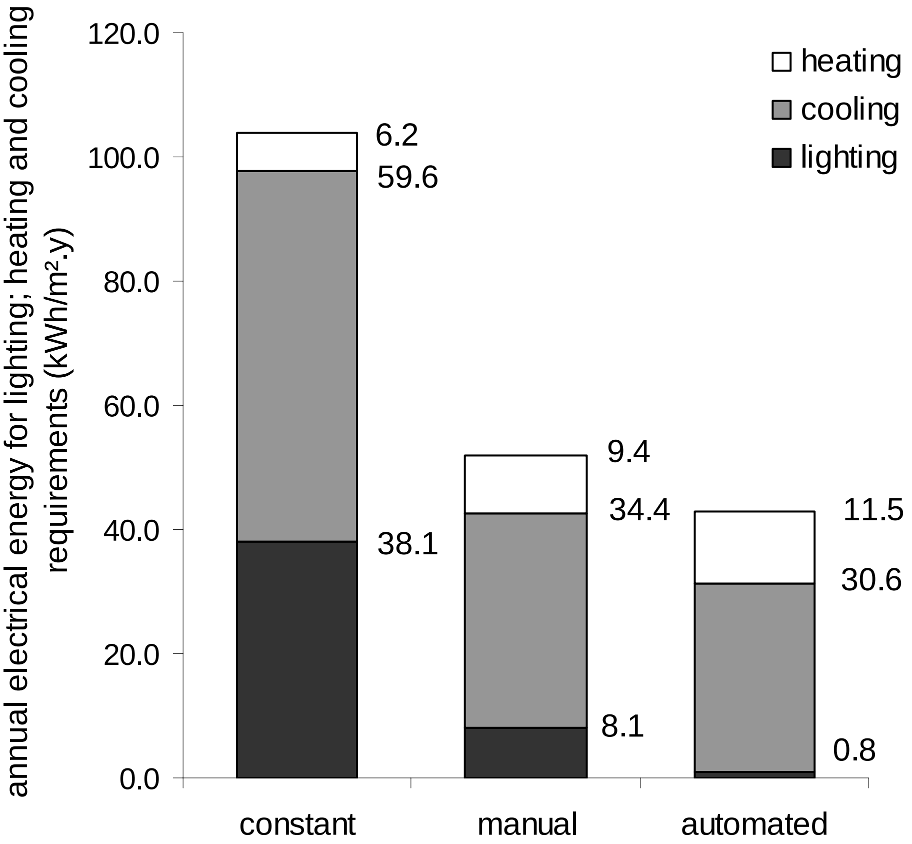

Figure 10 Simulated annual electrical energy for lighting, cooling requirements and heating requirements (kWh/m².y) for various lighting control options in Rome

4.4.2 Cooling

Cooling requirements, i.e. energy extracted to maintain office indoor temperatures below defined setpoints, are strongly affected by *constant* lighting use in Rome and Québec. Once *manual* control is enabled, cooling requirements in both cases drop dramatically; down to 58% of initial estimates for Rome, and 43% for Québec. Likewise, once *automated* controls are added, cooling requirements are further reduced to 51% of initial estimates for Rome, and 38% for Québec. Results support general knowledge that any reduction in lighting use will in turn reduce cooling requirements; amplifying the initial savings in lighting energy use alone. This amplification is well supported, independently of meteorological boundary conditions. By comparing the savings in lighting energy use, i.e. *automated* versus *manual* control, to related reductions in cooling requirements, it can be established that the amplification isn't linear. In general, it appears likely that anticipated reductions in cooling requirements are likely to flatten out along with incremental improvements in lighting technology and control.

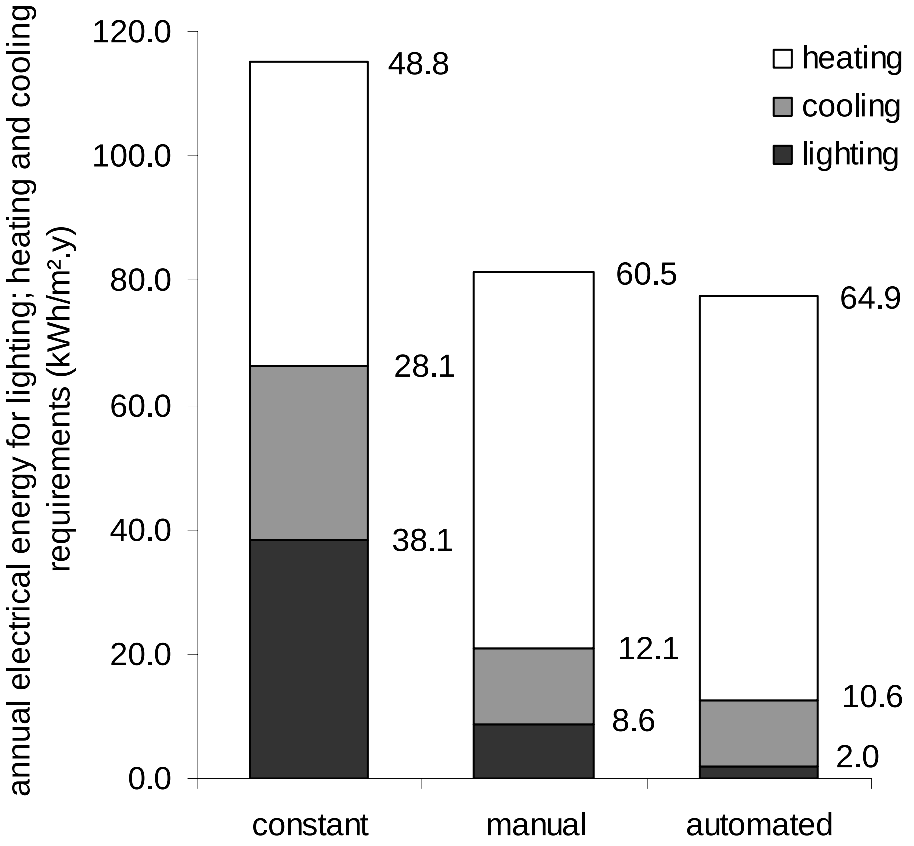

Figure 11 Simulated annual electrical energy for lighting, cooling requirements and heating requirements (kWh/m².y) for various lighting control options in Québec

4.4.3 Heating

A portion of the estimated savings in annual lighting energy use effectively reduces cooling requirements, as discussed in the preceding section. The remaining portion is either influencing the extent of the free-running period for the investigated office, i.e. when neither cooling nor heating are required to stabilize indoor temperatures, or otherwise producing an increase in annual heating requirements. The latter is observed for both locations. This reiterates general knowledge, at least in the north, that internal loads are sometimes useful in compensating heat loss through the building envelope. Just as with cooling requirements, the influence of reduced lighting use on heating requirements isn't linear, and increases in heating requirements are likely to flatten out along with incremental improvements in lighting solutions.

4.4.4 Primary energy use

Although reduced lighting use systematically lowers cooling requirements, heating increases by the same token. As the relationship between lighting use and energy required for indoor climate control appears to be non-linear, a single standard of measurement would be useful to compare the performance of advanced lighting control. As energy costs differ greatly between various locations in the world and usually depend on peak electricity demands as well, *primary* energy conversion is selected in the following for demonstration purposes only.

We refer as *primary*, energy which is embodied in natural resources and has not yet undergone any anthropogenic conversion or transformation. Buildings generally rely on the thermal output of fossil fuels (e.g. coal, oil and natural gas) for space and hot water heating, with distribution and system losses averaged around 10%. Other building end uses, such as lighting, cooling, ventilation, etc. operate on electricity, often generated by fossil fuel power plants. Mean conversion factors for fossil fuel power plants vary depending on a location's energy mix, but an average 3:1 ratio is widely accepted. Primary energy conversion factors can be estimated using publicly available programs and databases such as the Global Emission Model for Integrated Systems (GEMIS)[11]. Figure 12 and Figure 13

---

[11] www.oeko.de/service/gemis

provide the annual primary energy requirements for all three control options, when applied in Rome and Québec respectively, based on the aforementioned primary energy conversion factors for each end use and heating and cooling coefficients of performance (CoPs) of 1 and 3, respectively. The *total* primary energy requirements can be obtained by adding those for *lighting*, *cooling* and *heating*.

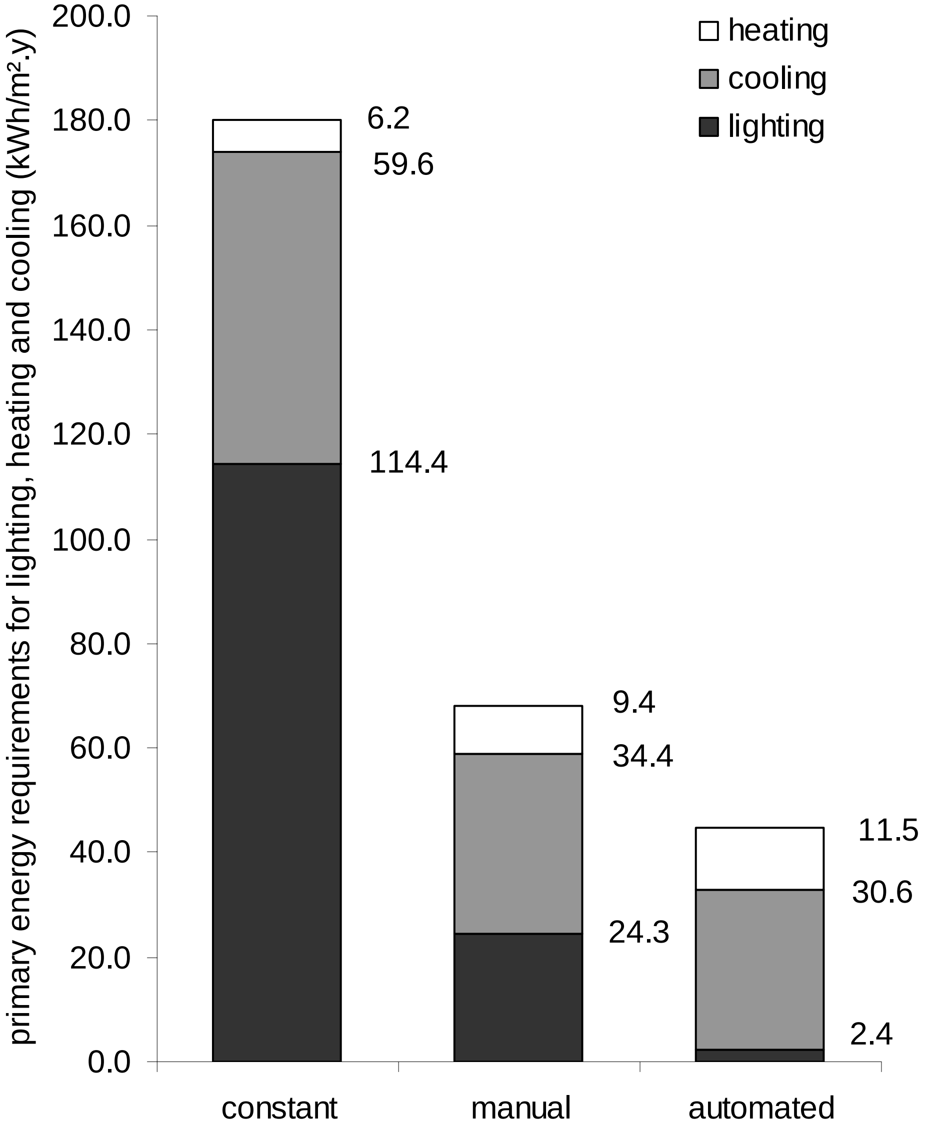

Figure 12 Annual primary energy requirements for lighting, cooling and heating, for various lighting control options in Rome

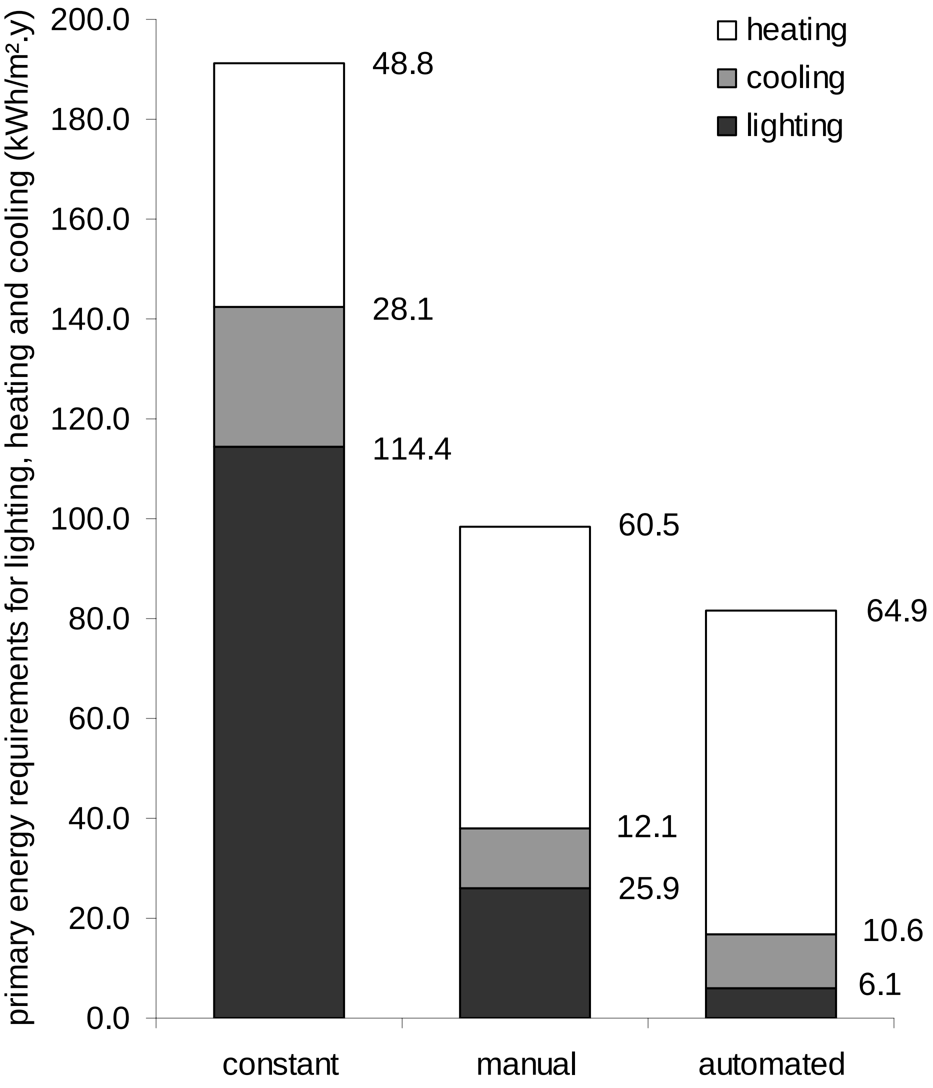

Figure 13 Annual primary energy requirements for lighting, cooling and heating, for various lighting control options in Québec

Under *constant* use, lighting energy overwhelms total primary energy requirements, comprising more than 60% of total requirements for both locations. Once *manual* lighting and blind control is enabled, total annual primary energy requirements drop to 68.1 kWh/m² for Rome; merely 38% of initial estimates under *constant* lighting use. In Québec, *manual* control reduces total primary energy requirements to 51% of initial estimates. The differences in total primary energy expenditure between *constant* and *manual* control reiterate the significance of selecting suitable reference cases against which should be compared the relative performance of automated lighting control. When *automated* control is applied in Rome, in addition to *manual* control alone, total primary energy savings in lighting are estimated at 21.9 kWh/m² per year. This produces cooling primary energy savings of 3.8 kWh/m² per year, while primary energy for heating increases by 2.1 kWh/m²; a net reduction of 1.7 kWh/m² per year for indoor climate control. In other words, the initial estimated savings in annual primary energy requirements for lighting, resulting from the introduction of *automated* lighting control, are amplified by approximately 8%, due to overall savings in primary energy requirements for indoor climate control.

When the same strategy is applied in Québec, annual primary energy savings in lighting are estimated at 19.8 kWh/m². Similarly, primary energy for cooling drops by 1.5 kWh/m², while primary energy for heating increases by 4.4 kWh/m²; a net increase of 2.9 kWh/m² per year for indoor climate control. In this instance, initial estimated savings in annual primary energy requirements for lighting, resulting from the introduction of *automated* lighting control, are no longer amplified but trimmed down by approximately 15%, due to the overall increase in primary energy requirements for climate control.

4.5 Discussion

Results show that by enabling manual lighting control in energy simulation through SHOCC, as opposed to using predefined core zone lighting diversity profiles, total primary energy expenditure is reduced by as much as 62%. This not only demonstrates the significance of advanced occupancy-based modelling in energy simulation, it underlines the importance of defining suitable reference cases for comparing the performance of automated lighting controls. In addition, results show that reduced lighting use through automated control may not always produce anticipated savings in primary energy for indoor climate control. In some cases, reduced lighting use is shown to even increase primary energy expenditure for indoor climate control, trimming down initial primary energy savings in lighting use alone.

Of course, the results would likely be different if, let's say, a location's primary energy mix were to be somewhat different. For instance in Québec, most of the electricity used in buildings is generated through hydroelectricity, with different conversion factors than with fossil fuel power generation (EQ 2001). In addition, electric-resistance heating is widely used in buildings in Québec for HVAC reheat applications (electrical heating coils) and zone requirements (baseboards heaters). Here, the *lighting:cooling:heating* ratio for primary energy conversion would likely be 3:1:3, rather than the initial 3:1:1. These differences would likely affect total primary energy savings linked to lighting technology. If on the other hand, heating requirements were to be met by local, ground-coupled heat exchangers on a water loop, once again both the ratio for primary energy conversion and the total primary energy savings would be different.

The argument to be made is that primary energy savings stemming from advanced lighting technology can hardly be estimated in isolation to indoor climate control strategies and system efficiencies, as well as a location's primary energy mix, supporting the need for integrated simulation. This also strongly supports the integration of advanced behavioural models, such as the Lightswitch2002 algorithm, to whole-building energy simulation, such as ESP-r; a demonstration of the usefulness of SHOCC.

This example application is also insightful as it informs us on the degree of uncertainty in lighting energy use in peripheral zones, and the subsequent influence this has on a room's thermal regime. If the energy impact of operable window behaviour is considered (which will be considered in the second part of this thesis), then accurately estimating internal loads (e.g. heat emitted from lighting fixtures) becomes critical. For instance, if internal loads are found to be generally high in a given room, then the additional air change rates from an opened window would likely be beneficial; providing a source of natural freecooling. If on the other hand internal loads are low, then the additional air change rates could possibly lead to greater heating requirements. The second part of this thesis addresses the energy impact of operable window behaviour as a function of these uncertainties.

4.6 Summary

The total energy impact of manual and automated lighting control has been investigated based on simulation studies using the new coupling of ESP-r, SHOCC and the Lightswitch2002 algorithm. Results demonstrate the significance of advanced occupancy-based modelling in energy simulation, and underline the importance of defining suitable reference cases for comparing the performance of automated lighting controls. Results also show that reduced lighting use through automated control may not always produce anticipated savings in primary energy for indoor climate control. In some cases, reduced lighting use is shown to even increase primary energy expenditure for indoor climate control, trimming down initial primary energy savings in lighting use alone. If the energy impact of operable window behaviour is considered (second part of this thesis), then accurately estimating internal loads (e.g. heat discarded from lighting fixtures as a function of behavioural models) becomes critical.

5 Personal control of hybrid ventilation in harsh climates

The second part of this thesis focuses on how the integrated SHOCC/ESP-r approach can be used to provide insight on the sustainability (e.g. energy saving potential or penalty) of novel yet untried strategies that rely on user interactions, such as adaptive comfort control through manual use of operable windows in hybrid environments. Before considering any new SHOCC/ESP-r development, it is first necessary to review the current knowledge on innovative developments in the area of occupant control over thermal environments, as well as the state-of-the-art in hybrid ventilation. The following chapter reviews current knowledge on thermal adaptation and associated control.

5.1 Hybrid Ventilation

Simply put, *ventilation* is the intentional introduction of air from the outside into a building. Historically, ventilation has served two purposes: (i) the removal or dilution of contaminants, odours and/or moisture to ensure proper indoor air quality (IAQ); and (ii) the provision a thermally-comfortable indoor environment (ASHRAE 2001).

Intentional airflow caused by wind pressures or by differences in indoor and outdoor temperature is referred to as *natural ventilation*, while airflow produced by fans is considered *mechanical ventilation*. *Infiltration* and *exfiltration* are distinguished from *natural ventilation* as unintentional air leakage from the building envelope (ASHRAE 2001). *Hybrid ventilation* – often referred to as *mixed-mode ventilation* - is essentially a combination of *natural* and *mechanical ventilation*. The approach used to deliver air within a room - whether *natural*, *mechanical* or *hybrid* – distinguishes *dilution ventilation*, where fresh air is considered to be fully mixed with room air, from *displacement ventilation*, where cool fresh air is distributed at the floor level then entrained by convection near warm bodies such as room occupants. However, this distinction is mainly theoretical; usually, there is always some dilution and convection occurring in actual conditions.

5.2 Energy considerations

In temperate climates, larger airflows generally improve both IAQ and comfort simultaneously. However, in regions characterized by climatic extremes, such as hot/arid, hot/humid or extreme cold conditions, greater ventilation rates are likely to increase energy consumption due to the excessive air-conditioning processes. In such instances, a balance is often sought between energy conservation on one hand and the health and well-being of occupants on the other. This dichotomy has remained the focus of much research and development in building science and industry since the sharp rise in oil prices in the 1970's.

Under the auspices of the International Energy Agency’s Implementing Agreement on Energy Conservation in Buildings and Community Systems (IEA-ECBCS), sixteen IEA countries participated from 1998 to 2002 in Annex 35: a research collaborative on *Hybrid Ventilation in New and Retrofitted Office Buildings*. The Annex 35 working definition of *hybrid ventilation* designates systems that "provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or season of the year" (Heiselberg 2002). Underlying this definition of hybrid ventilation are two chief concepts: first is the recognition that under suitable conditions, natural ventilation may be satisfactory - even preferable - for thermal comfort and indoor air quality, implying a potential decrease in the environmental impact of building operations. Second is the acknowledgement that supplementary mechanical systems - for fresh air distribution as well as climate control - *may* well be required during the harshest of conditions.

5.3 Principles

The extent to which natural forces are sufficient to meet various comfort and IAQ requirements largely depends on climate, as well as building design and operation. Given the number of combinatorial arrangements of building form, fabric, components and systems, the above definition does not adequately reveal the true diversity of hybrid solutions found in the Annex 35 literature[12], and so it has been found necessary to categorize hybrid solutions into three principles (Heiselberg 2002):

1. Natural and mechanical ventilation;
2. Fan-assisted natural ventilation; and
3. Stack- and wind-assisted mechanical ventilation

The *natural and mechanical ventilation* principle designates dual-mode systems where natural or mechanical ventilation are alternately chosen as the unique ventilation strategy. The I Guzzini Illuminazione Building (Figure 14) is an example of *natural and mechanical ventilation*. Here, natural ventilation is provided using the traditional perimeter air entry approach through operable windows. The building energy management system (BEMS) automatically reverts to mechanical ventilation and cooling once indoor temperatures exceed 25°C (Principi et al. 2002).

Figure 14 The I Guzzini Illuminazione Building, in Recanati (Macerata), Italy: an example of *natural and mechanical ventilation*

Air friction and contraction along ducts or through heating and cooling coils, energy recovery equipment, filters, etc. will produce what are referred to as *pressure losses*. These pressure losses may impede on the natural airflow within designed ventilation paths and

---

[12] hybvent.civil.auc.dk

mechanical fans are sometimes integrated to compensate such pressure losses. The distinction between *fan-assisted natural ventilation* and *stack- and wind-assisted mechanical ventilation* is made only on the relative importance of natural versus mechanical forces in compensating overall system pressure losses. *Fan-assisted natural ventilation* makes use of back-up mechanical fans strictly to compensate *occasional* insufficiencies of otherwise autonomous, naturally-driven ventilation systems, such as in the Bang and Olufsen Headquarter Building in Strier, Denmark (Hendriksen et al. 2002) (see Figure 15). In this project, fresh outdoor air is drawn through perimeter inlets, while return air is extracted through stairwell roof vents. When natural forces are insufficient to properly ventilate the offices, backup fans located in the roof vents are switched on.

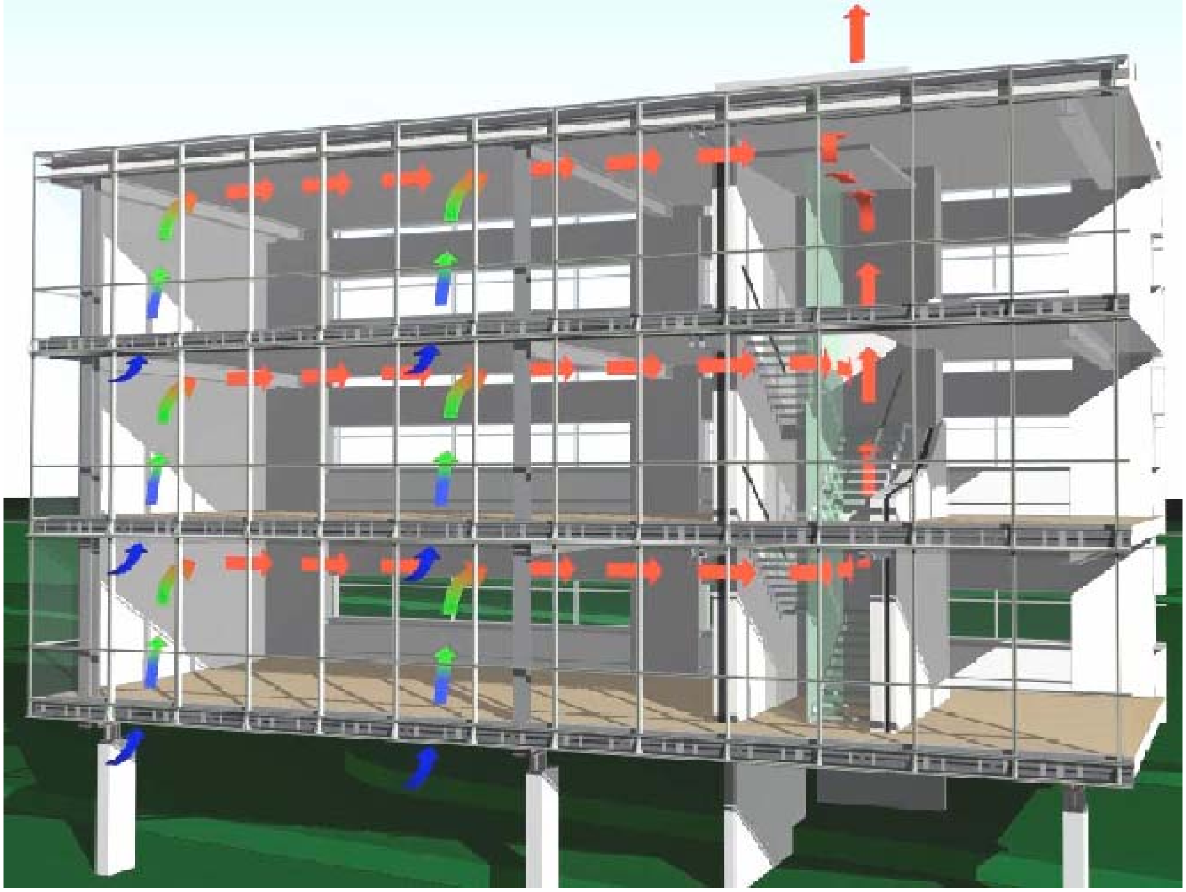

Figure 15 The Bang & Olufsen Headquarter in Strier, Denmark: an example of *fan-assisted natural ventilation*

S*tack- and wind-assisted mechanical ventilation* describes low-pressure mechanical ventilation systems that exploit available natural forces to *partly* offset overall system pressure losses, such as in the Media School in Grong, Norway (Tjelflaat 2002). In this project, fresh outdoor air is drawn from a distant vent (Figure 16, bottom-left picture), then channelled through an underground air culvert before being circulated within classrooms. Air is eventually fed through a continuous buffered skylight which acts as a continuous return air duct.

Figure 16 The Media School in Grong, Norway: an example of stack- and wind-assisted mechanical ventilation

5.4 How natural is hybrid?

Any system pressure losses hamper natural airflow. To what extent are available natural forces sufficient to compensate such system pressure losses? Schild (2001) explores this question through weather data analysis. Figure 17 illustrates the time distribution of natural pressures produced by wind and stack effects for six Norwegian cities, assuming a 10m high building. Based on these findings, Schild concludes that buildings in Norway must have airflow paths with pressure drops of less than 10 Pa to be truly considered naturally ventilated. In practice, it is virtually impossible to meet overall system pressure loss targets of ~10 Pa when considering major air conditioning equipment. In the case of the Media School, a run-around heat recovery system generates total pressure losses of 53 Pa, with filters adding another 20 Pa (Schild 2001). It is for this reason that the Media School can be considered a case of *stack- and wind-assisted mechanical ventilation*; with similar system pressure losses, *back-up* fans in *fan-assisted natural ventilation* would constantly be *backing-up*.

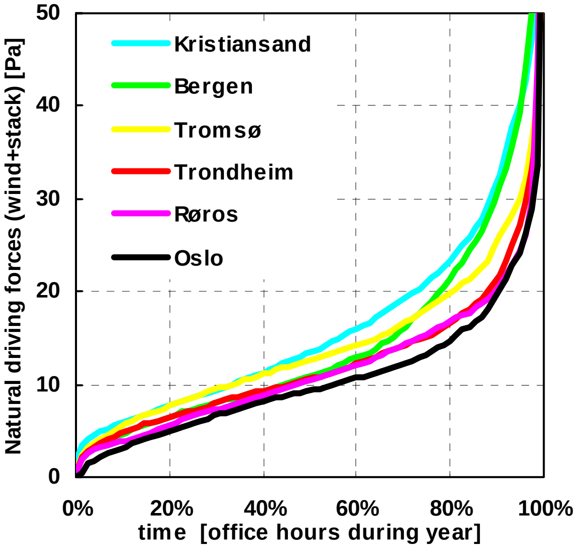

Figure 17 Time distribution of available natural ventilation pressures during working hours for six Norwegian cities. Output from program *COMISweather*[13]. Used with permission from author Peter G. Schild, 2005.

5.5 Energy savings related to stack- and wind-assisted mechanical ventilation

The installed fans in the Media School are designed to meet a total system pressure loss of 105 Pa; a level exceeding available natural pressures, yet extremely low for a mechanically-ventilated building. Thus it would not be contentious to suggest that any potential energy-related benefits derived from exploiting natural forces when faced with such low system pressure losses may in fact be quite trivial. Even so, the Media School is designed to channel natural airflow through the building, hence constituting a *hybrid* scheme. Natural ventilation can therefore reduce overall pressure losses and eventually, to some extent, fan consumption. Just how effective is further reducing pressure losses in saving energy? Again, Schild provides some insight by demonstrating that the most significant savings in fan energy are achieved by specifying low-pressure drop (low SFP) ventilation systems

---

[13] www.byggforsk.no/prosjekter/hybvent/COMISweather.htm

(e.g. ~100 Pa), while the additional gain in energy savings provided by exploiting natural driving forces is negligible in comparison (Schild 2001).

If natural forces seem to play a marginal role in lowering fan energy consumption in a *stack- and wind-assisted mechanical ventilation* system, they may even end up conflicting with the proper operation of the system if not harnessed adequately, as the relative strength of wind and stack effects increases as system pressure drops. Designing *stack- and wind-assisted mechanical ventilation* based on natural ventilation availability may therefore have more to do with ensuring proper operation of the system than on energy considerations. On the other hand, if matching building operational tasks with the quality of the energy source, or exergy, is a design goal in itself, then hybrid ventilation would in principle be more beneficial. Basing building design on exergy goals would tend to motivate reductions in consumption of electricity (high grade energy) rather than on a low-grade energy task such as space heating (see discussion on primary energy conversions in section 4.4.4). As ventilation fans operate solely on electricity, and inefficiently at that, reductions in fan use rather than heat production would prove to be more beneficial. Exergy is highlighted as a contributing factor in the choice of hybrid ventilation of Swedish schools, as part of a national plan to phase out nuclear production of electricity (Wahlstrom et al. 2002).

5.6 Hybrid ventilation in cold climates: how low can you go?

We instinctively depict natural ventilation schemes as perimeter air entry approaches, as illustrated in Figure 18; an expected propensity as most buildings in the world resort to such techniques for ventilation purposes. It is however dubious to expect comfortable conditions with perimeter air entry approaches during the coldest of conditions, as thermal stratification and draughts would likely occur, even with local heating mechanisms provided within the room. There is some debate over which temperature should be used as an acceptable lower threshold. For instance, air inlet temperatures are usually kept above 12°C in dilution ventilation approaches, while 18°C is usually considered a minimum in displacement ventilation designs. This not only depends on airflow rates and a number of architectural parameters (air inlet characteristics and placement, room geometry, etc.), its acceptability varies over time, and among individuals. It is not the aim here to determine the value of this threshold, only to establish its existence.

Let us consider the aforementioned hybrid ventilation principles in the light of their handling of low inlet air temperatures. With *natural and mechanical ventilation*, there is little empirical evidence found in the literature to suggest that inlet temperatures below ~10°C could constitute universally accepted thresholds, although it is theoretically possible to design for lower temperatures in specific cases, e.g. rooms with high internal gains, distant air inlets from occupied zones. For the purpose of this discussion, it is reasonable to establish that beyond 0°C, perimeter air entry in natural or free-running modes would likely be quite unacceptable. Beyond that, *natural and mechanical ventilation* resorts to full mechanical ventilation by design.

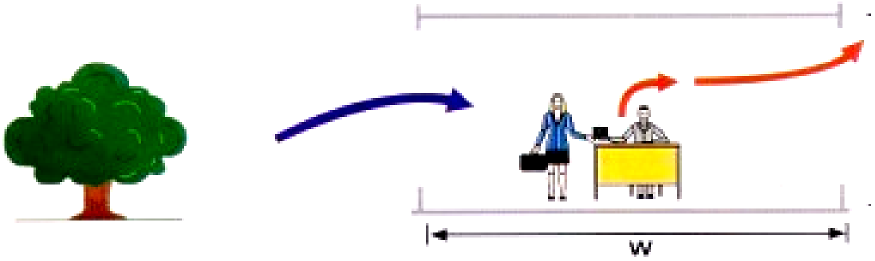

Figure 18 Naïve representation of the traditional perimeter air entry approach

In *fan-assisted natural ventilation*, buffer zones are introduced to stabilize and condition outside air *before* delivery within occupied rooms. The ventilation principle remains naturally-driven peripheral air entry, yet added enhancements such as mechanical preheating compensate for the low inlet temperatures. Paradoxically, buffer zones impede on natural airflow by adding pressure losses, as discussed earlier, and the approach must therefore rely on backup systems such as demand-controlled mechanical extraction. This system introduces a concept of compromise in hybrid ventilation: natural airflow autonomy is partially sacrificed for greater stability of inlet temperatures. It is noteworthy that Annex 35 pilot study projects resorting to *fan-assisted natural ventilation* have had notable difficulties in ensuring comfortable conditions, mainly due to draughts, when outside air temperatures are very low (Aggerholm 2002). This is somewhat to be expected in windy conditions as small buffer zones (e.g. ribbed-pipe heating units in air inlets as in the Bang

& Olufsen Headquarter Building), have response times of several minutes while natural turbulence is often described in time scales of seconds. This means that wind turbulence may be pumping outside air in and out of an opening without adequate compensation from buffer zones. It would therefore seem impractical to apply *fan-assisted natural ventilation* solutions in very cold conditions.

Buffer zones in *stack- and wind-assisted mechanical ventilation* are further isolated from occupied zones in order to better stabilize air temperatures and velocities. Yet, as discussed earlier, this stabilization is costly: wind and stack effects no longer constitute the main driving force that ensures airflow, rather at best, they are channelled in a complementary manner to reduce overall pressure losses. Compromising natural airflow for greater control is here pushed to the point where natural driving forces play only a marginal role. The buffer zones introduced in *stack- and wind-assisted mechanical ventilation,* e.g. culverts or solar chimneys, function well when properly separated from occupied rooms.

5.7 Discussion

The division between occupied versus unoccupied zones (e.g. rooms versus solar chimneys or culverts) is critical when considering a claimed benefit of natural/hybrid ventilation: although there is considerable evidence to suggest that operable windows tend to increase occupant satisfaction, as presented in the following chapter, the presence of a culvert or a solar chimney, located anywhere upstream or downstream of an occupied zone, may hardly improve occupant satisfaction, unless one considers the ethical appreciation of working in a sustainable building as a sign of satisfaction. In fact, it is hardly possible from an occupant's perspective to distinguish these solutions from a purely mechanical ventilation scheme. As there appear to be no direct benefit to the occupant, the end result may be that *stack- and wind-assisted mechanical ventilation* designs should solely be justified based on economic or energy/exergy life cycle costing. It is hoped that this review is helpful in circumscribing the potential energy saving potential of personal use of operable windows in hybrid environments, namely in harsh climatic conditions.

5.8 Summary

This chapter reviews the current state-of-the-art in hybrid ventilation principles and applications, with a special focus on potential energy savings in harsh climatic conditions, such as those found in Canada. The review shows that energy savings stemming from well-suited, centrally-controlled hybrid ventilation concepts for harsh climatic conditions have little to do with natural forces and more to do with minimizing airflow resistance within designated airflow networks. The review also reveals that few pilot studies have focused on occupant behaviour with regards to indoor climate control as a potential source of energy savings.

6 Thermal adaptation: applying the theory to hybrid environments

This chapter reviews two principal schools of thought in matters of thermal comfort: heat balance models and adaptive comfort theory, and relates them to hybrid ventilation concepts dealing with occupant preference and control over the indoor climate. Recent findings on the relationship between adaptive comfort theory and personal action are reviewed in greater detail, with attention given to the practical limitations of relying on thermal adaptation in hybrid environments under extreme conditions.

6.1 Thermal neutrality

The central concept underlying the *heat balance* model of the body is *thermal neutrality*, a physiological state relatively constant among individuals, where external and internal heat gains counter heat losses to the environment. This equilibrium is based on simplified mathematical representations of the human body, modelled as one or several nodes. The more established models are Fanger's single-node model (1972) and Gagge et al.'s two-node model (1986). ASHRAE 55 (1992) requirements are mainly based on effective temperature contours predicted by Gagge's two-node model, while the basis for the ISO 7730 (1994) is Fanger's main contribution: the now well-established Predicted Mean Vote/ Percentage People Dissatisfied (PMV/PPD) index, derived from his one-node model. Both models were compiled from laboratory experiments on human subjects under steady-state conditions. The PMV/PPD index integrates what Fanger considered the six most important variables which influence thermal comfort. Four are environmental variables: temperature, radiation, air velocity and humidity. Out of all the possible personal variables, Fanger retained only the following two: metabolic rate and clothing insulation, possibly because they are unavoidable; every occupant produces internal metabolic heat, and is dressed for work!

Although it is generally agreed that the heat and mass exchange within the human body under steady-state conditions may be modelled with acceptable accuracy, data input uncertainty remains significant (Jones 2001, Brager and de Dear 1998, Ong 1997).

Comparison of the Fanger and Gagge models against more complex models also reveal significant discrepancies in comfort predictions under transient conditions (Jones 2001), a strong reminder that both models are derived from steady-state experimentation. Similar discrepancies are observed for draught models, with differences in occupant response to draught varying as a function of activity level, velocity direction and personal control of air delivery devices (Griefahn et al. 2001, Toftum 2001). If model uncertainty is so great to the point that determining their value in real life becomes a challenge, how useful then becomes the standard (Parsons 2001, Mahdavi and Kumar 1996)?

Does the PMV accurately predict the field Actual Mean Vote (AMV)? A review of field validation studies of the PMV/PPD index in buildings with mechanical heating, ventilation and air-conditioning (HVAC) is found in Fanger and Toftum (2001). In a field study on thermal satisfaction and indoor air quality in 12 mechanically-ventilated office buildings in Montreal, Haghighat and Donnini (1999) found that 84% of surveyed occupants agreed with the ASHRAE 55 winter comfort zone, yet only 54% were in agreement with the summer comfort zone. Some of the reported discrepancies between the PMV and AMV may be attributed to perceived IAQ (Fanger and Toftum 2001, Haghighat and Donnini 1999), a relationship not covered by the standards. As reported earlier in the thesis, this also seems to be the case for other non-thermal factors, such as lighting (Rowe and Wilke 1995). Brager and de Dear (1998) report several studies showing frequent discrepancies between the PMV and AMV in actual buildings, especially naturally ventilated ones in warm climates, where the PMV regularly predicts a warmer thermal sensation than the occupants actually feel (Fanger and Toftum 2001). As reported by McCartney and Nicol (2001), this phenomena has in fact been observed since the early 1970s (Humphreys 1975, Nicol and Humphreys 1972), when compared results of field studies of thermal comfort in many countries showed that different groups of people were comfortable at remarkably different temperatures. The reasons for the discrepancies are not yet fully understood, but appear to be attributable to an inadequate allowance for people's physiological, psychological and behavioural adaptive responses to the indoor and outdoor climates (Humphreys 1997). This leads us to the second school of thought in matters of thermal comfort in the built environment, *adaptive thermal comfort* theory.

6.2 Thermal adaptation

Humphreys' *Adaptive Principle*: "If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Humphreys 1997). Adaptive models do not in principle conflict with heat exchange models, for adjustments to heat exchange process may be among the actions taken in order to secure comfort. Referring to previous studies in thermal physiology, perception theory and behavioural psychology, Brager and de Dear (1998) define three modes of adaptation: *behavioural adjustment*; *physiological acclimatization*; and *psychological habituation and expectation*.

Behavioural adjustment includes conscious or unconscious modifications which modify heat and mass fluxes governing the body's thermal balance. Three sub-categories are defined: *personal adjustment* to the surroundings, e.g. drinking; *technological or environmental adjustment*, e.g. opening windows; and *cultural adjustment*, e.g. adapting dress codes and schedules. *Physiological acclimatization* includes genetic adaptation and temporal acclimatization. This concept is still strongly disputed by Fanger and Toftum (2002), who argue that thermal responses are relatively constant among individuals. In response to discrepancies between PMV and AMV in naturally-ventilated buildings in warm climates, they instead suggest that individuals in warm climates expect warm conditions in their work environments, but given a chance would prefer cooler environments. Consequently Fanger and Toftum have introduced their own adaptive model - *e* - an expectancy correction factor to the PMV index, a function of region, season and indoor environment, allowing greater convergence between the PMV and the AMV. Evidence of *physiological adaptation* in high temperature environments, e.g. increased perspiration, cardiovascular responses, etc., are however well documented in Brager and de Dear (2001). *Psychological habituation and expectation* include cognitive and cultural variables in the thermal perception of - and response to - environmental stress.

The adaptive model recognises the potential for a feedback loop where past and current thermal experiences affect current thermal sensations (Jones 2001, Brager and de Dear 1998). A more detailed review of perception theory in matters of thermal sensation in the built environment is given by Ong and Hawkes (1997a, 1997b). Although exercised environmental control is categorized by Brager and de Dear (1998) as a *behavioural* *adjustment*, the perception and legibility of personal control fall into this category (Brager and de Dear 1998, Hawkes 1997, Heschong 1979). A review of the impact of thermal monotony is also helpful in understanding the role of personal preference in thermal variations (Brager and de Dear 2001). In any case, there is little disagreement over the benefits of increasing personal control (Brager and de Dear 2001, Fanger and Toftum 2001, Hawkes 1997, Baker and Standeven 1996).

6.3 Adaptive comfort control

From a perspective on sustainability, one of the main contributions of adaptive thermal comfort models is a potential reduction of mechanical cooling given the wider tolerance of variations in indoor thermal conditions when personal environmental control is made available (Brager and de Dear 2001, Baker and Standeven 1996). One proposed way of reducing cooling loads in hybrid environments is to consider a variable comfort temperature instead of a constant cooling setpoint. Based on an extensive field measurement campaign, the ASHRAE *Project 884: Developing an Adaptive Model of Thermal Comfort and Preference* (de Dear et al. 1997), de Dear and Brager (1998) have developed a new comfort standard for naturally ventilated buildings, to be included as an option to the presently revised ASHRAE 55 Standard, *5.3 Optional method for determining acceptable thermal conditions in naturally conditioned spaces*. In essence, it relates the comfort temperature to the monthly mean outdoor air temperature and includes an inferred range of acceptable temperatures based on PMV calculations. Hensen and Centnerova (2001) argue that the time constant of thermal adaptation is more likely to be a few days than a month, and suggest that the daily mean outdoor temperature be used as input for the adaptive comfort standard.

Earlier work on adaptive algorithms is reviewed in Brager and de Dear (2001). Based on observations illustrated in Figure 19, Humphreys (1978) proposed an algorithm relating the comfort to the mean outside air temperature.

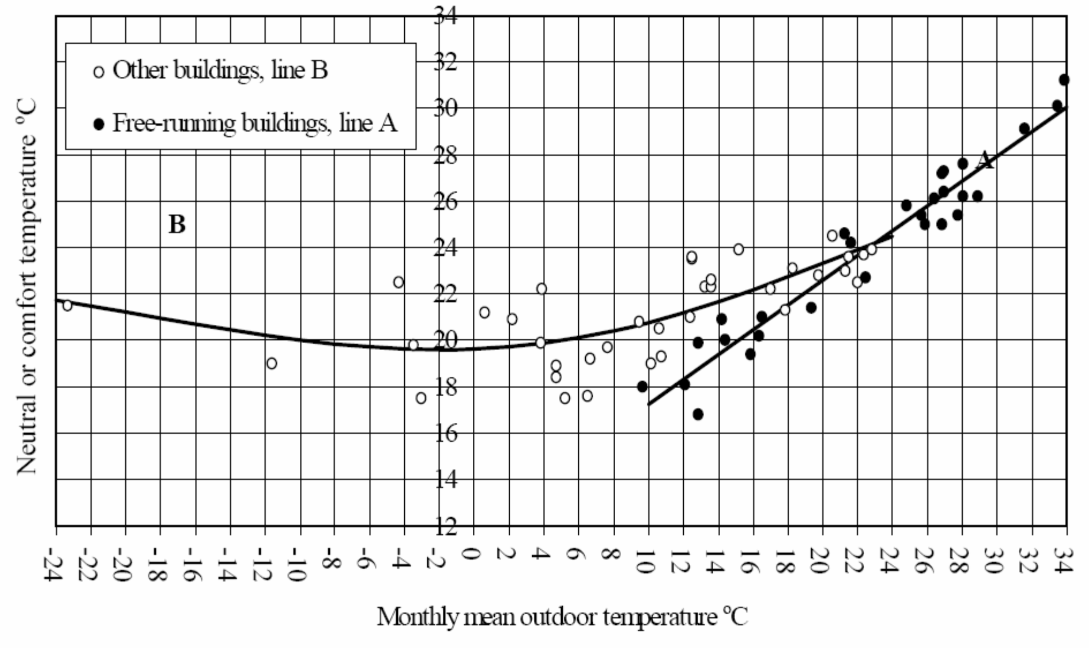

Figure 19 Neutral or comfort temperature versus monthly mean outdoor temperature, from Humphreys (1978) as quoted by McCartney and Nicol (2001).

Later studies reported by McCartney and Nicol (2001) showed that an exponentially-weighted mean outside temperature gives a more accurate relationship. Humphreys and Nicol (1995) found that applying the algorithm as it stood would result in too low internal temperatures when outside temperatures are very cold and a lower temperature limit has been added to the algorithm, as illustrated in Figure 20. Supplementary adjustments, including provisions for regional variations, have been added and the final form of the algorithm is presented in McCartney and Nicol (2001). Brager and de Dear (1998) state concerns regarding Humphreys and Nicol’s adaptive control algorithm: although it is derived from field observations of naturally ventilated buildings, its suggested application includes air-conditioned buildings. This indeed seems paradoxical at first since Humphreys and Nicol suggest different occupant expectations for free-running as opposed to air-conditioned buildings. However, Humphreys and Nicol have stated in the past their preference for mixed-mode or hybrid ventilation through equal opportunities of using locally-controlled AC units or natural ventilation, justifying the use of the adaptive control algorithm with air-conditioning (Humphreys and Nicol 1998).

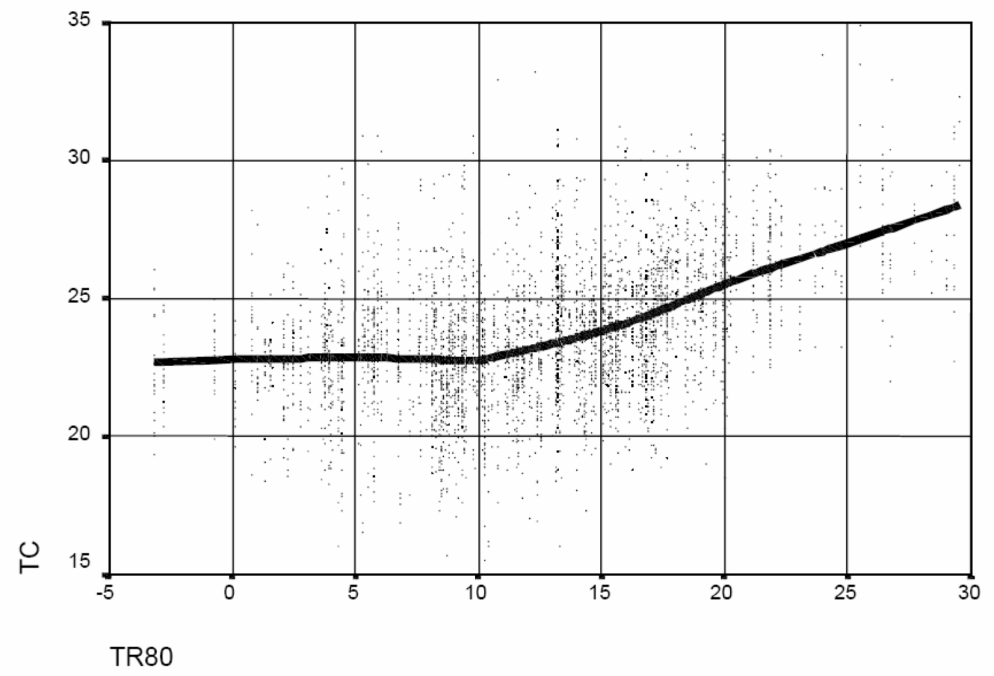

Figure 20 Comfort temperature (T_C °C) versus running mean outdoor temperature (T_{R80} °C) from McCartney and Nicol (2001). "80" refers to a time constant used in a proposed adaptive comfort algorithm, corresponding to a half-life of 3.5 days.

6.3.1 Adaptive comfort control for heating

Integrating adaptive comfort control within hybrid ventilation solutions would in theory encourage energy savings in summer, yet there is little support for this in winter. Any *physiological acclimatization* would most likely equal thermal stress and thus would acquire a negative connotation. To some extent, the same may be said for *psychological habituation*: the appreciation of working in an eighteenth-century building may compensate the occasional rubbing of hands on a cold winter day but one intentionally strives by design to avoid any trade-offs in that sense. In fact, the preceding literature review shows that there is little evidence to suggest that wider tolerance of thermal conditions is expected below ~10°C. This is one of the basic assumptions of the ASHRAE 55 adaptive comfort model (Brager and de Dear 2001). This is also clearly supported by Haghighat and Donnini (1999) who show that there is little evidence of general occupant dissatisfaction to centrally-controlled uniform environments in winter, specifically in Canadian office environments. This supports the applicability of both the ASHRAE 55 and the ISO 7730 standards for centrally-controlled uniform work environments. Tendencies shown in Figure

19 and Figure 20 suggest even higher expectancies in indoor temperatures during winter, as measured comfort temperatures seem to hover at ~23°C instead of ~20-21°C, suggesting a potential increase in heating demand if adaptive comfort models are used in winter instead of the ASHRAE 55 or ISO 7730 standards (Hensen and Centnerova 2001).

6.3.2 Adaptive comfort control for cooling

The preceding analysis suggests that energy savings from adaptive comfort control would appear only attributable to reductions in mechanical cooling. Yet as reported in Brager and de Dear (2001), the scope of application of the ASHRAE 55 adaptive comfort option is very narrow, based on the following conditions to its application:

1. Naturally conditioned spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. It is specifically noted that the windows must be easy to access and operate.
2. Spaces can have a heating system, but the method doesn't apply when it is in operation.
3. Spaces cannot have a mechanical cooling system (e.g., refrigerated air-conditioning, radiant cooling, or desiccant cooling).
4. Spaces can have mechanical ventilation with unconditioned air, but opening and closing of windows must be the primary means of regulating thermal conditions.
5. Occupants of spaces must be engaged in near sedentary activity (1-1.3 met), and must be able to freely adapt their clothing to the indoor and/or outdoor thermal conditions.

Conditions 1 and 5 can be considered as reasonable. Conditions 2 and 4 suggest control functions on heating and ventilation supply once windows are opened, and although this is not standard practice it is conceivable for the future. Condition 3 essentially rules out hybrid approaches, which is curious given that Condition 2 only restricts the *use* of heating equipment. Is it not feasible to consider restricting the use of air-conditioning equipment? Is there no way of having the standard apply to hybrid environments? Is this restriction based on the assumption that occupants are irresponsible when it comes to the use of air-conditioning devices? It is hoped that the following pilot study provide some useful insight on this issue: the first dealing with proximity to windows as a prerequisite, the other dealing with preference when alternatives are available.

6.3.3 Personal control and satisfaction: the Berkeley Civic Center

According to Brager et al. (2004), the exact influence of personal control in explaining differences in comfort sensations and AMV votes between people in naturally-ventilated versus air-conditioned buildings could only be hypothesized before recently because of the limits of the existing field study data that formed the basis of that research. The objective of the more recent ASHRAE RP-1161 was to quantitatively investigate how personal control of operable windows in office settings influences local thermal conditions and occupant comfort. Brager et al. collected over 1000 survey responses, crossed-linked to concurrent physical assessments of workstation microclimate conditions, at the Berkeley Civic Center, located in the San Francisco Bay area. The building is naturally-ventilated (i.e. no air-conditioning) and is predominantly open-plan yet fairly narrow (i.e. two workstations deep from the perimeter), providing various cooling opportunities for occupants, with subjects on the perimeter having greater access to operable windows than those in core zones.

Subjects who have more control over thermal conditions of their workplace (in particular, the operable window) had a neutral temperature that was 1.5°C warmer than subjects with minimal control, even though they experienced the same thermal environments and exhibited no differences in clothing insulation or metabolic rate. More importantly, their neutral temperatures more closely approximated the actual level of warmth prevailing in their workplaces, compared to the group of subjects with low or negligible levels of personal control. Given that the two groups were broadly exposed to the same average thermal conditions, but the group with more control shifted their neutrality closer to their average thermal exposure, this offers the first empirical confirmation of a hypothesis that was offered during the ASHRAE RP-884 project to explain the shifting thermal expectations issue.

This finding provides clear evidence that subjects with greater access to control are more tolerant of, and in fact may prefer, conditions that may not be in the center of the comfort zone. The corollary of this, witnessed in countless thermal comfort studies in air-conditioned offices, is that people who have limited or no control over their office environment, as is the case in the vast majority of air-conditioned office buildings, tend to be less tolerant and accepting of suboptimal thermal environmental conditions.

6.3.4 Preference in hybrid environments: the Wilkinson building

Can these *shifting thermal expectations* be observed in cases where indoor climate control can be ensured both through operable windows and/or air-conditioning? Should we expect that occupants systematically make use of passive means, or is there a breaking point above which artificial climate control becomes more appealing? Rowe investigated this question by monitoring thermal conditions and occupant response and behaviour in 25 cellular offices of the University of Sydney School of Architecture, housed in the Wilkinson Building (Rowe 2003). The hybrid climate control strategy is low-tech, and based on the *laissez faire* principle that room occupants are the best sensors of thermal comfort and air quality. In the Wilkinson Building, occupants have control over windows and doors for natural ventilation, as well as local supplementary air-conditioning units with default controls that require regular, deliberate occupant activation of mechanical cooling. Through linear regression, Rowe found that mean indoor air temperatures in occupied rooms measured at 15:00 correlated very well with daily outdoor minimum temperatures, yet appeared to flatten out at ~17°C, suggesting greater personal use of the air-conditioning units. Beyond this 17°C threshold, Rowe found that mean indoor air temperatures remained at ~25°C, suggesting an upper *ceiling* limit in preference to thermal adaptation, similar to the lower *floor* limit of ~10°C during cold conditions as illustrated in Figure 20. Although Rowe does not provide any detailed information on the nature of the statistical distribution of this ceiling, it appears that beyond 17°C mean indoor air temperatures are all found to be above 22°C while remaining below 28°C (yet with a few exceptions near 30°C). As stated by Rowe, a temperature range of ~6°C on any given day indicates substantial differences in individual preference and there can be no doubt that the high comfort and satisfaction ratings for the study area owe a great deal to the freedom of choice of mode and temperature control options (Rowe 2003).

If Rowe's hypothesis of an upper *ceiling* limit to the application of adaptive comfort control is true, then in mixed-mode environments, the curved trend illustrated in Figure 4 would no longer tend towards 100% (i.e. probability of 1.0) with increasing outdoor air temperature, but rather flatten out or even drop beyond a certain point. Rather than an *S* curve, typical of logistic regression models, a bell-curve - albeit strongly skewed to the right – might better represent probabilistic behaviour of operable window use in *hybrid* environments.

6.4 Discussion

Further analysis of the Wilkinson data could reveal whether the observed range in preferred temperatures is randomly distributed amongst people (i.e. due to arbitrary garment patterns, metabolic rates, etc.) or attributed to systematic patterns of preference and choice amongst individuals. In other words, do results suggest that certain occupants generally prefer narrow temperature ranges, e.g. 22-25°C, and systematically opt for mechanical cooling, while others readily welcome the wider temperature swings of naturally-ventilated environments? If such population clustering exists, this would imply at least two distinct behavioural patterns; one more closely supporting the traditional position of the heat-balance approach, i.e. that when given a choice people tend to select cooler conditions than those found under free floating environments (Fanger and Toftum 2002), while the other supporting thermal adaptation. Another hypothesis may be that each individual has an adaptive breaking point, beyond which artificially-controlled indoor climates are preferred; it is just that for some, this breaking point appears to be quite close to comfort thresholds predicted by the heat-balance approach. The two presented case studies are of great worth as exploratory, longitudinal investigations in the area, but can hardly constitute a sufficiently transversal basis for regression. This is compounded by the fact that both studies were carried out in very mild climates suitable for passive cooling (e.g. Sydney and Berkeley). The following chapter describes a pilot study on operable window use in the Canadian context.

6.5 Summary

Heat balance models and adaptive comfort models have been reviewed in the light of personal preference and control over indoor thermal environments. Adaptive comfort control algorithms, based on field evidence of thermal adaptation where occupants could exercise effective control over their thermal environments (mainly by opening windows) are also reviewed.

7 Pilot study on personal operable window use

The preceding chapter reviewed current knowledge on the application of adaptive comfort control in hybrid environments. What little we do know on occupant preference of natural or mechanical environments does provide valuable insight on the extent of thermal adaptation in office environments yet the evidence also suggests a wide range in preference between individuals at any given moment, which could be partly explained by population clustering in regards to thermal preference. For instance, some may prefer the thermal swings associated to natural ventilation, while others may systematically ignore natural conditions and instead opt for artificially-maintained environments. This may lead to analogous population clustering schemes found in lighting behavioural models, as discussed in section 2.2.2.3. In addition, temporal events such as an individual's daily arrival and departure have been shown to be key variables in lighting behavioural models; parameters which have not been fully accounted for to describe personal control over indoor climates, whether through the use of operable windows or personal air conditioning devices. The following pilot study investigates operable window use, with a special focus on population clustering into active or passive users, and behaviour on arrival and departure.

7.1 Purpose of the investigation

The purpose of the field investigation is to gather empirical evidence that would help substantiate the significance of certain key concepts regarding operable window use, which have traditionally been associated to lighting behaviour, i.e. personal control of blinds and electric lights, specifically:

1. Can building occupants be characterized as either *active* or *passive* users with regards to operable window use?
2. Do building occupants systematically rearrange their environment to default settings upon departure, i.e. closing previously-opened windows as they leave for the day?
3. Do building occupants arrange their environment at default settings upon arrival, i.e. opening windows for the duration of the day as they arrive?

If certain key behavioural patterns are found to be common to those regarding lighting use, then the underlying assumption in SHOCC of initially handling occupant-controlled entities in abstraction of any given behavioural model would be further justified (see section 3.1.1). In addition, published field studies on thermal adaptation and operable window use have naturally focused on buildings located in mild climates, such as Berkeley California or Sydney Australia. There is much to learn on how people behave in heating-dominant climates with harsh peak summer conditions (i.e. harsher than Berkeley or Sydney), as in large parts of the US and Canada. Unfortunately, the author was not aware at the onset of his doctoral studies of accessible sample buildings which could be characterized as being hybrid, i.e. in which alternate methods of indoor climate control are available and chosen at the discretion of the occupant. It was ultimately decided to pursue the investigation on a mechanically cooled building with operable windows in the Québec City area, providing a case of how occupants perceive and control operable windows in environments where, in principle, overheating is not a major concern, a condition essentially ignored in past field studies.

7.2 Building description

The chosen sample building is the *Pavillon Charles-DeKoninck* on the *Université Laval* campus; a five-storey building with a semi-enclosed classical courtyard (see Figure 21). It houses classrooms, cellular offices for university professors, graduate students and research personnel, as well as general administrative office areas. It is characterised by a significant façade-area-to-building-volume ratio.

All peripheral spaces have at least one operable window, and two in most cases. All operable windows are inward-opening hopper style windows located near the ceiling, operable using traditional *school house* poles. All spaces are mechanically ventilated, heated and cooled. Heating is provided through a peripheral hot-water system which is thermostatically-controlled in every two offices. Mechanical cooling is provided by rooftop air-handling units, delivering at a constant volume rate[14].

---

[14] The temperature of mechanically-delivered air in peripheral offices of the *Pavillon Charles-DeKoninck* is determined based on average return-air temperatures from multiple zones. Certain cooling units deliver air to peripheral zones which have distinctively-different façade orientations. This inadequate zoning design has been linked to increased occupant complaints during spring and fall, i.e. seasons when both cooling and heating may be simultaneously required for differently-oriented zones. Apart from these seasonal anomalies,

Figure 21 Pavillon Charles-DeKoninck, Université Laval, front entrance (north-east façade).

7.3 Methodology

7.3.1 Data acquisition

Lack of funding prevented direct measurement of routine indoor environmental parameters, such as dry- and wet-bulb temperatures, local air speeds, etc, and so observations were made from outside the building; a similar non-intrusive method to Inoue et al.'s (1988) method for observing blind use in buildings. Reinhart (2004, 2001) discusses the limitations of these approaches, notably on the inherently limited knowledge of short-term occupancy status. However, as the aforementioned questions do not necessarily require such detailed data, the *observed* status of operable windows (*closed* or *opened*), as well as the *presence* of at least one occupant per office, were initially established as working independent variables. Other key parameters included outside air temperature and whether the window/office was exposed to direct solar radiation at the time of observation. One point to consider in this regard is that previous working models describing personal use of operable windows have almost exclusively been based on outdoor air temperature as the sole environmental parameter, suggesting that behaviour may be as strongly correlated to

---

indoor conditions are reported to be within ASHRAE55 recommendations (communication with André Loubier, Division des aménagements et des locaux, Université Laval, 2003).

prevailing weather patterns than to high resolution observations of indoor environmental parameters, e.g. draughts, sensed conditions. This behavioural response has been suggested previously (Morgan et al. 2002, Brager and de Dear 1998), and for this reason the measurement of outdoor air temperature appears warranted. One advantage of note of the method is that many personal observations (e.g. many offices) can be taken within a very short time frame, i.e. in contrast to Fritsch et al.'s (1990) excellent study which is based solely on four offices. This hints at a more *transversal* rather than *longitudinal* quality of the resulting data set.

A total of 211 individual windows were observed in late summer and early fall 2002, as well as spring 2003. Observations included the status of operable windows, lights and blinds[15]. Those taken in 2002 usually comprised of three observations per day: two in the morning and one in the afternoon, all during normal occupancy hours. In one instance, an additional observation was taken late during a Friday evening to establish the status of windows over a weekend (assuming that occupants did not come in during the weekend). In 2003, additional observations were systematically taken in the early hours of the morning (i.e. 06:00 solar time) to establish the status of windows, blinds and lights *after* previous-day departures and *before* current-day arrivals. This made up a total of 10 128 observations. All data transformation and statistical analysis has been done with the SAS statistical package (2001).

7.3.2 Data transformation

Any raw data set requires some transformation before statistical analysis. First, irrelevant data was discarded, such as observations made for classrooms and meeting rooms, leaving only offices, either single-occupancy or limited to small groups of individuals. New variables are introduced. The *definite* occupancy status (i.e. when one can definitely establish that an occupant has been present before or during an observation) per window bay was established based on any changes in observed environmental settings during the day (e.g. changes in operable windows, blinds, lights, etc.). If such changes are observed during the day, then the definite occupancy status was established as "in", or else "out".

---

[15] The status of task lighting, office doors, etc. was taken as an indication of definite presence in the room.

Outdoor air temperature measurements were taken at different times during a single observation set, and at different points around the building. As the measured temperature ranges for a given observation set are limited to ~2°C, as the manufacturer-stated tolerance of the temperature sensor is ±1°C, and finally as there is some uncertainty on estimating outdoor air temperatures at the height of an office from observations made at ground level, temperatures measured during the observation set were simply averaged for the entire observation. Similarly, observations on direct solar exposure were reduced to characterizing the window bay as belonging to typically *exposed* façades, e.g. south-east (SE), south-west (SW), south-east courtyard (SEc) and north-east courtyard (NEc), or *sheltered* façades, e.g. north-east (NE)[16], north-west (NW) and north-west courtyard (NWc).

Observations per window bay per office were then collapsed into general observations per office, as it the behaviour of office *occupants* towards operable windows which is the object of study, rather than the status of individual windows. In the case of *definite* occupancy status per office, this was done by establishing if *any definite* occupancy status observations were made vis-à-vis *any* windows of a given office. Similarly, the status of office operable windows was collapsed into a single variable; if *any* office windows were *opened*, then the office window variable is set as "open", or else "closed". This produced a new data set based on 85 offices.

7.3.3 Results analysis

7.3.3.1 Population clustering

The first question of interest is whether building occupants can be grouped into *active* versus *passive* users towards operable window control just as in lighting behaviour. The working definition of a *passive* operable window user is here defined as someone who has never opened a window when occupying their office, at least during the full extent of the observations. It should be noted however that the observations do not cover the extremes of the Québec climate (hot and humid in summer, very cold in winter). As such, the evidence should be considered as inconclusive and preliminary in nature. Nonetheless, it is worth

---

[16] The sampled section of the building's north-east façade, in contrast to the courtyard-side north-east façade, never received direct solar radiation during observations because of tree cover.

noting that occupants in 12 of the 85 investigated offices, or 14.12%, had never once opened a single window during the observations, based on a simple frequency analysis of the binomial *active/passive* distribution, as indicated in Table 3.

Table 3 Binomial active/passive frequency distribution based on façade orientation

	passive	**active**
NE	0 (00.00%)	7 (08.24%)
NEc	2 (02.35%)	4 (04.71%)
NW	2 (02.35%)	14 (16.47%)
NWc	0 (00.00%)	8 (09.41%)
SE	1 (01.18%)	11 (12.94%)
SW	5 (05.88%)	22 (25.88%)
SWc	2 (02.35%)	7 (08.24%)
Total	**12 (14.12%)**	**73 (85.88%)**

Although this finding is also insufficient to generalize the proportion of passive users in other buildings, it does question the validity of generalizing the behaviour of *whole populations* using classical empirical approaches, such as linear or logistic regression models, without taking into account population heterogeneity. Rather, such models should ideally preserve the heterogeneity of building populations by restricting dynamic behaviour prediction to *active* users.

When the observed outcome of an experiment is categorical in nature, e.g. the number of *passive* users in a building, statistical operations such as the chi-square test can reveal if the outcome is significantly different between independent categorical variables. In this case, it is of interest to verify if the proportion of *passive* users is statistically different between façades, i.e. that the observed differences between façades are not random. If the observed differences are indeed random, then the evidence should be considered inconclusive as to whether various façade orientations can explain differences in observed outcomes. Façade orientation is linked to various degrees of solar exposure and related risks of overheating. Differences in passive user distributions between façades may reveal whether solar exposure and overheating can trigger operable window use.

When cell counts are lower than 5, as is the case here for certain façades, Fisher's exact test, rather than the chi-square test, is recommended. The outcome of Fisher's exact test is a two-sided p-value: the greater the p-value, the greater the risk of falsely rejecting a null hypothesis. In this case, the null hypothesis is that passive users are equally distributed amongst façades. If the two-sided p-value is lower than some previously-defined critical value, e.g. 5%, then the null hypothesis can be safely discarded and the alternative hypothesis can be recognized, i.e. that the distribution of passive users is indeed statistically different between façades.

Table 3 gives the frequency (i.e. cell count) of *active/passive* users per façade. From this table, there does not appear to be any obvious relationship between façade orientation and the proportion of *passive* users. The resulting p-value from Fisher's exact test is 53.11%, which is significantly greater than the commonly-chosen, critical 5% value. In this instance, there is no basis to reject the null hypothesis, and therefore the evidence should be considered as inconclusive as to whether façade orientation is significant or not.

Table 4 presents similar statistics as a function of how façades are labelled as either *sheltered* or *exposed* to solar intensities. Surprisingly, a greater proportion of *passive* users are found in exposed façades. In this instance, the resulting p-value from Fisher's exact test is 19.62%, which again suggests that these differences are random. Again, there is no basis to reject the null hypothesis, and the evidence should as well be considered as inconclusive as to whether solar exposure is significant or not.

Table 4 Binomial *active/passive* frequency distribution based on solar exposure

	passive	**active**
Exposed	10 (11.76%)	44 (51.76%)
Sheltered	2 (02.35%)	29 (34.12%)
Total	**12 (14.12%)**	**73 (85.88%)**

7.3.3.2 Behaviour when departing

The second question of interest, again as in lighting behaviour, is whether occupants reset operable window settings upon departure, i.e. are previously-opened windows in turn closed at the end of the day? Here, the analysis is limited to a subset of offices which had some daily variation in operable window use during days when subsequent observations were made outside occupancy hours (i.e. late in the evening or early in the morning). Only six days of observation could provide any useful insight in this regard. Table 5 provides the frequency of offices that had at least one window left open upon departure, for each day of observation. The "operated" variable indicates the number of offices, out of the initial 85 office data set, that had windows operated during that day. The "left open" variable indicates how many of the "operated" offices had left windows open upon departure. Minimum daily outdoor air temperatures during occupancy (i.e. ~08:30) are provided under "min T", while maximum daily outdoor air temperatures (e.g. ~15:00) are provided under "max. T".

Table 5 Binomial frequency distribution of whether previously-opened windows were closed upon departure

	operated	**left open**	**min. T**	**max. T**
2002-08-30	35 (41.12%)	23 (65.71%)	15.2°C	17.5°C
2003-05-07	32 (37.65%)	20 (62.50%)	7.0°C	12.2°C
2003-05-08	28 (32.94%)	13 (46.43%)	10.0°C	12.9°C
2003-05-26	32 (37.65%)	15 (46.88%)	13.5°C	17.8°C
2003-05-27	37 (43.53%)	18 (48.65%)	14.9°C	22.0°C
2003-05-28	39 (45.88%)	14 (35.90%)	15.7°C	22.6°C
average	**33.8 (39.80%)**	**17.2 (51.01%)**	**12.7°C**	**17.1°C**

The number of offices, out of the 85 office data set, that had at least one window left open upon departure ranges between 13 and 23. This does not imply that a significant proportion of windows remained open beyond normal occupancy hours; offices have in most cases two or more windows. If at least one window remained open on a given day, then that office counts as being "left open". For instance, the number of offices with at least one window left open on May 28 2003 is 14; assuming two windows per office, this may mean only 7 windows were left open, i.e. approximately 3 % of the initial 211 windows sample. Yet ultimately, this does not support the widely-assumed assumption that occupants close their windows upon departure (Fritsch et al. 1990).

One other related question of interest is whether the proportion of offices with windows left open depends on outdoor conditions, e.g. maximum outdoor air temperature. Building occupants may be more sensitive to the impact of leaving an open window overnight during colder conditions. Yet Table 5 does not reveal any such relationship and given the limited number of days of observation, it is highly likely that any statistical testing, as carried out in the previous *passive/active* distribution analysis, would undoubtedly lead to inconclusive evidence. Just as in the previous *passive/active* distribution analysis, Fisher's exact test on the distribution of offices with windows left open as a function of both façade orientation and solar exposure is inconclusive.

It is rather interesting to note that the proportion of occupied offices that had at least one open window during the day (i.e. "operated") remains relatively constant despite a 10.4°C range of maximum outdoor air temperatures. This range, i.e. between 10°C and 25°C, is where the sharpest rise in the proportion of opened windows is predicted based on Nicol and Humphreys model (2004), as illustrated in Figure 4 (see section 2.2.2.1). Here, based on parameters provided in Table 1, Nicol and Humphreys' model predicts a 35% probability of having opened windows at 12.2°C for UK buildings, which coincides closely to the observed proportion of offices with one or more open windows at the *Pavillon DeKoninck*. The predicted probability jumps to 75% at 22°C; a probability which is way beyond the observed maximum proportion of 45.9% at the Pavillon DeKoninck. Although the evidence is inconclusive, it may be nonetheless hypothesized that during colder conditions, building occupants in both naturally-ventilated and mechanically-cooled buildings tend to operate windows in a similar manner, but that during warmer conditions, the probability of using windows sharply increases in naturally-ventilated buildings, more so than in mechanically-cooled buildings. This may be explained by the obvious fact that in naturally-ventilated buildings, operable windows are often the sole means of cooling. As discussed in the initial chapters of the thesis, the evidence presented in Rowe (2003) also supports this hypothesis. Evidently, more research in this area is warranted.

7.3.3.3 Behaviour when arriving

The last question of interest, again as in lighting behaviour, is whether building occupants choose to open windows upon arrival, possibly independently of sensed indoor conditions. If so, just as with *active/passive* user population clustering, this may provide greater insight on how to apply logistic regression models like Nicol and Humphreys' model (2004). The investigation is again limited to a subset of offices which had some daily variation in operable window use during days when previous observations were made outside occupancy hours (i.e. early in the morning). Again only six days of observation could provide any useful insight in this regard. Table 6 provides the frequency of offices with at least one window being open upon arrival – all windows being previously closed - for each day of observation. Arrival is here defined as the first hour of normal occupancy (i.e. before 09:00).

Table 6 Binomial frequency distribution of whether previously-closed windows were opened upon arrival

	operated	**open on arrival**	**min. T**	**max. T**
2003-05-07	14 (16.47%)	7 (50.00%)	7.0°C	12.2°C
2003-05-08	14 (16.47%)	8 (57.14%)	10.0°C	12.9°C
2003-05-09	12 (14.12%)	4 (33.33%)	5.2°C	9.5°C
2003-05-26	20 (23.53%)	6 (30.00%)	13.5°C	17.8°C
2003-05-27	23 (27.06%)	11 (47.83%)	14.9°C	22.0°C
2003-05-28	16 (18.82%)	7 (43.75%)	15.7°C	22.6°C
average	**16.5 (19.41%)**	**7.2 (43.67%)**	**11.1°C**	**16.2°C**

It is first important to point out that the "operated" count in Table 6, i.e. the number of offices with at least one open window, is different that the count reported in Table 5. This is explained by the fact that offices with at least one window left open upon departure were discarded from the presently-investigated data subset. Of the remaining offices with opened windows, the proportion of those with windows being opened upon arrival ranges from 30.00% to 57.14%. It may be speculated in this case that overheating could hardly occur in these air-conditioned offices at such early hours in the morning. If this is the case, then these findings could be significant as they would suggest that certain *active* occupants behave almost in a routine matter, i.e. that opening a window is in some way part of their daily ritual, similar to how *passive* blind and light users behave towards lighting and shading devices upon arrival.

It may be expected that anticipated outdoor temperatures may influence this behaviour, i.e. that occupants may feel more inclined in opening a window if they expect outdoor conditions will remain or become more favourable during the course of the day. Just as with the previous query on behaviour upon departure, there doesn't appear to be any obvious relationship between the number of offices with windows open upon arrival and outdoor conditions, although the "operated" count tends to increase as outdoor conditions get warmer. Again, given the limited number of days of observation, it is highly likely that any statistical testing, as carried out in the previous analysis, would undoubtedly lead to inconclusive evidence. As expected, Fisher's exact test on the distribution of offices with windows opened upon arrival as a function of both façade orientation and solar exposure is inconclusive. Further observations during heat waves and peak winter conditions would likely reveal more notable discrepancies.

7.4 Discussion

Despite the limited scope and preliminary nature of the pilot study, the evidence helps to substantiate to some degree the significance of certain key concepts with regards to operable window use, which previously have been linked to lighting behaviour. Specifically, the field evidence suggests that:

1. Occupants may be characterized as either *active* or *passive* users, where the latter can be considered as people who don't open windows.
2. *Active* users may leave windows open upon departure.
3. *Active* users may open windows upon arrival.

On one hand, these preliminary findings question certain assumptions of previously-published operable window control models. For instance, Fritsch et al. (1990) consider that windows are systematically closed upon departure. As well, these findings provide useful insight on how to address the applicability of certain logistic regression models such as Nicol and Humphreys' model (2004): building populations appear to be heterogeneous in regards to window control, e.g. certain never open windows, while others appear to routinely open them upon arrival, etc. Although there is insufficient evidence here to either question or support Nicol and Humphreys' general model, the evidence does suggest that simulating a building population's response to operable windows solely based on sensed temperature may be an oversimplification, and likely inaccurate in mechanically-cooled environments.

The findings also suggest that behavioural responses towards environmental control may in part be considered as abstract in nature. This supports the underlying assumption found in SHOCC of initially handling occupant-controlled entities independently of any given behavioural model (see section 3.1.1).

7.5 Summary

The significance of certain key concepts in behavioural modelling, namely population clustering into *active* or *passive* users, or temporal events, such as *arrivals* and *departures*, has been investigated by analyzing original field evidence of operable window use in an air-conditioned building. Preliminary results analysis suggests that such population clustering regarding operable window use is indeed observed, while arrivals and departures appear to be marked by systematic personal adjustments to operable windows. These findings are considered as preliminary evidence of an abstract quality to certain key behavioural traits; a concept embraced by some of the SHOCC functionality as described in Chapter 3.

8 Quantifying the total energy impact of adaptive comfort control

How would the use of operable windows, based on the aforementioned findings as well as those presented in previous publications, affect energy use in buildings, specifically in the case of hybrid environments, and more specifically, in harsh climates such as Canada's? McCartney and Nicol (2001) report provisional calculations based on monitored energy use in two office buildings (one in the UK, the other in Sweden), fitted with their revised adaptive control algorithm. Their calculations suggest up to 30% savings in air-conditioning consumption without affecting the actual mean comfort vote (AMV). Similarly, Rowe reports that the Wilkinson Building requires less than one quarter of estimated energy use for the same building with full air conditioning (Rowe 2003). Are these results reliable? How are reference cases (i.e. simulated buildings used for comparison) defined? What additional assumptions have been made? Reproducibility is always critical. This chapter presents a preliminary working behavioural model for predicting the use of operable windows in hybrid environments, its subsequent integration within SHOCC, and a demonstration of the energy impact of the defined control model through an example application.

8.1 A working model of personal control of operable windows

As reviewed in section 2.2.2.1, Nicol and Humphreys' model estimates the probability of having opened windows as a function of prevailing temperatures, based on an impressive collection of field responses from many countries. Yet as suggested early on in this thesis, no such coefficients exist for North America. Unfortunately, the *Pavillon Charles-DeKoninck* (DKN) database presented in the preceding chapter is insufficient to either validate Nicol and Humphreys' model, namely in regards to outdoor air temperature ranges, or even estimate empirical coefficients for a Canadian location. Furthermore, the DKN database holds information on how occupants respond to operable windows in a fully air-conditioned building, here with little feedback response between the dual modes of environmental control, i.e. natural and artificial. It is doubtful that a similar model to Nicol and Humphreys', resulting from further analysis of the DKN database, could realistically predict behaviour in hybrid environments by extrapolation. Underlining the importance of further investigations would be stating the obvious.

As a working hypothesis within the scope of this thesis and for demonstration purposes only, a behavioural model for predicting operable window use in hybrid environments is formulated based on the following findings and assumptions:

1. Only *active* users operate windows. This is supported by the preceding analysis of the DKN database.
2. *Active* users are more likely to operate windows as outdoor conditions become more suitable. Nicol and Humphreys' model is used to predict this likelihood of opening windows, based on empirical coefficients for the U.K. Although the DKN analysis is inconclusive in this regard, this is largely supported elsewhere (Fritsch et al. 1990, Warren and Parkins 1984). Stochastic variations are computed at run-time by comparing the predicted probability against the outcome of a standard, uniformly-distributed random function[17]. Once a window is opened, it remains open until departure.
3. Once indoor conditions exceed predefined cooling setpoints (e.g. 24°C), windows are closed to allow local air-conditioning units to provide mechanical cooling to the occupied room. This is a strict interpretation of how hybrid environments could operate, i.e. that natural ventilation is only considered valid when indoor conditions are kept within narrow confines.
4. As an additional option, cooling setpoints may de dynamically adjusted to 26°C when windows are opened, providing some means to account for thermal adaptation, as supported by past findings (Brager et al. 2004, Rowe 2003).

The likelihood of initially opening windows upon arrival and as well as the likelihood of leaving windows opened upon departure are not yet considered in the algorithm. Subsequently, windows are assumed within the context of this investigation to be closed outside normal occupancy hours. Although the evidence detailed in Chapter 7 does suggest that such behaviour could be expected, the dataset in insufficient and too preliminary in nature to regress some operational model for simulation purposes. Future work on this question is obviously required. In addition, as leaving windows opened outside occupied hours would undoubtedly increase heating requirements in a cold climate, it is assumed for demonstration purposes only that some method of supervisory control is available to prevent leaving windows opened outside normal occupied hours, e.g. directives to cleaning

---

[17] C standard library *rand* function.

personnel, automated controls closing windows, etc. The aim would be to initially counter such anticipated energy penalties. It is hoped that adopting such control strategies would minimize to some degree the bias in simulation results of assuming that windows are always kept closed outside normal occupied hours.

The hypothesized model has been integrated within SHOCC in the same spirit as blind control, including the capability of considering more than one active and/or passive user (see section 3.1.3). In ESP-r, the output of SHOCC is processed to dynamically increase prescheduled infiltration rates and cooling setpoints, similarly to how prescheduled casual gains are overwritten. As the example application presented in the Chapter 4 is a single zone model, the additional infiltration rates are computed using DeGidds and Phaff (1982) single-sided natural ventilation model:

$$Q = Aeff\sqrt{0.001V^{2} + 0.0035H\Delta T + 0.01}, \quad \text{where:} \qquad (2)$$

Q is the air volume rate (m^3/s)
$Aeff$ is the effective area of opening (m^2)
V is the wind velocity (m/s)
H is the opening height (m)
ΔT is the temperature difference (K)

Other approaches to single-sided ventilation prediction are provided in Haghighat et al. (2000) and Fürbringer and van der Maas (1995).

8.2 Example application

For demonstration purposes, the energy impact of the preceding working model is investigated through simulation using SHOCC/ESP-r. In addition, the exercise provides insight on the significance of adaptive comfort control in relation to the wide ranging thermal regimes stemming from various lighting control options, as investigated in Chapter 4. In other words, the example application can give cues on the relationship between behavioural models in lighting and behavioural models describing operable window use.

Three control options, related to those described in section 4.3, are investigated:

- *constant24°C* – continual overhead lighting use during occupied hours, without blinds, operating windows and cooling setpoint at 24°C;
- *manual24°C* – occupant-controlled ON/OFF light switching, with manual control over blinds, operating windows and cooling setpoint at 24°C; and
- *manual26°C* – occupant-controlled ON/OFF light switching, with manual control over blinds, operating windows and cooling setpoint at 26°C.

The chosen test case is the single occupancy perimeter office presented in Chapter 4. Again, cooling-dominant (Rome) and heating-dominant (Québec) climates are considered. The primary energy conversion factors are those derived in section 4.4.4. The office is assumed to have a single window that offers an effective free area of 0.1 m^2 when opened, with an opening height of 0.2 m. Although mechanical cooling can be deactivated based on the use of operable windows, continuous mechanical ventilation is considered during occupied hours. This reflects the mandatory requirements in Canada of providing mechanical ventilation at prescribed rates (QCC 2001, CNB 1995). To reconcile mandatory mechanical ventilation and adaptive comfort control, a *dedicated outdoor air approach* is considered, where fresh air and space load conditioning are considered as separate processes (Hamilton et al. 2003, Jeong et al. 2003). A review of similar regulatory issues facing hybrid ventilation applications in Canada is presented in Bourgeois et al. (2002). This covers an array of issues ranging from fire safety to the quality of the workplace, including indoor climate.

8.2.1 Results

Annual estimated electrical energy use for lighting, as well as cooling and heating requirements, are presented in Figure 22 for Rome, and in Figure 23 for Quebec. Lighting energy use in the *constant24°C* case, for both climates, is the same as *constant* use shown in Figure 10 and in Figure 11. Lighting energy use in *manual24°C* and *manual26°C* cases, again for both climates, is the same as *manual* use shown in Figure 10 and in Figure 11. Only the heating and cooling requirements are different in comparison to those shown in Figure 10 and in Figure 11.

As in Chapter 4, various energy uses are converted into primary energy requirements as a single standard of measurement. Annual primary energy requirements for Rome and Québec are presented in Figure 24 and in Figure 25, respectively. The differences in primary energy requirements between the *constant24°C* option in Figure 24 and in Figure 25 against the *constant* option in Figure 12 and in Figure 13 are indicative of the differences in energy use between *active* and *passive* operable window users under important internal loads (i.e. stemming from lighting use): results in Figure 12 and in Figure 13 evoke energy use relating to *passive* users (i.e. windows are never opened), while those in Figure 24 and in Figure 25 reflect energy use related to *active* users. For both Québec and Rome, cooling loads drop significantly, while heating loads increase by the same token. This can be attributed to the frequency of hours when windows are open during cooler periods (i.e. under 21°C), as predicted by the model. Yet overall, results suggest that the use of the operable window could likely reduce total primary energy requirements, yet only slightly (i.e. by approximately 1.2% in Rome and by 0.5% in Québec). These minor differences in relative performance suggest that savings in cooling energy are roughly equal to the increase in heating demand.

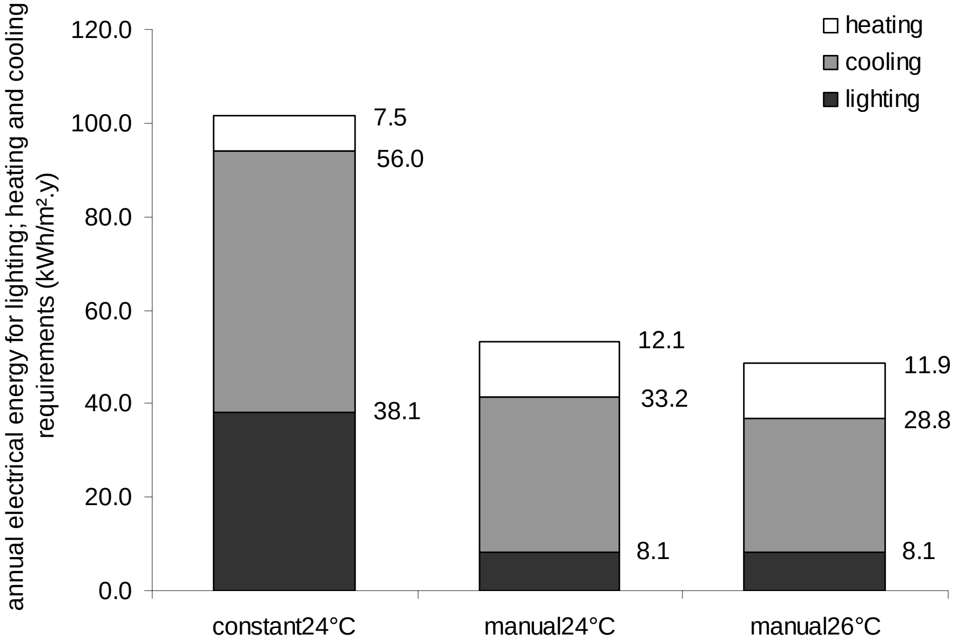

Figure 22 Simulated annual electrical energy for lighting, cooling requirements and heating requirements (kWh/m².y) for various adaptive comfort control options in Rome

Once *manual* lighting control is enabled in both *manual* and *manual24°C* options, as shown in Figure 12 and in Figure 13, and in Figure 24 and in Figure 25, respectively, primary energy expenditure increases for both locations. In Rome, total primary energy requirements go from 68.1 kWh/m².y to 69.6 kWh/m².y; a 2.2% increase. In Québec, total primary energy requirements go 98.6 kWhr/m².y to 101 kWh/m².y; a 2.5% increase. Again, the relative performance loss is minor. By comparing *manual24°C* and *constant24°C* options, it may be tentatively concluded, at least based on the output of the hypothesized model, that the increased air exchange from open windows appears beneficial only in cases with high internal loads.

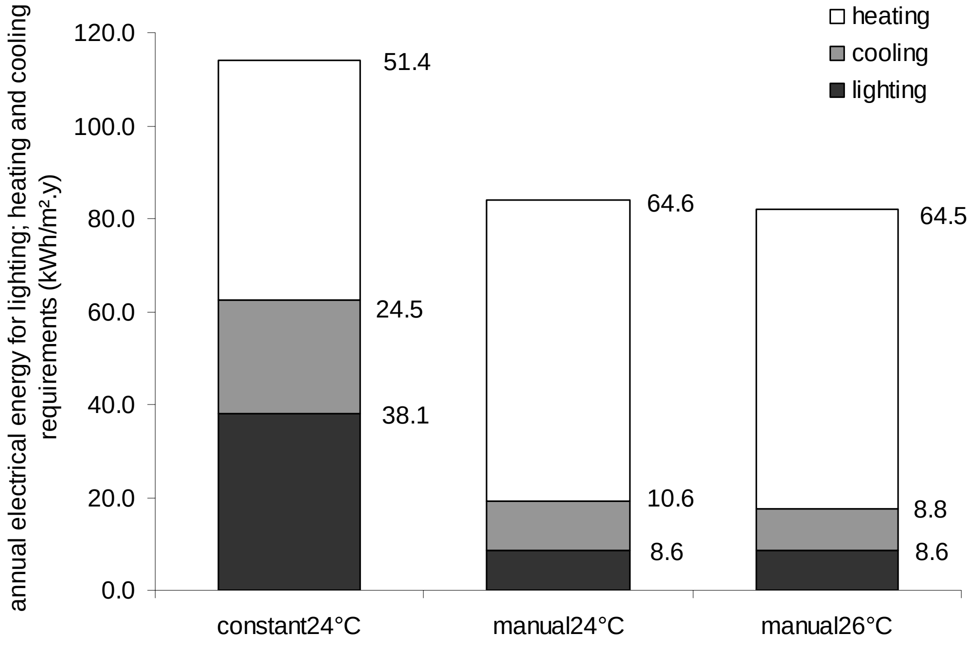

Figure 23 Simulated annual electrical energy for lighting, cooling requirements and heating requirements (kWh/m².y) for various adaptive comfort control options in Québec

By relaxing cooling setpoints to 26°C when operable windows are opened (i.e. *manual26°C*), primary energy requirements for cooling are reduced by 4.4 kWh/m².y in Rome and 1.8 kWh/m².y in Québec; a 13.3% and 17.0% reduction respectively. The primary energy requirements for heating are reduced as well. As only the cooling setpoint has been modified between options *manual24°C* and *manual26°C,* this reduction in heating is likely due to the increased energy storage resulting from higher ambient conditions in the room, later released as useful heat outside occupancy hours (i.e. at night). This produces a reduction in total primary energy of 6.6% in Rome and 1.8% in Québec when compared to *manual26°C* cases. However, it is possible that higher setpoints may only be anticipated during very warm conditions, i.e. when clothing behaviour is adapted to heat wave-like conditions. In other words, it may be questionable to assume that a cooling setpoint of 26°C may be acceptable during cooler periods of the year, putting into question these preliminary findings on reduced heating loads.

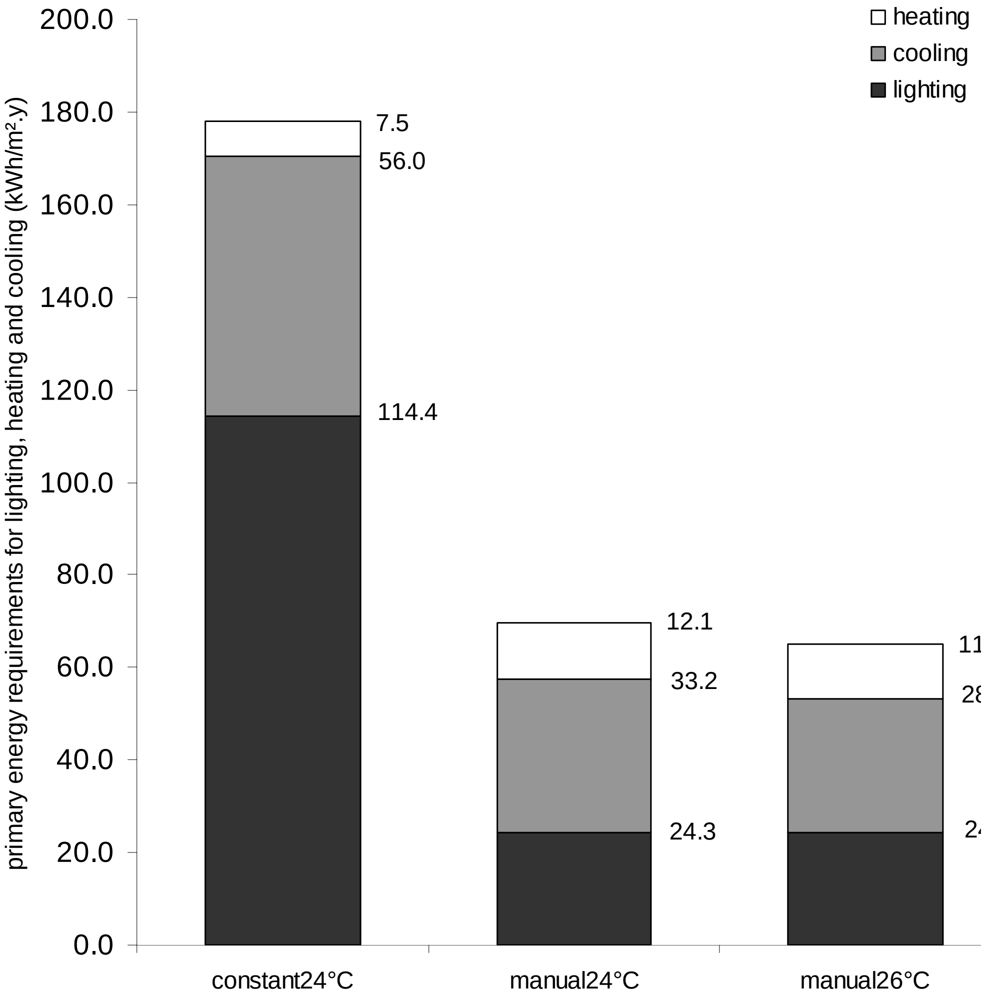

Figure 24 Annual primary energy requirements for lighting, cooling and heating, for various adaptive comfort control options in Rome

If total primary energy requirements for *manual26°C* are compared to *manual* cases in Figure 12 and in Figure 13, then only in Rome does this hypothesized adaptive comfort control algorithm appear beneficial: total requirements are reduced by 4.6%. In Québec, total primary energy requirements increase by 0.7%. This appears largely attributable to the overall 4.0 kWh/m².y increase in heating requirements in Québec.

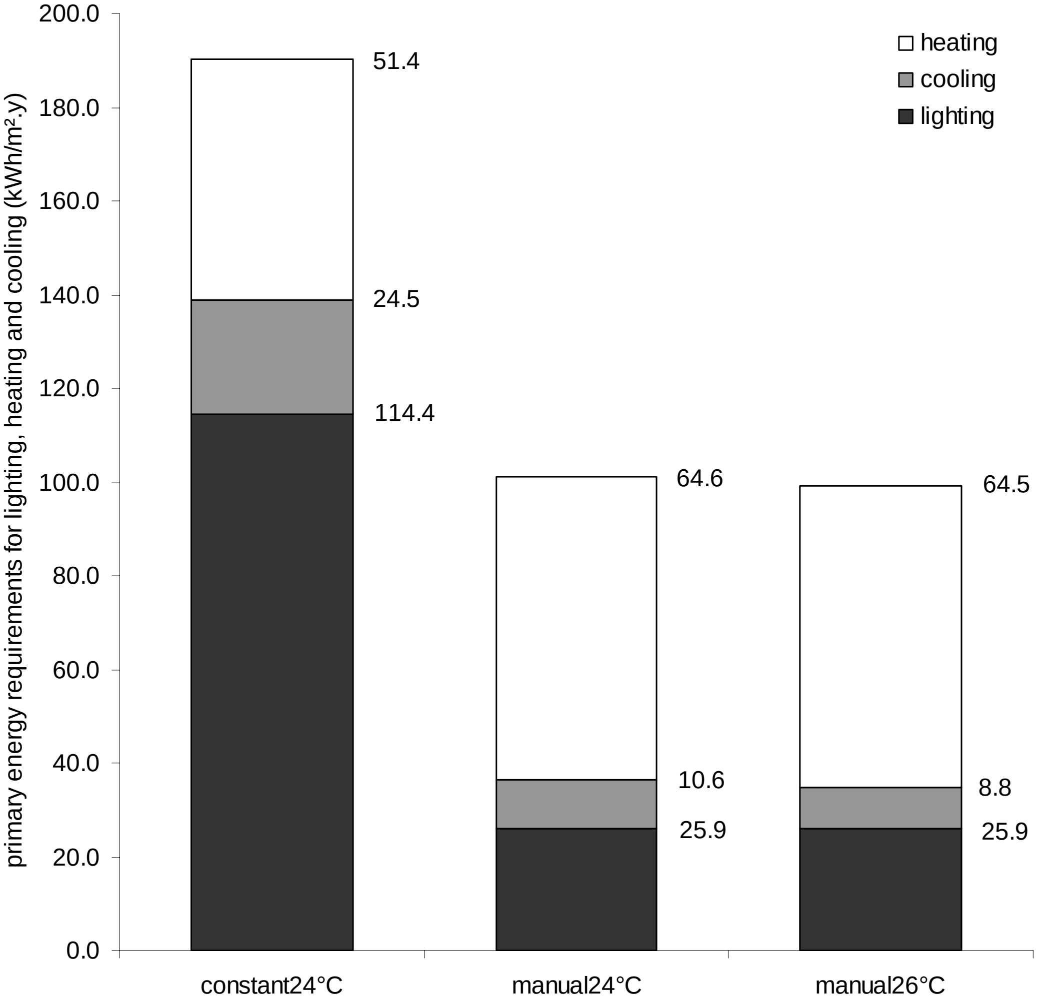

Figure 25 Annual primary energy requirements for lighting, cooling and heating, for various adaptive comfort control options in Québec

8.3 Discussion

The integration of operable windows is shown to be, at least based on the outcome of the hypothesized model, either a benefit or a penalty depending on location, design and lighting use (i.e. principal internal load). For both locations, and in cases with high internal loads, operable window use appears beneficial in reducing cooling loads; relieving the excess heat emitted from lighting fixtures. Once *manual* lighting control is enabled, the use of operable windows appears to become a penalty overall in both locations. As in Chapter 4, this reiterates the importance of defining suitable reference cases for lighting use. Once a more aggressive adaptive comfort control algorithm is integrated (e.g. *manual26°C*), total energy expenditure is reduced in Rome (cooling-dominant), and slightly increased Québec (heating-dominant). This only partly supports the claim that adaptive comfort control can reduce energy expenditure, at least in cooling-dominant climates. One can speculate that in locations with milder climatic conditions (e.g. Berkeley or Sydney), adaptive comfort control would likely be even more beneficial.

Considerable care should be taken when considering these findings as the study is deprived of a whole-building context: the modelled office is considered in isolation from the rest of its building host and the interdependent effect of building and mechanical systems is not considered. For instance, the air exchange resulting from an open window will be different if the room is located at the upper level of a tall building rather than in a one-storey one, and not equivalent if the building is pressurized or depressurized through mechanical systems. In addition, a large number of variables which can affect window opening behaviour, such as window geometry and placement, acoustical nuisances, rain penetration, etc., have been neglected. Yet, all things being equal, if *manual* lighting control is considered as a reference case, as discussed in Chapter 4, then results suggest that in Québec, and likely in other heating-dominant locations, the introduction of operable windows and adaptive comfort control may increase total primary energy expenditure (in the investigated case by 2.5 $kWh/m^2.y$ or 2.5%). Yet the additional primary energy requirements in Québec, as well as in Rome, are only attributable to additional heating requirements due to open windows, and not to additional cooling requirements.

This last preliminary finding appears to substantiate one of the conditions to the ASHRAE 55 option for adaptive comfort control, namely that this method of indoor climate control should not apply when heating systems are in use. If adaptive comfort control algorithms such as disabling local mechanical cooling supply when windows are open are deemed successful in lowering primary energy requirements for cooling, as suggested in the literature and in these preliminary simulation results, similar approaches could reduce primary energy requirements for heating. One can speculate that if an occupant temporarily opens a window during cooler periods, it may be because he or she requires instantaneous cooling (e.g. after a lunch-time jog). This short-term solution can provide instantaneous relief, but potentially can increase heating demand as local thermostats will inevitably respond to decreasing thermal conditions over time, as demonstrated in the preceding simulation cases. Possible solutions could be throttling back heating supply once windows are opened (e.g. setting thermostatic control at 15°C); once instantaneous relief is provided, the occupant is required to close windows to adjust thermal settings back to standard setpoints (e.g. 21°C).

Just as Rowe's study (see section 6.3.4) provided greater insight on how people responded to adaptive cooling control in the Wilkinson Building (Rowe 2003), future buildings and adaptive heating solutions will have to be designed, built and monitored to provide similar insight for heating-dominant climates, including field-based behavioural models. In the meantime, it is hoped that tools like SHOCC can provide useful insight, although preliminary in nature, on the impact and suitability of various potential approaches.

8.4 Summary

Based on past empirical evidence reviewed in Sections 2.2.2.1 and 6.3 and on findings analyzed in Chapter 7, a working model for predicting manual control of operable windows has been hypothesized and integrated within SHOCC/ESP-r. The total primary energy impact of certain adaptive comfort control strategies in response to operable window use has been investigated through SHOCC/ESP-r simulations. The choice of lighting models (traditional diversity factors versus manual lighting control models) greatly influences the internal thermal regime, which in turn largely determines the energy savings or penalties which may arise from personal control of operable windows and adaptive comfort control. Although personal use of operable windows lowers cooling requirements through adaptive comfort control, heating requirements increase by the same token, underlining the importance of future development in formulating similar control strategies for heating periods.

9 Conclusion

9.1 Thesis objectives

This thesis has set out to bridge the gap between building energy simulation and empirical evidence on occupant behaviour. It has addressed current limitations in whole-building energy simulation with regards to detailed occupancy prediction (i.e. when occupants as individual agents occupy a modelled environment), occupant-sensing control (i.e. as driven by the mere presence of one or more occupants, such as occupancy-sensing lighting controls), as well as advanced behavioural models (i.e. active personal control, such as manual switching of lights operable window control).

SHOCC (Sub-Hourly Occupancy Control), the principal development of the study, has successfully integrated these concepts and models as a self-contained simulation module that targets all occupancy-based phenomena in whole-building energy simulation. SHOCC has been successfully integrated with the free software ESP-r. Once the necessary features for handling occupant mobility and personal attribution of control for various targeted devices are set in place in SHOCC, then empirically-derived behavioural models can be dynamically accessed through appropriate control libraries. The model is designed so it can centrally control various technical parameters in building energy simulation, which are normally associated to or taken over by occupants in real life (e.g. heat injections, control of various devices, indoor climate control setpoints). Similarly, the model is designed for future expansion so alternate behavioural models can be added. ESP-r/SHOCC simulations have been shown to be affordable within the practical use of building energy simulation practice, with additional computational penalties within 2% of overall simulation time.

The practical contribution of this coupling is first demonstrated through limited simulation runs focusing on the total primary energy impact of different lighting controls. Simulation results show that occupant behaviour has tremendous influence over predicted energy use in buildings, revealing possible shortcomings of certain modelling assumptions commonly made for building energy ratings and compliance methods. For instance, results show significant discrepancies in total (i.e. primary) energy savings linked to automated lighting controls, including potential savings in heating and cooling, depending on whether constant lighting use or manual on/off switching is considered as a reference against which advanced technological improvements should be compared.

Preliminary results analysis from original pilot study suggest that key behavioural parameters, such as individual or group predispositions towards personal control (which are found to be significant in previously published lighting behavioural models), could also characterize personal use of operable windows. This preliminary finding suggests that certain behavioural concepts could be considered as abstract in nature. This would support the elaboration of a common approach to modelling occupant interactions in whole-building energy simulation.

SHOCC has finally been used to investigate the feasibility (e.g. energy saving potential or penalty) of novel yet untried strategies that strongly rely upon user interactions, such as adaptive comfort control in hybrid environments through manual use of operable windows. Simulation results based on a hypothesized model of personal use of operable windows, stemming from the aforementioned field study as well as published empirical evidence, suggest that adaptive comfort control could indeed reduce cooling requirements for both heating- and cooling-dominant climates, yet heating requirements appear to rise by the same token for both climate types, due to the occasional use of operable windows during cooler conditions. The usefulness of the development is here illustrated by underlining the need for similar heating control functions to avoid the heating penalties associated to the personal use of operable windows.

9.2 Outlook

Advanced behavioural models have been demonstrated to be quite accurate under previously-investigated conditions. Despite this, there is a considerable need for more field studies in behavioural responses. This cannot be overemphasized. Whatever insight on energy use is provided by accessing these models through SHOCC is limited to the accuracy of the models themselves. In addition, their widespread use in simulation is somewhat thwarted by the strong dependency on detailed population data, such as past and current room occupancies and vacancies, as well as behaviour. The only current method of providing this information in SHOCC is through the Lightswitch2002 population predictor, which requires as input mean arrival and departure times, average times taken for meals, etc. While the technique is quite suitable for routine occupancy patterns, i.e. a single occupancy office or a classroom, it may be unsuitable to tackle the increasingly complex occupancy patterns found in many environments. For instance, white collar workers increasingly tend to stray away from the traditional 9-to-5/five-day work week. In addition, there is limited knowledge on how people perceive and control their environment in space types other than single offices. More field studies are certainly required to address these uncertainties. Yet equally important are the methods to efficiently implement such knowledge. Population flow models that have been used in the past in civil engineering (e.g. traffic flow, building evacuation) could be adapted to address these limitations (Nassar and Nada 2003).

Another critical limitation of using a high resolution approach to model building occupants concerns the validity of applying a given behavioural model independently of the number of controlling individuals present in a space. For instance, the Lightswitch2002 algorithm is based on field studies mainly dealing with single- or double-occupancy cellular offices. The current version of the algorithm applied in lighting simulation (e.g. DAYSIM) deals only with a single occupant, either *active* or *passive* in their control over lights and blinds. There is no well-defined method of applying the algorithm in cases with more than one controller. Yet Reinhart (2001) reports field evidence of certain occupants adopting a form of supervisory management of lighting environments; making decisions for the rest of the group. This concept of *group leader* is found in Boyce (1980), and is often associated to *active* users identified by Love (1998). Based on this limited *qualitative* evidence, the postulate in SHOCC is that any *active* controller has supervisory control over *units* (e.g. blinds) when concurrently sharing control with any number of *passive* controllers. This way, personal control resulting from the social interactions of many is collapsed to the behaviour of the dominant controller. This warrants future field validation. In addition, it can be speculated that such a postulate applies well to a small group of people sharing the same office environment, yet one can hardly expect this to hold for large open-plan office areas (Bordass et al. 1994, Boyce 1980), or when the number of passive controllers far surpasses the number of active users. There are also issues of proximity which become significant at a certain scale (Brager et al. 2004). A great deal of research in the area of social interactions is required before such a concept can be widely-accepted or better yet substituted with a more complete behavioural model involving many individuals. Nonetheless, it is necessary to provide a mechanism to resolve arising issues of *asynchronous cohabitation* (i.e. when *active* and *passive* controllers share control, though individual occupancy patterns differ).

These postulates one may be forced to implement in SHOCC (i.e. to counter the current limited knowledge in behavioural patterns) may actually provide strong cues for future field studies. For instance, the aforementioned *asynchronous cohabitation* of spaces by different active and passive users may be demonstrated as being a significant factor in energy usage. One would benefit from knowing more on active/passive frequency distribution and how they cohabit in existing buildings through future field studies, an aspect which has not been fully considered in the past. Coupling hypothetical behavioural models to energy simulation programs through SHOCC may provide a means of initially investigating the sensitivity of other parameters, helping out with the design of future field studies.

Appendix A - SHOCC data structures and flow

The purpose of this appendix is to provide sufficient information on SHOCC's data structure design and data flow processes, namely for purposes of reproducibility. SHOCC features presented in this document are pertaining to a beta version developed solely for simulation purposes within the scope of this doctoral thesis (late 2004). The reader should be advised that SHOCC will have been further developed by the time the thesis will be made available, and consequently some features will have become obsolete. The presented behavioural models are restricted to the Lightswitch2002 algorithm, including Lightswitch2002's default population predictor to stochastically determine daily arrival and departure events. A more detailed, though undocumented, presentation of SHOCC data structures, along with related source code, is accessible by browsing the SHOCC web site[18]. By clicking on the bold-contoured cells, one can navigate to a lower-level of encapsulation, while the associated source code pops up by clicking on the small icons.

This appendix is a two-step walkthrough, starting with SHOCC input and data pre-processing (i.e. before an actual parent program simulation is initiated), and then by illustrating how SHOCC operates in tandem with a parent-program at run-time.

Input and data pre-processing

There are two instances where SHOCC data are inputted: a *library* of generic elements and a *project* of zone-specific elements. For the reader's sake, a more hands-on walkthrough is provided to illustrate SHOCC's data sharing mechanisms.

Scheduling: a first example of library/project data sharing

Individual times of daily arrival and departure for every *occupant* within a *group* are computed based on inherited data from a library *schedule*. Figure 26 first illustrates generic weekly scheduling data within a SHOCC library. Mean arrival and departure times from Monday to Sunday, as well as mean meal and break duration (in minutes), are provided for two distinct schedules, "nightshift" and "daycare".

---

[18] http://pages.infinit.net/f77/shocc.htm

As described in the main chapters of the thesis, within a given *project* thermal *zone*, one or more *spaces* may be defined to account for individual cellular offices, or even workstations. Within each *space*, one or more entities can be defined, including one or more *groups* of *occupants*. *Groups* inherit generic library *schedule* and *individual* definitions. As shown in Figure 27, the "classroom" *space* contains one *group* of "students", whose weekly scheduling patterns are taken from the "daycare" schedule shown in Figure 26.

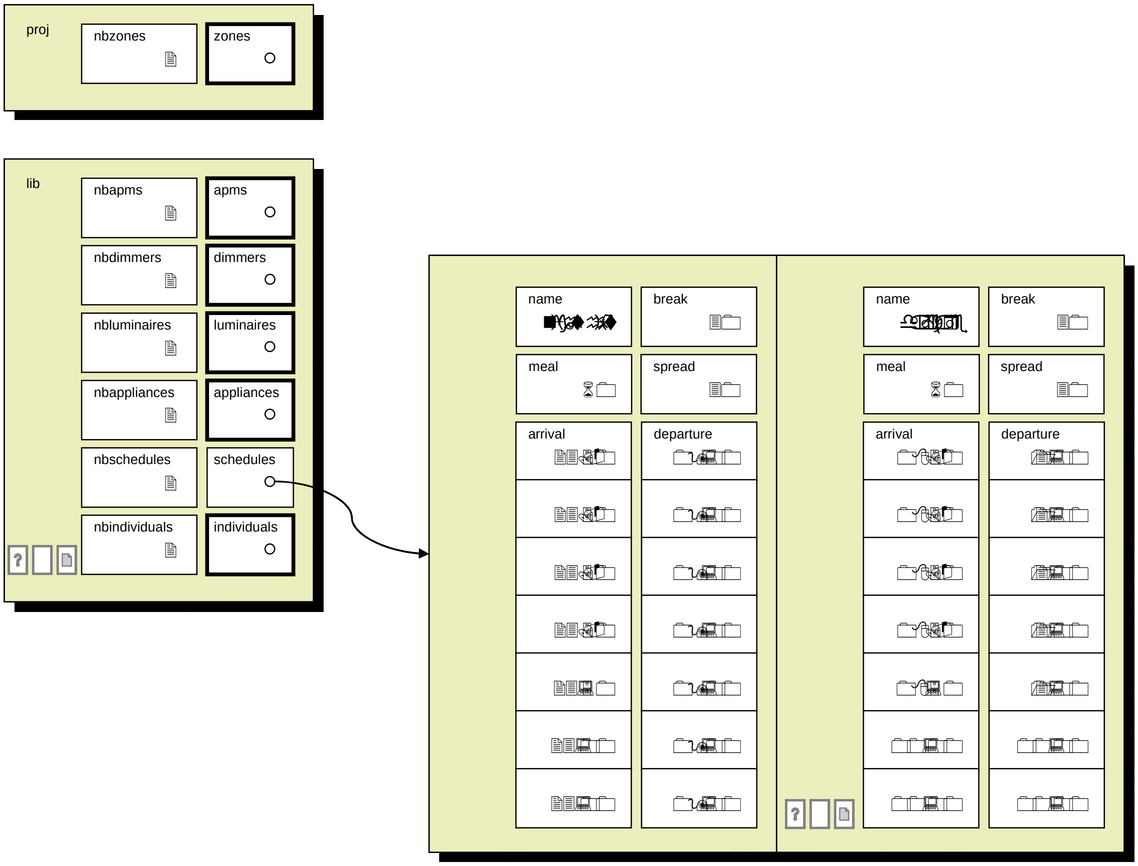

Figure 26 SHOCC scheduling data

Figure 28 illustrates how SHOCC loops through each *group* per *space/zone* to update daily events. Figure 29 and Figure 30 describe respectively the *LSTrueAD* and *LSTrueEvents* functions (in Figure 28), illustrated at the *occupant* level. The prefix *LS* indicates that the population predictor used to define daily events in SHOCC is the same as in Reinhart's Lightswitch2002 algorithm.

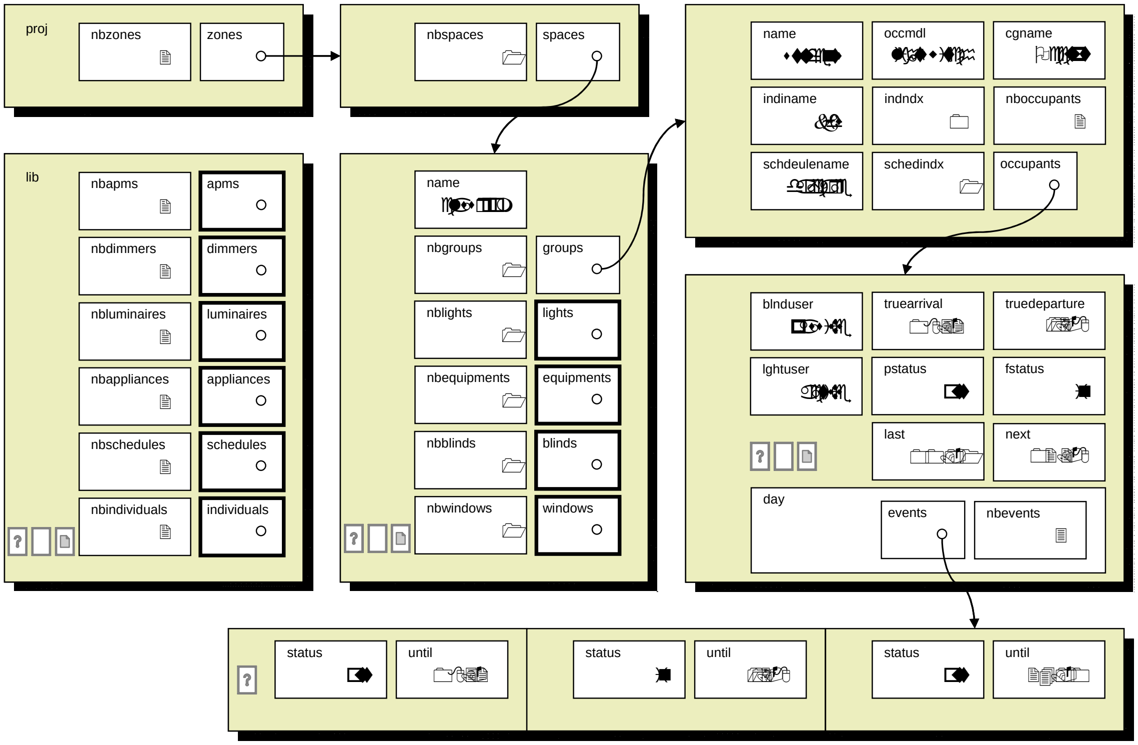

Figure 27 SHOCC group and occupant data

The output of *LSTrueAD* (i.e. an *occupant*'s *true* - versus *scheduled* - daily arrival and departure times) is computed stochastically at the start of every new day within a simulation, based on the statistical *spread* defined in Figure 26 and a random number generation process (Gaussian distribution). For instance in Figure 27, the first "student's" *true* arrival time is computed at 8.32 hours (i.e. 8:19), while his or her *true* departure time is expected at 11.58 hours (i.e. 11:35).

Based on the length of day and a continuous working stint duration of at least 45 minutes, *LSTrueEvents* computes whether enough time is available to schedule *breaks* and/or mid-day *meals*. Here, the output is an *occupant*'s number of daily *events* and when these *events* occur. For instance in Figure 27, it should be read that "3" events are computed for that "student" during that day, and that he or she is absent until 8.32 hours (i.e. arrival), remains in the space until 11.58 hours (i.e. departure), and subsequently absent until 24.0 hours (i.e. the end of the day).

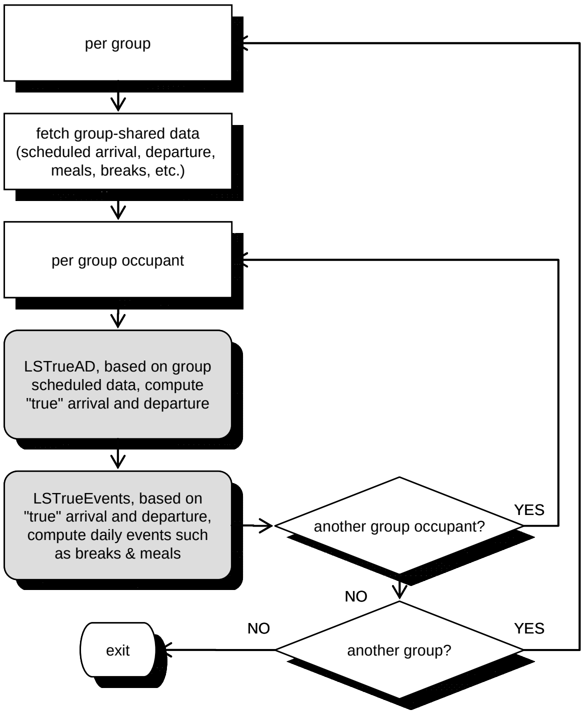

Figure 28 SHOCC daily update of occupant mobility data

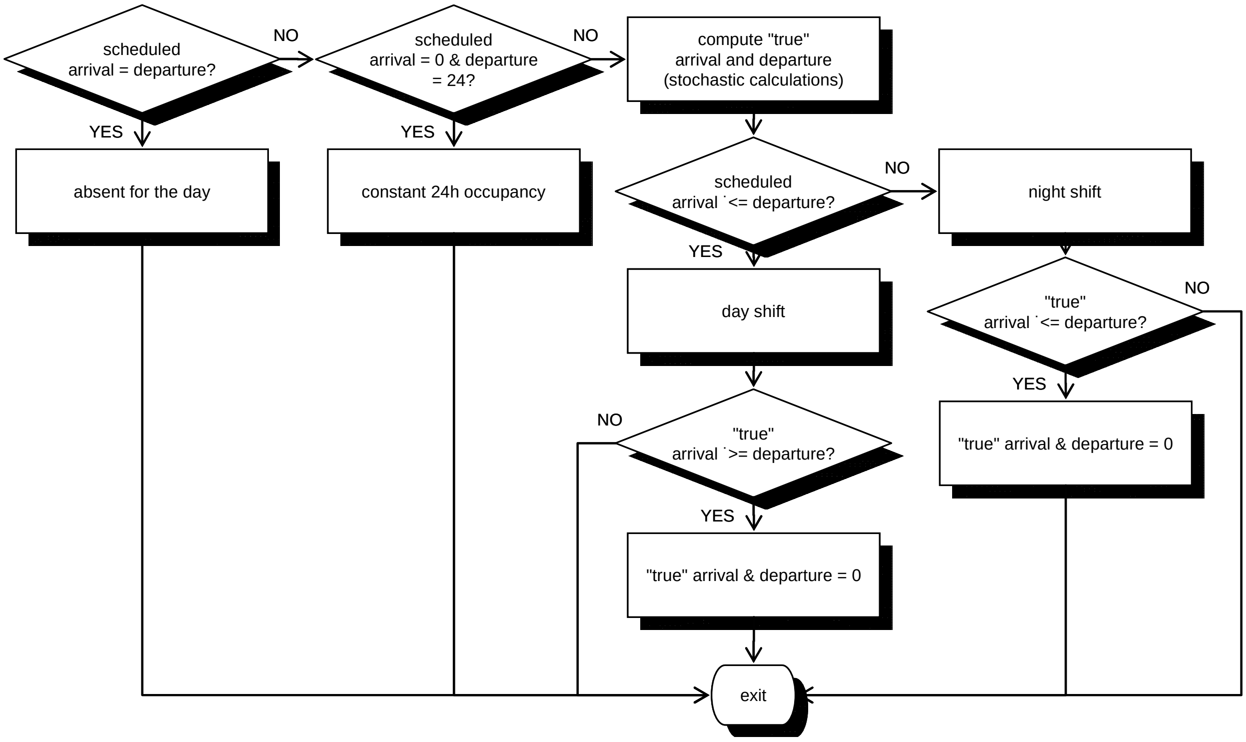

Figure 29 LSTrueAD function

Figure 30 LSTrueEvents function

Personal control: a second example of library/project data sharing

As described earlier in the thesis, it is a straightforward process in SHOCC to differentiate between groups in a given space, as well as individual occupants within groups, when it comes to attributing control over specific entities. A number of automated attribution control functions are available in SHOCC to facilitate this task. For instance, in the case of a school computer lab, it is matter of choosing the right input keyword if an overhead lighting fixture is to be controlled by *any* one occupying the lab, whether students or teachers, rather than teachers alone. Similarly, control over individual PCs in the lab can be automatically attributed to *every* single student arriving in the lab at different instances during the day. This way, plug loads in the lab will vary according to short term changes in individual occupancy levels. This *any/every* differentiation mechanism is used in abstraction of controlled entities. This is illustrated in Figure 31, where the "south_win" blinds are potentially controlled by *any* "teachers" or "students" present in the "classroom".

Additional control options are available in SHOCC when it comes to advanced behavioural models. As presented earlier in the thesis, the Lightswitch2002 algorithm processes personal control over lights and blinds differently whether users are considered *active* versus *passive* controllers. Attributing such psycho-social predispositions amongst *group occupants* within SHOCC is done by processing generic *individual* data. In Figure 32, three out of four (i.e. 75%) individual "adults" are likely to be *active* blind users, while there is no probability of individual "kids" ever controlling blinds during a simulation. Based on this, all "students", who inherit psycho-social traits from "kids", are defined at the pre-simulation stage as *passive* blind users, as shown in Figure 27.

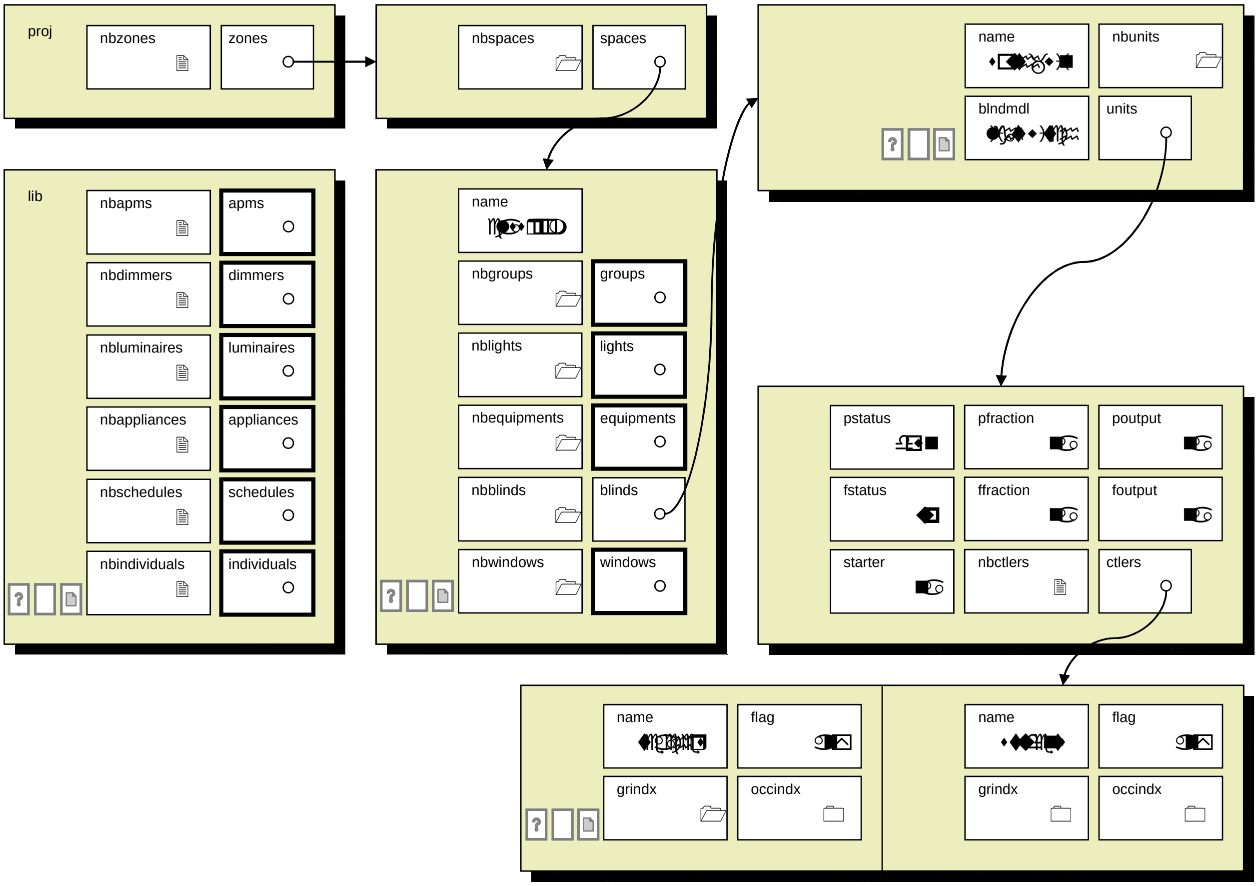

Figure 31 SHOCC blind data

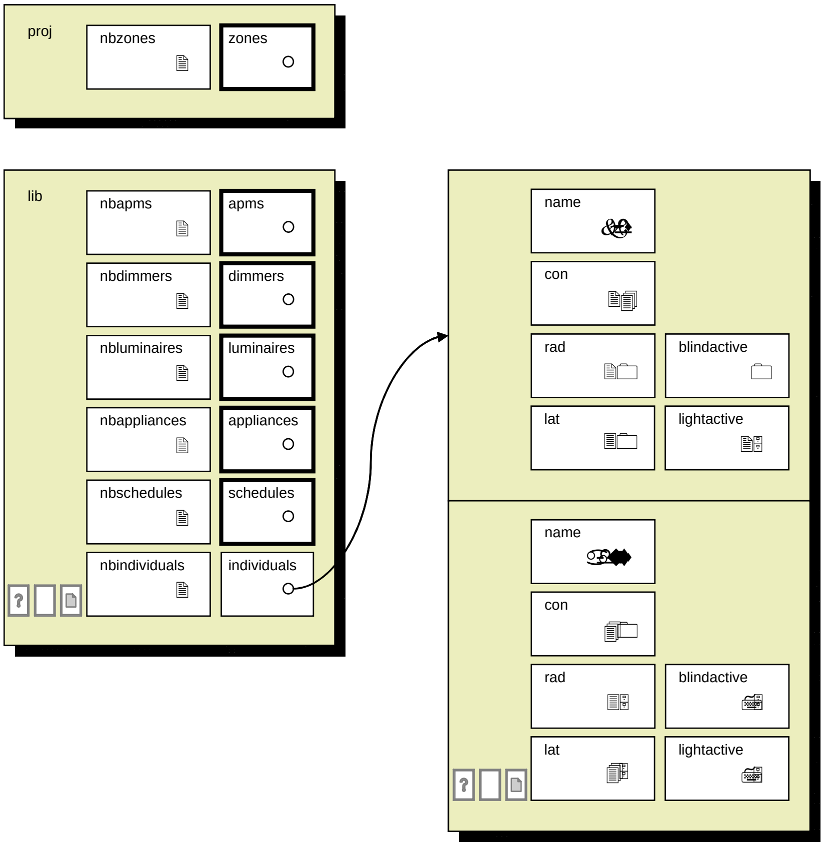

Figure 32 SHOCC individual data

Processing SHOCC data at simulation run-time

With the exception of processes described in Figure 28 through Figure 30, where occupancy patterns are processed on a daily basis, no information is provided on how other SHOCC *space* entities are updated during a simulation, especially at greater frequencies (i.e. at 5 minutes intervals). The following sub-sections provide greater insight on how the status and output of various SHOCC entities are renewed at simulation run-time, starting with population.

Occupancy

Figure 33 illustrates how short-term occupancy events (i.e. "in/out") are computed based on pre-processed data at daily frequencies (i.e. as computed in Figure 28 and then stored in Figure 27). As presented earlier, SHOCC itself does not control the flow of time (e.g. over the course of an annual simulation); rather it takes *current* time as well as *past* current time (i.e. the *current* time at the preceding time step), computed and sent by the parent program (e.g. ESP-r), as input at every time step.

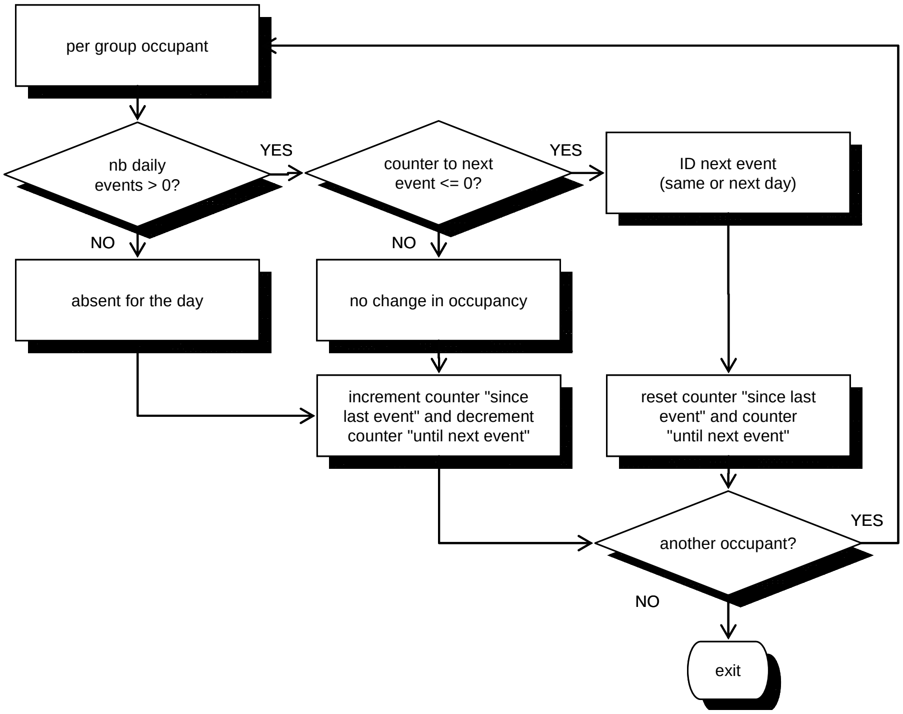

Figure 33 Short-term SHOCC occupancy control

The difference between ESP-r's *past* and *current* time determines the temporal interval used to increment or decrement an occupant's *last* and *next* event counters, processed here in Figure 33 and then stored in the appropriate data cell in Figure 27. More on ESP-r's use of past and current time in its numerical solutions is provided in (Clarke 2001); suffice to state at this point that both *times* are updated and made available at any given moment during simulation within ESP-r.

Equipments

As presented earlier, when left unattended, equipments such as PCs will gradually decrease energy expenditure after a while (e.g. by severing feed to display monitors) based on factory-set advanced power management (APM) profiles. There does not appear to be any straightforward way to determine the instantaneous heat output of equipment when in use. For instance, the total energy expenditure of a photocopy machine (as well as its heat output) will directly depend on the number of copied items over a given time frame. Even a small laptop will give off variable rates of heat depending on its use (e.g. gaming versus word-processing). SHOCC assumes a more simplified approach to compute the energy expenditure of equipment, based on averaged data published in engineering handbooks (ASHRAE 2001) as well as common factory-set APM profiles (Roberson et al. 2002). The basic postulates in SHOCC are that equipment units are considered to be in use if any designated *controllers* (i.e. occupants) are present, and corollary to this is that they start powering down once *controllers* leave. Both postulates are somewhat simplistic, as it is quite possible that people may indeed be at their workstations while their PCs are off, or powering down, or that APM profiles are disabled thereby leaving PCs on during prolonged periods. In addition, the literature review does not reveal any reliable field-based statistics on user behaviour, e.g. the probability of office workers consciously switching-off their computers when leaving for the day. Until more reliable information in this regard is published, the aforementioned postulates on equipment use will remain available as optional control mechanisms in SHOCC.

The status (i.e. "on/off") and heat output (in W) of individual *equipment* (e.g. PCs) can be determined following the process described in Figure 34. For each equipment *unit* (i.e. individual instances of a library *appliance*), the function loops through all designated unit *controllers* to check their occupancy status (i.e. "in/out"). If at least one *controller* is "in", then the status of the *unit* is set at "on" and its heat output is set at nominal values defined by its associated APM profile. If instead none are "in", the function loops once again through all designated *controllers* to determine how long ago the last *controller* left. If the computed lapse of time is longer then its first-stage APM setting, then the appropriate output fraction is used to update the *unit*'s current heat output. At that point, the *unit*'s status is reset, indicating that it has begun the process of actually powering "off". Subsequently, the *unit*'s output will follow its APM profile settings until the final stage is reached, at which point its output will remain constant until at least one of its *controller* returns.

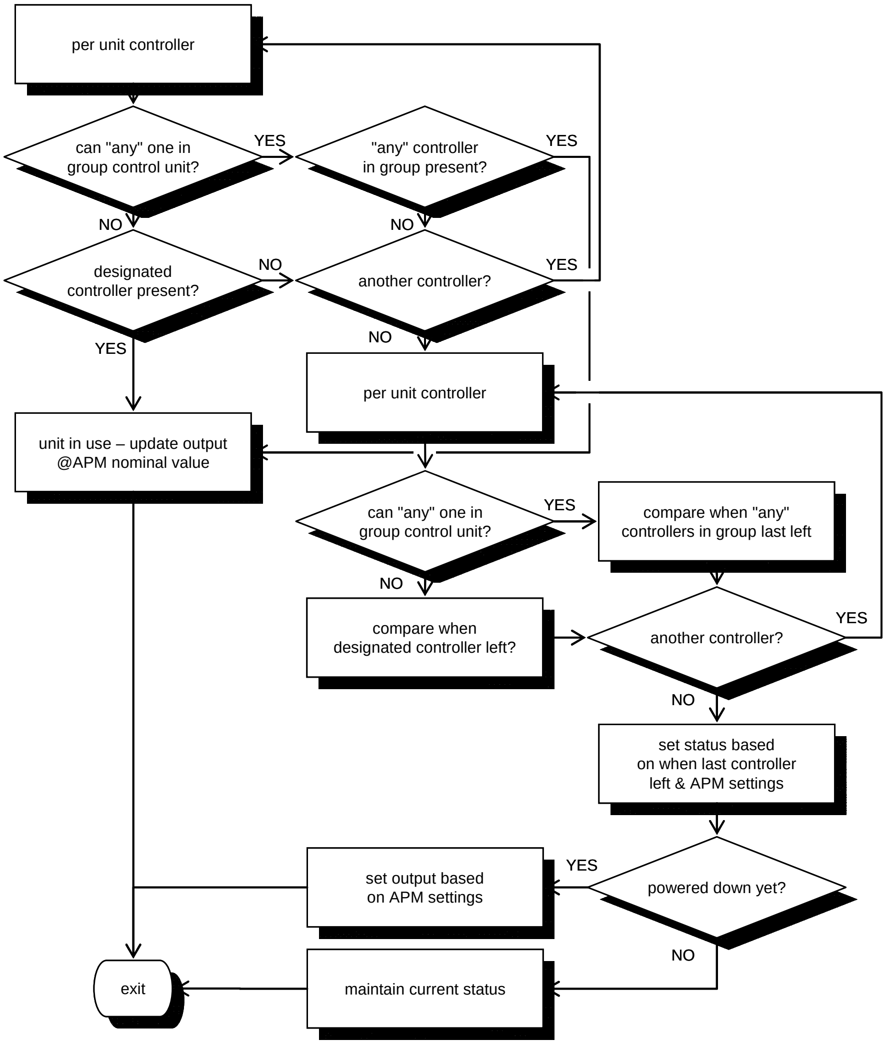

Figure 34 Short-term SHOCC equipment control

Blinds

The preceding example illustrates how SHOCC computes *unit* status and output at simulation run-time for entities that do not have any associated field-based behavioural model, e.g. equipment. As presented earlier in the thesis, more advanced, behavioural control is demonstrated using manual control of blinds as a first example, based on the Lightswitch2002 algorithm (note: the Lightswitch2002 algorithm also covers automated blind control which aims at optimizing daylight availability while avoiding direct glare. This is not developed in the current SHOCC version). The working hypothesis in SHOCC is that any *active* controller has supervisory control over units (e.g. blinds) when concurrently sharing control with any number of *passive* controllers. This way, personal control resulting from the social interactions of many is collapsed to the behaviour of the dominant controller.

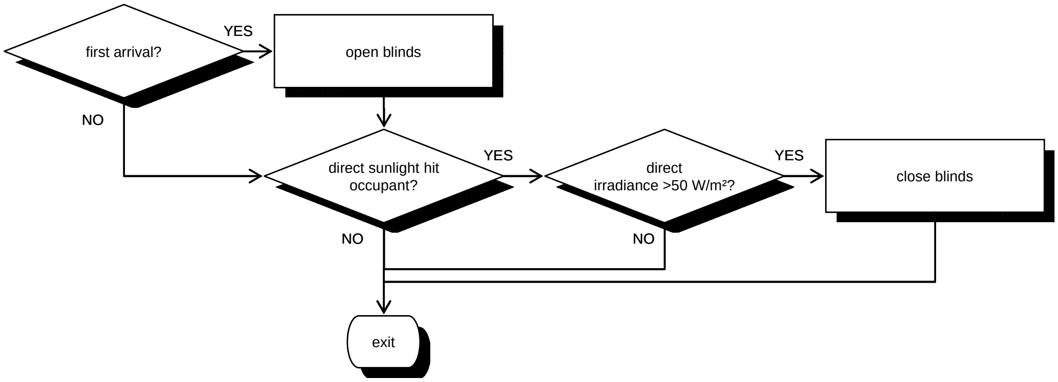

Figure 35 Original Lightswitch2002 *active* manual blind control

To illustrate how this concept operates within SHOCC, it is suitable to first show how the Lightswitch2002 blind control works for *active* blind controllers (i.e. *passive* controllers consistently keep blinds lowered), as depicted in Figure 35. Figure 36 illustrates the modified Lightswitch2002 manual blind control that takes into account three possibilities: *active* controllers only; *passive* controllers only; and *asynchronous cohabitation*. The outcome may differ depending on occupancy patterns.

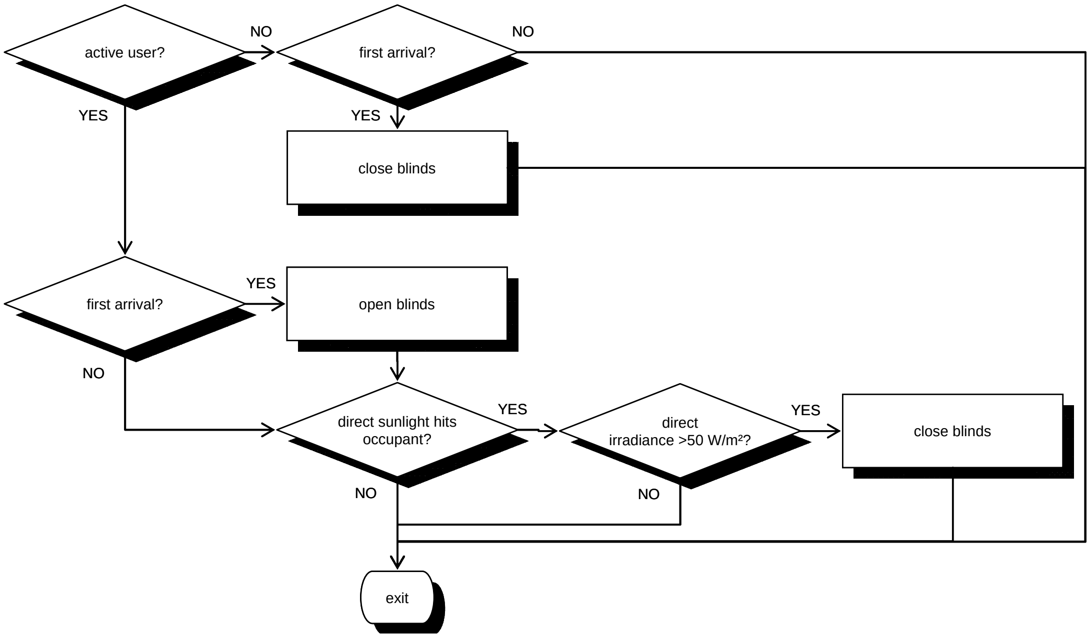

Figure 36 Modified Lightswitch2002 manual blind control

The function in Figure 36 first considers whether the designated (i.e. dominant) controller is *active* or not regarding blind control, then whether the controller is first arriving, and so on. To do this, SHOCC must first acquire the necessary information by looping through designated blind controllers, as illustrated in Figure 37, before calling the *LSManualBlind* function (i.e. the Lightswitch2002 blind control function shown in Figure 36). As presented earlier in the thesis, data flow in Figure 34 and Figure 37 provides some insight on the benefits of encapsulating *group/occupant* data accessed through high-level interfacing, as well as code reusability, i.e. both equipment and blind control make use of higher-level functions which reveal the current state of occupancy patterns without revealing the internal workings of group/occupant data structures.

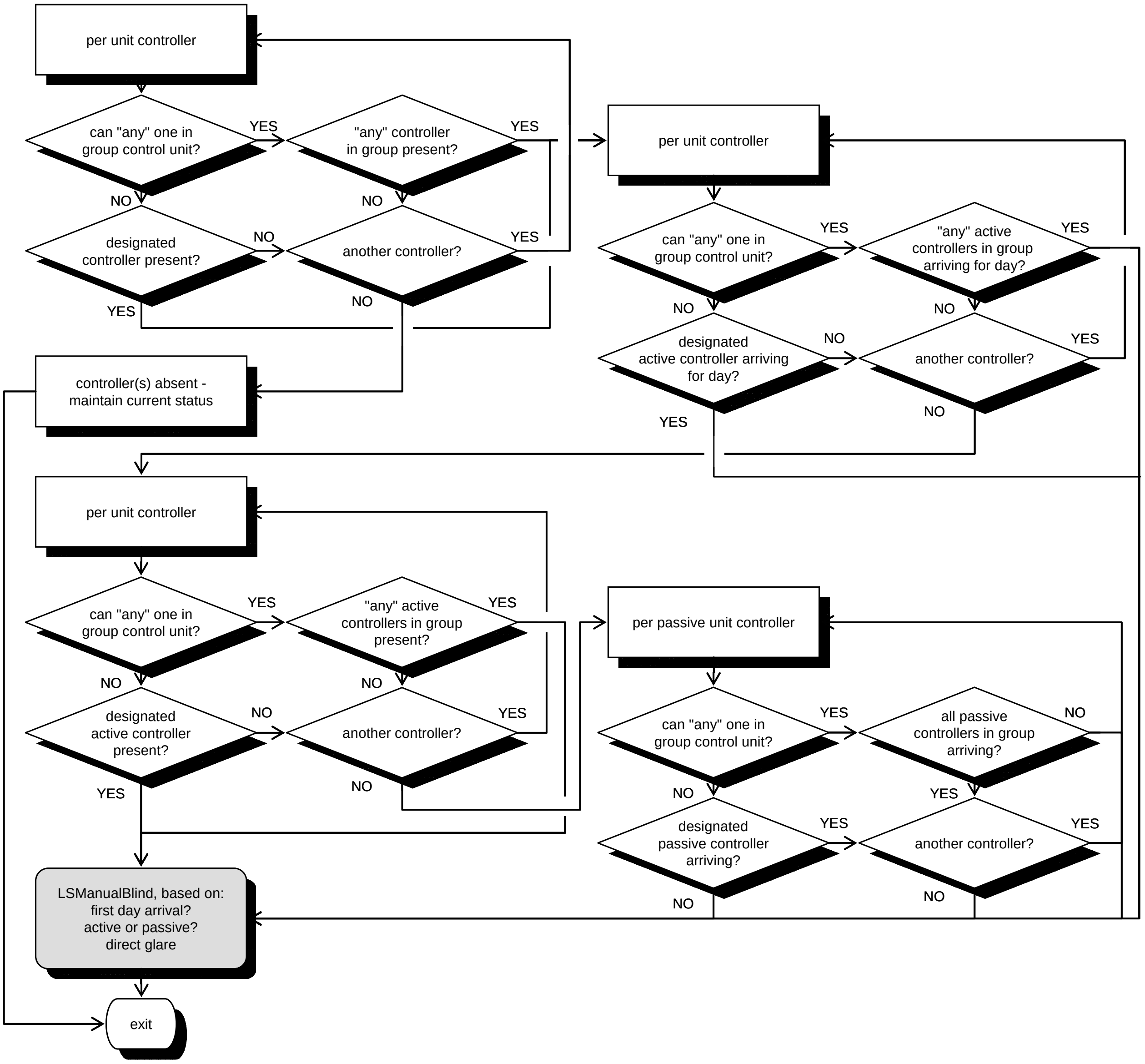

Figure 37 Short-term SHOCC blind control

Lights

A postulated order of precedence is imposed in SHOCC to solve such potential conflicts, as illustrated in Figure 38.

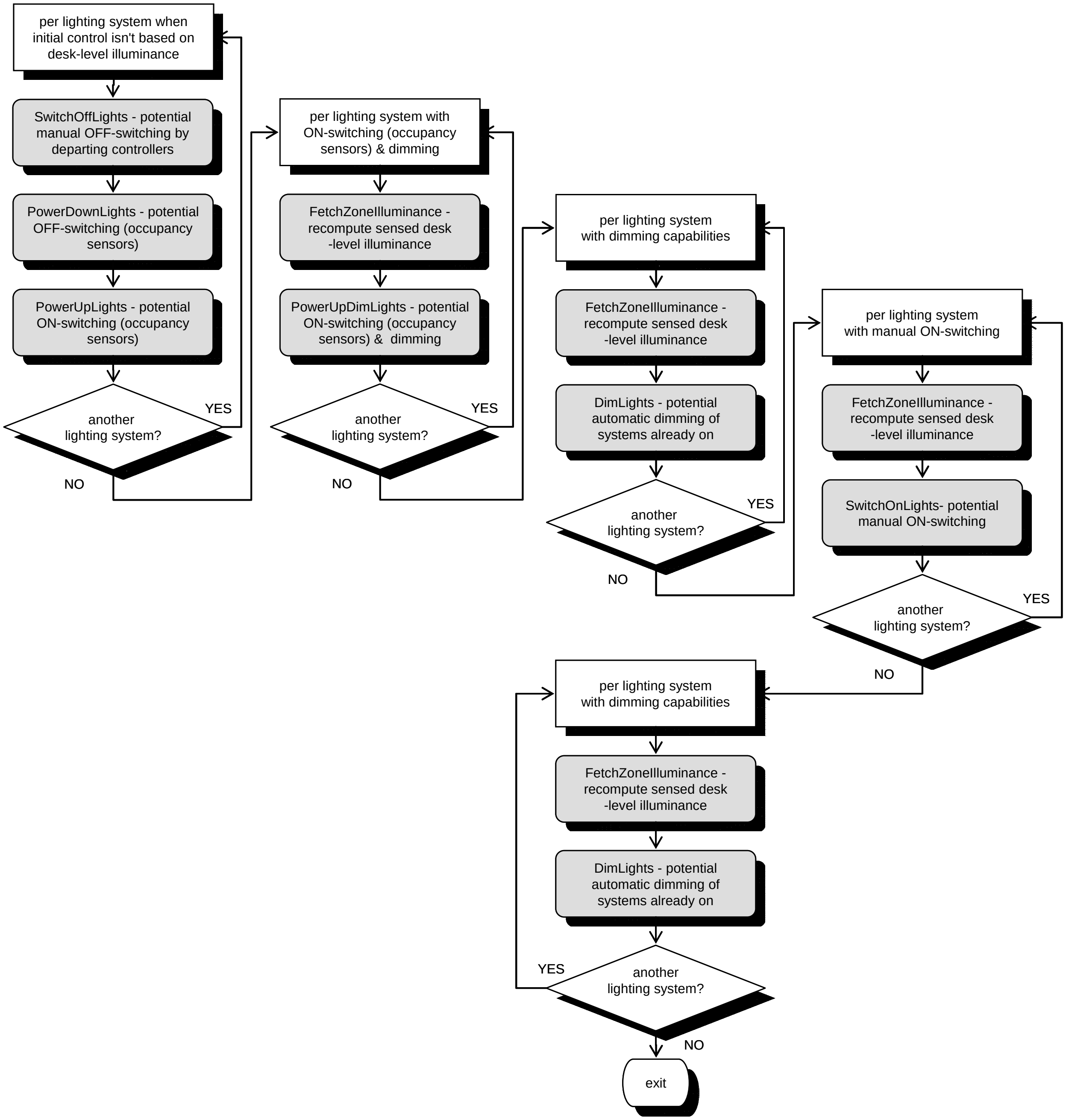

Figure 38 Short-term SHOCC light control

SHOCC first processes lighting control that doesn't initially consider sensed illuminance either by photocells or by the controlling dominant occupant. This includes manual off-switching patterns when leaving (i.e. part of the Lightswitch2002 algorithm, described in Figure 39), as well as occupancy-sensing systems which are powering off (see Figure 40) or powering up (see Figure 41). These systems are processed first as their resulting output remains fixed for the current time step. Next, SHOCC processes automated on-switching with dimming capabilities in isolation, as illustrated in Figure 42. The logic is that these systems will automatically power up once someone arrives/returns regardless if additional illuminance is actually required. SHOCC then processes dimmed systems which remain on. At the exception of manual off-switching when leaving, only automated controls have been considered up to this point, since their signal processing (e.g. occupancy-sensing, photocell-sensed illuminance) and subsequent actuation (e.g. on/off switching, dimming, etc.) is executed in a fraction of the time it takes an occupant to process the resulting desk-level illuminance. At this point, any manual on-switching patterns are processed, as illustrated in Figure 43, finally followed by subsequent corrections from any dimmed systems which remain on; an automated response to manual settings.

Figure 39 *SwitchOffLights* function

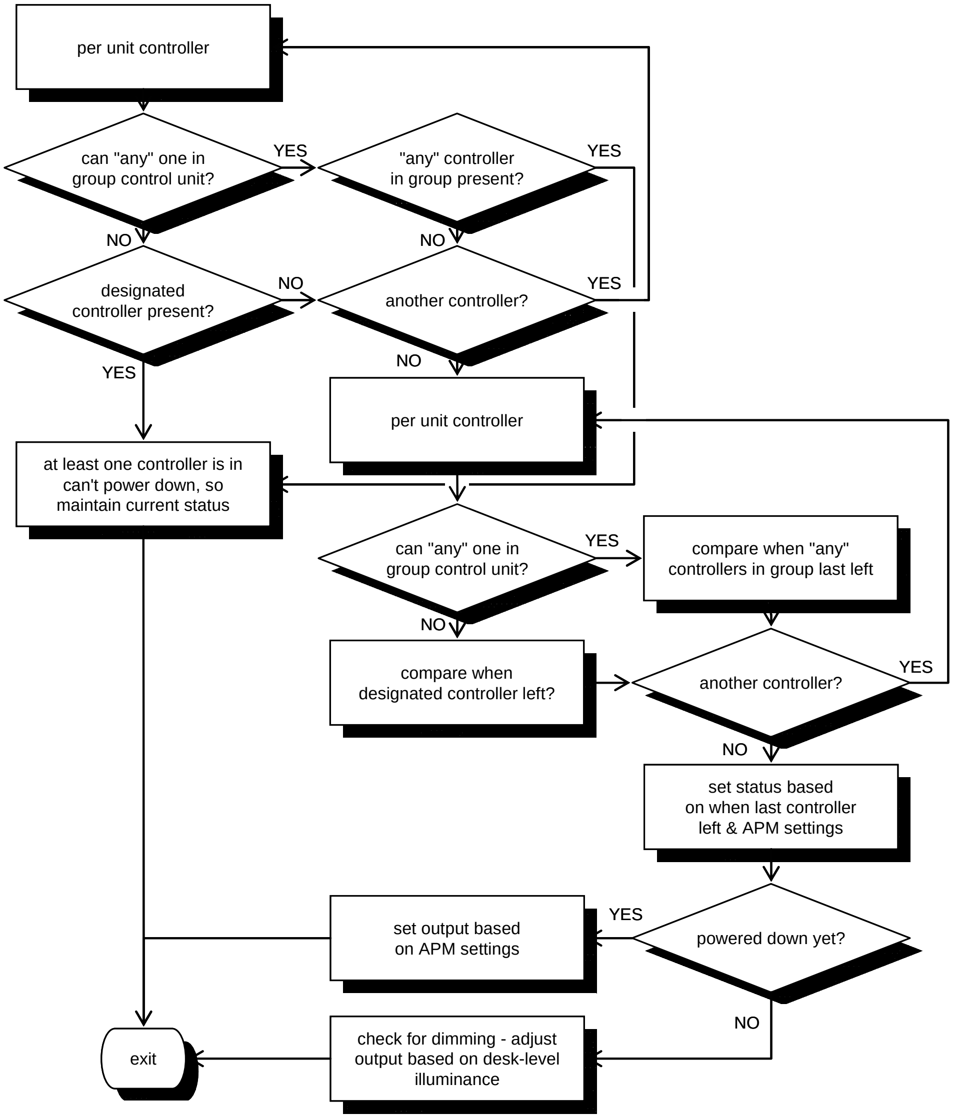

Figure 40 *PowerDownLights* function

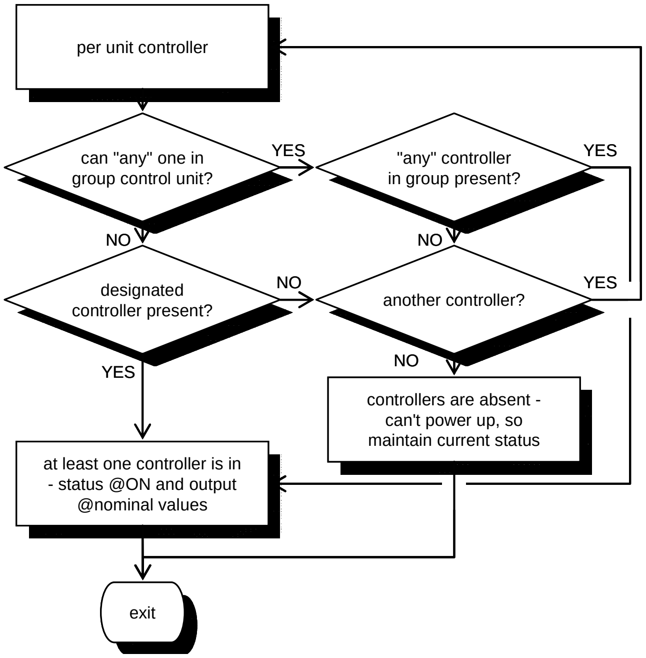

Figure 41 *PowerUpLights* function

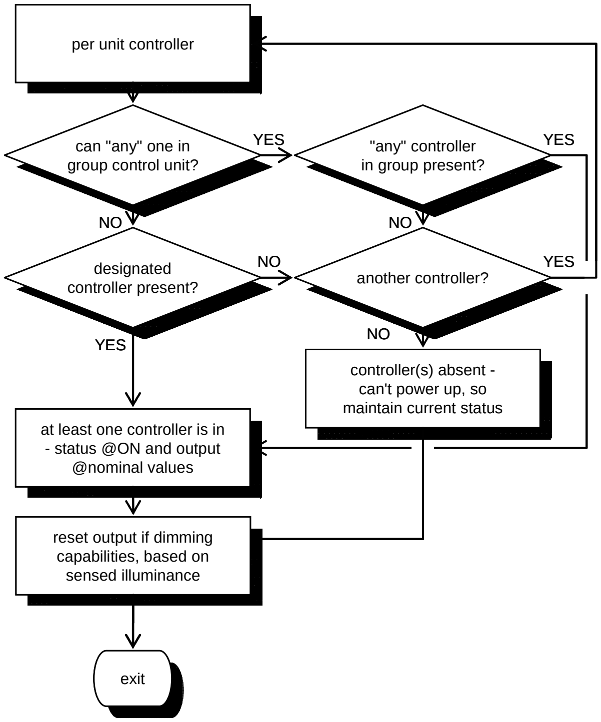

Figure 42 *PowerUpDimLights* function

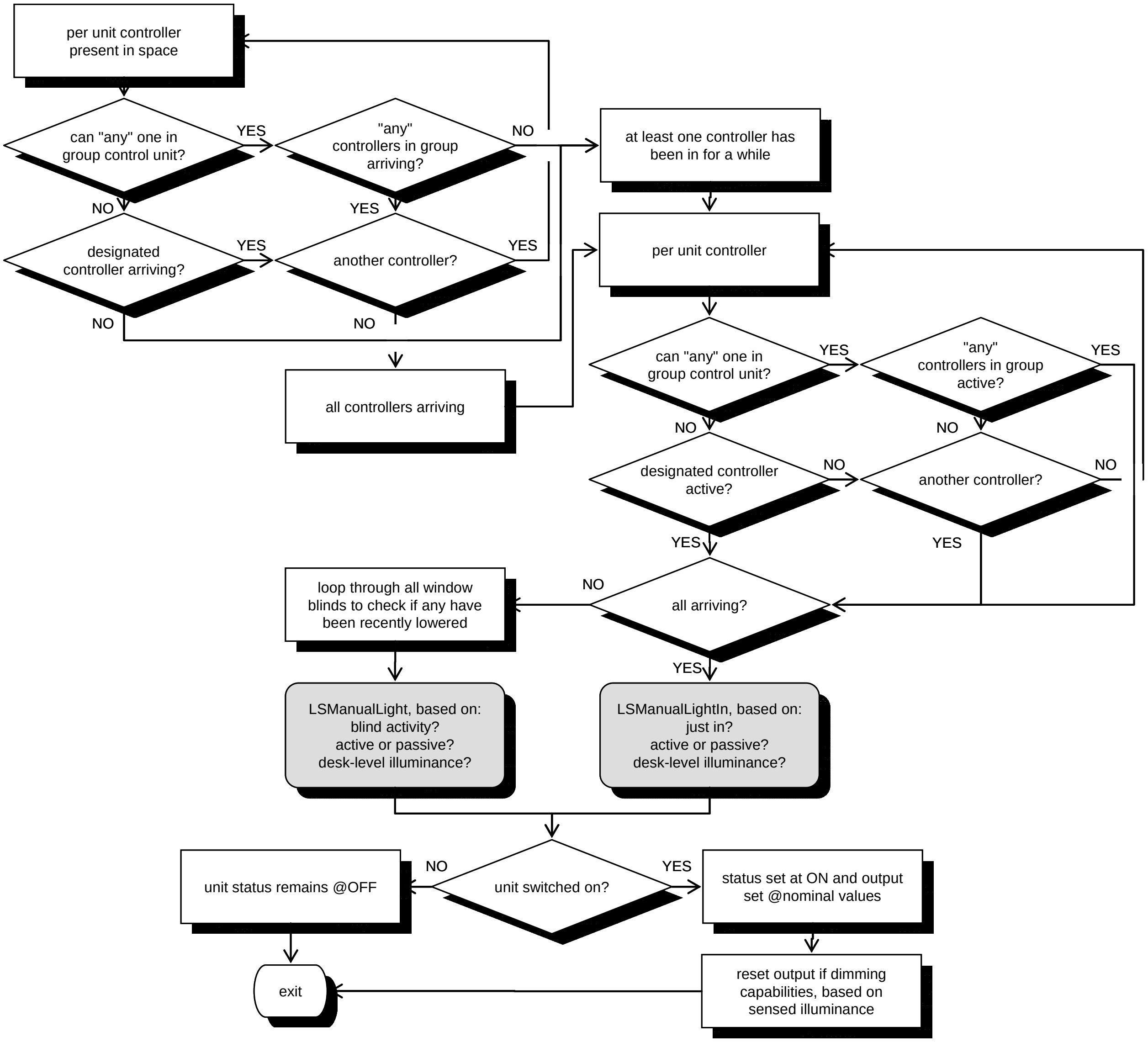

Figure 43 *SwitchOnLights* function

Just as with manual blind control, SHOCC must first loop through designated light controllers and gather the necessary data before calling the *LSManualLightOut* function (i.e. the Lightswitch2002 light control function shown in Figure 39), as well as the *LSManualLight* and *LSManualLightIn* functions (i.e. the Lightswitch2002 light control functions shown in Figure 43). The control functions shown in Figure 40, Figure 41 and Figure 42, whose output does not depend on behavioural modelling, are very similar in design to equipment control.

Appendix B - Linking SHOCC to ESP-r

How SHOCC is linked to ESP-r is best presented by comparing *before* (i.e. unSHOCC'ed) and *after* (i.e. SHOCC'ed) versions of ESP-r's data flow control (July 2004 archived version downloaded from ESRU's ftp site). Just as in Appendix A, the pre-simulation processes are first presented, followed by how SHOCC works in tandem with ESP-r at run-time. Subject matter presented in Appendix A may be considered as a prerequisite to understanding how SHOCC is linked to ESP-r.

Pre-simulation stage

During the early phases of design, it is typical to rely on basic definitions, such as standard diversity profiles for internal casual gains, when running ESP-r. As the design evolves, and more information becomes available, it is then possible to override basic definitions through more complex calculation computations. This option is available in ESP-r for advanced lighting control (i.e. overriding user-defined casual gains) as well as multizone airflow networks (i.e. overriding user-defined infiltration rates).

An example is illustrated in Figure 44, where the *MZCASG* routine first differentiates between *controlled* (e.g. dimmed) versus *uncontrolled* lighting casual gains at the pre-simulation stage, while the *MZCASI* routine later computes internal gains (i.e. *controlled* and *uncontrolled*) to complete the zone matrix coefficients at simulation run-time.

A similar process is illustrated in Figure 45, only here additional SHOCC functionality is added. At the pre-simulation stage, the ESP-r simulator calls SHOCC's *InitProj* function to initiate its own void project; only ESP-r and SHOCC zone numbers match at this point. Then a SHOCC library (i.e. project-wide definitions) is read from file and stored in the *lib* structure (i.e. SHOCC's library root structure), as described in the preceding chapter. Similarly, for every ESP-r thermal zone, SHOCC zone entities are read and stored in respective *zone* branches of the *proj* structure (i.e. SHOCC's project root structure).

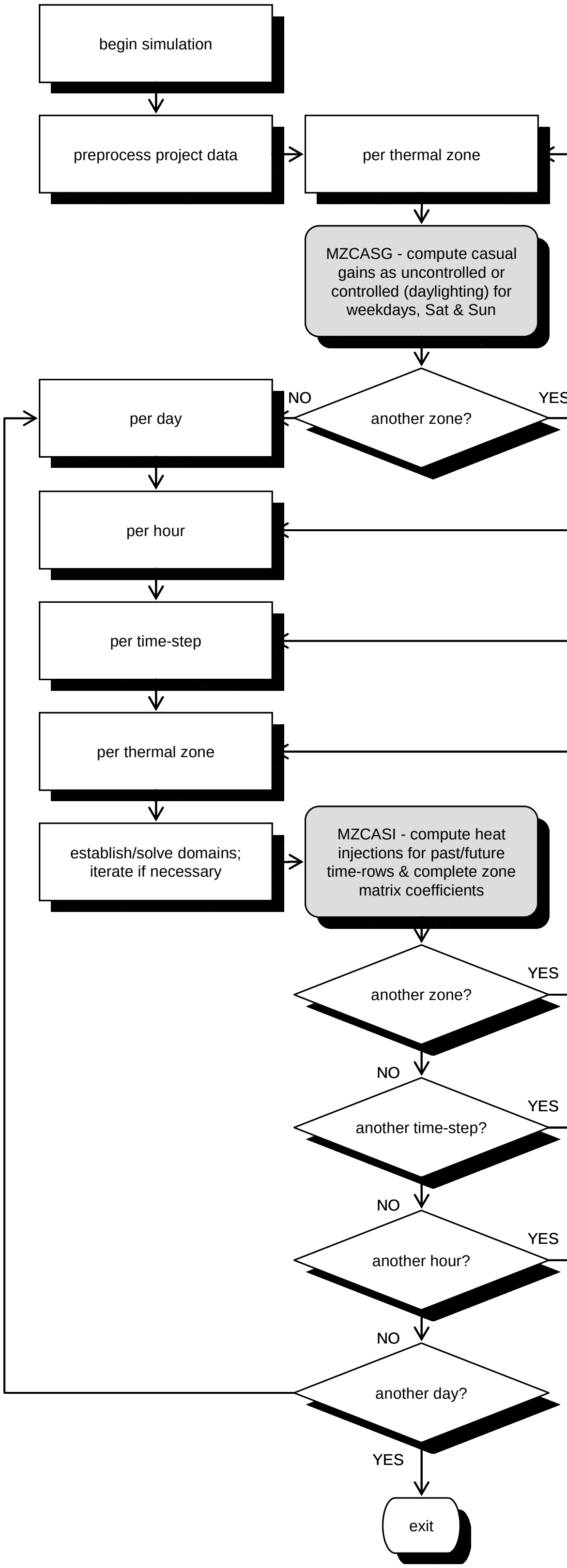

Figure 44 ESP-r's pre-simulation stage and simulation time control (unSHOCC'ed)

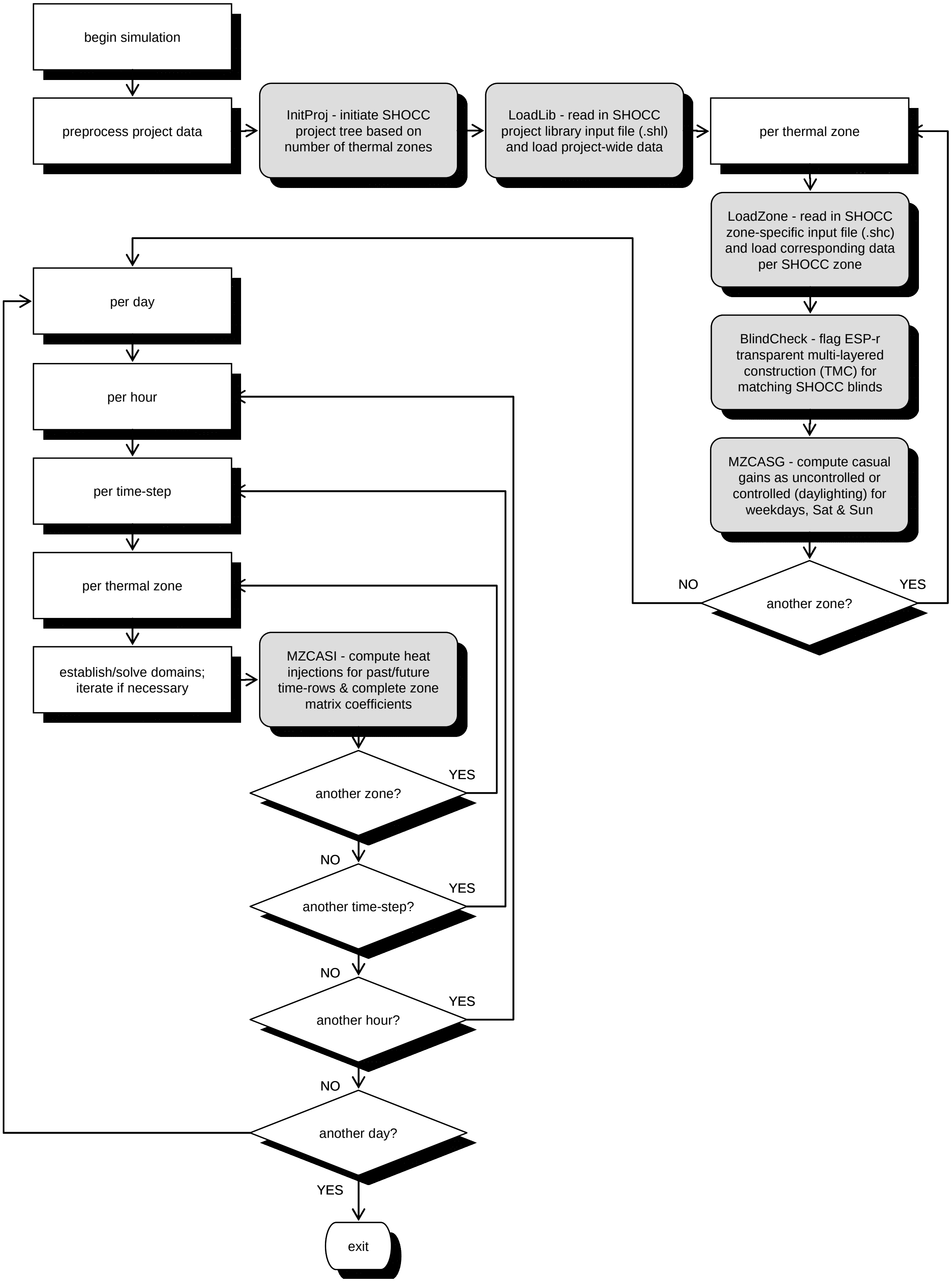

Figure 45 ESP-r's pre-simulation stage and simulation time control (SHOCC'ed)

At this point, ESP-r and SHOCC can be considered as parallel applications which share only the same number of thermal zones. The pre-simulation stage must be completed at the zone-level by linking ESP-r and SHOCC entities by matching ID strings. The simplest case is linking ESP-r transparent multi-layered constructions (TMCs) to SHOCC blinds though SHOCC's *BlindCheck* function. A similar approach is used to link SHOCC entities which may discharge heat (e.g. occupants, lights, PCs, etc.) to ESP-r casual gains. Figure 46 illustrates the original *MZCASG* function, first identified in Figure 44. Pre-processing casual gain data is a two-step process. First, sensible gains are processed individually on an hourly basis for every typical daytype (e.g. weekday, Saturday and Sunday), based on their radiative and convective split. In the second step, radiative and convective gains for all loads are reduced by summation as a single value for every hour per daytype, yet also stored separately whether they are *controlled* or *uncontrolled* gains.

Again, the process is quite similar when SHOCC is enabled, as shown in Figure 47. The difference is that the ESP-r simulator calls SHOCC to verify matching entities through its *ShoccLoad* function. If no match is found, then the process continues as it should. If a match is found, the linked casual gain is then discarded altogether as the related output (e.g. in watts) will be dynamically processed and sent back by SHOCC at run-time.

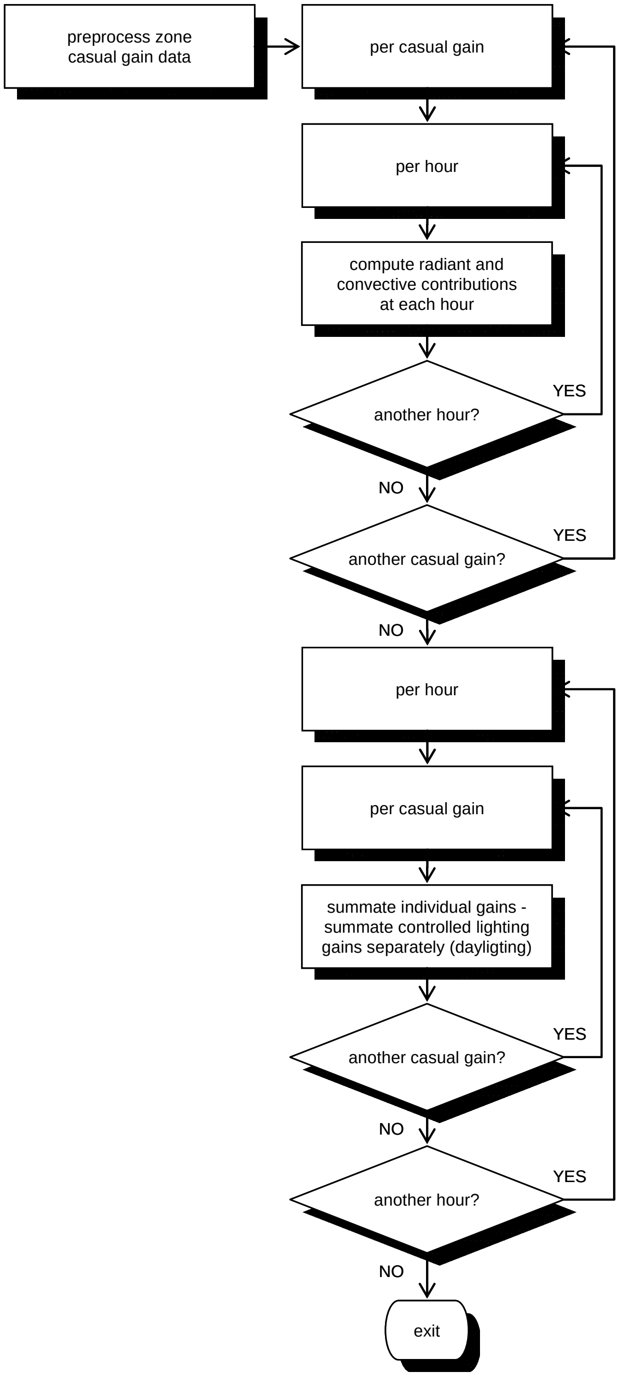

Figure 46 ESP-r's *MZCASG* routine (unSHOCC'ed)

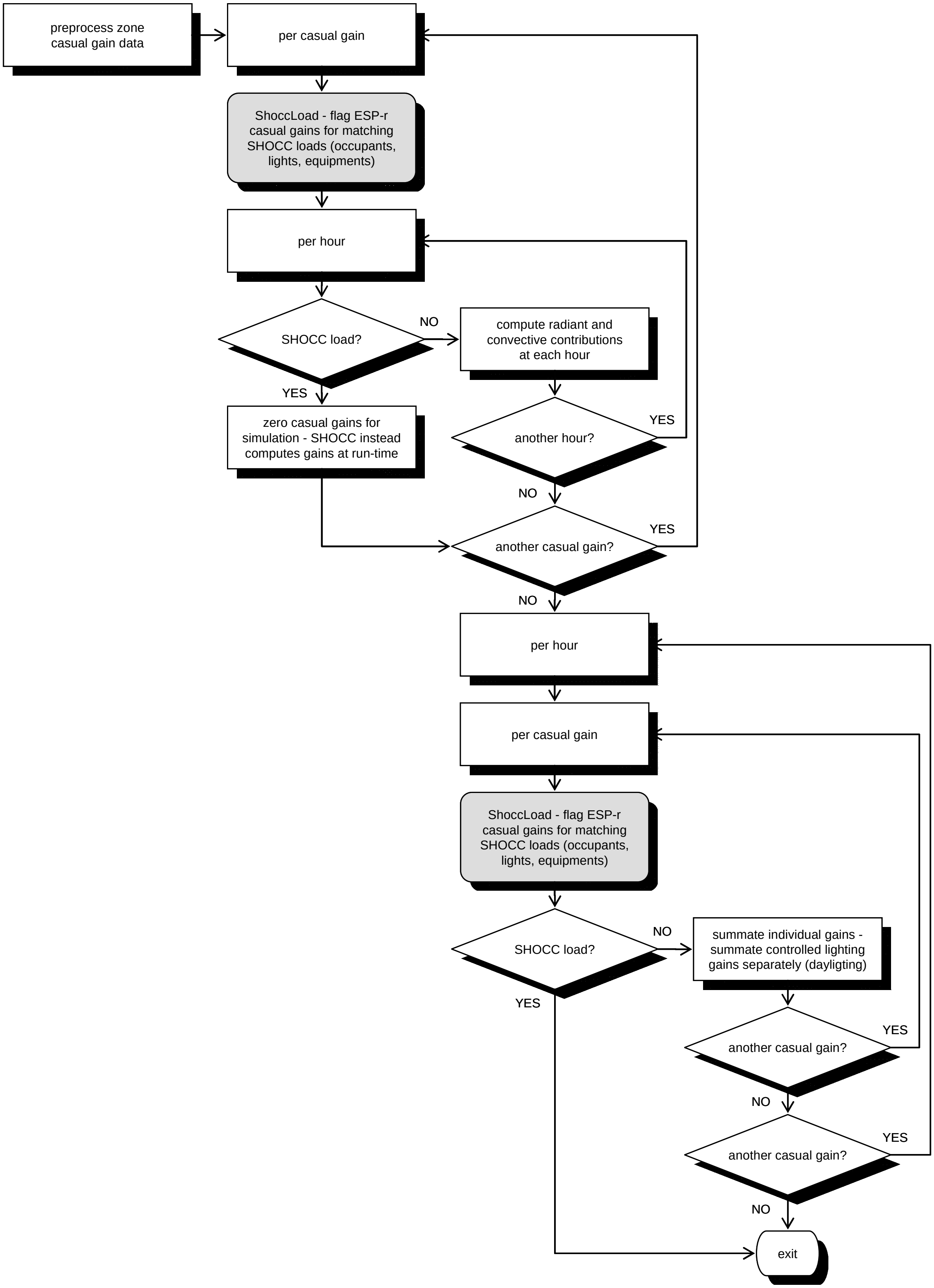

Figure 47 ESP-r's *MZCASG* routine (SHOCC'ed)

Simulation run-time

Once the pre-simulation stage is completed, all relevant ESP-r and SHOCC entities have been linked. At this point, the original ESP-r simulator can initiate the actual simulation, as illustrated in the lower part of Figure 44 and Figure 45, all the while processing SHOCC output as input. The first step to ensure proper data exchange is to update SHOCC occupancy in sync with ESP-r time.

Updating SHOCC occupancy

The ESP-r simulator calls SHOCC to update its own occupancy status at various frequencies (e.g. daily and at every time step). This is a fairly straightforward process, at daily and time-step frequencies shown in Figure 45, with higher-level calls to SHOCC occupancy functions described in Figure 29 (i.e. daily) and Figure 30 (i.e. time-step).

Updating SHOCC blinds

The ESP-r follows the logical sequence of technical domain processing/solving, starting with solar processes. It is within this technical domain that blind/shutter control is available, if desired. Figure 48 illustrates the original control options for ESP-r blind/shutter control. Based on the control parameters, alternate TMC properties can be retained before completing solar calculations.

Figure 49 shows how SHOCC blind control is added as another control option, with *UpdateBlind* function being nothing more than a higher-level call to the function described in Figure 37 in the preceding chapter. Depending on the *UpdateBlind* reply, alternate optical data may be selected.

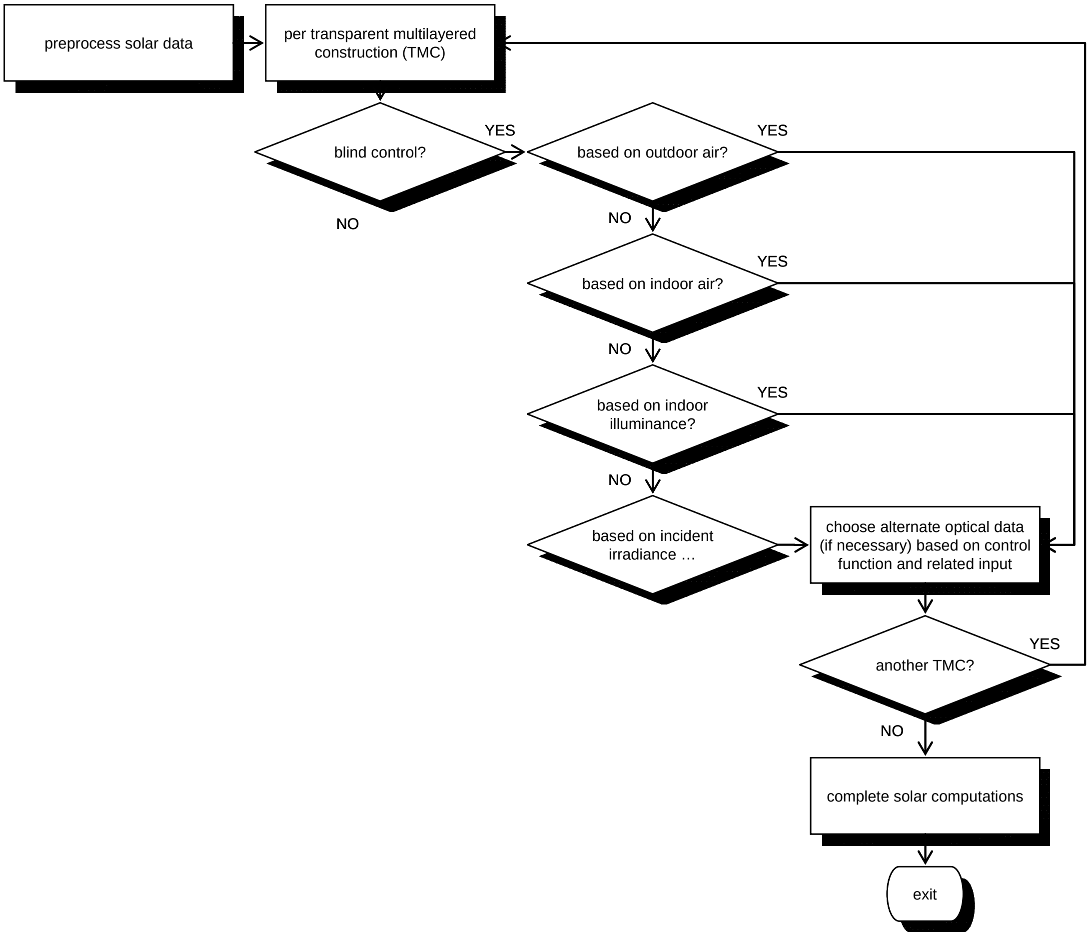

Figure 48 ESP-r's blind/shutter control (unSHOCC'ed)

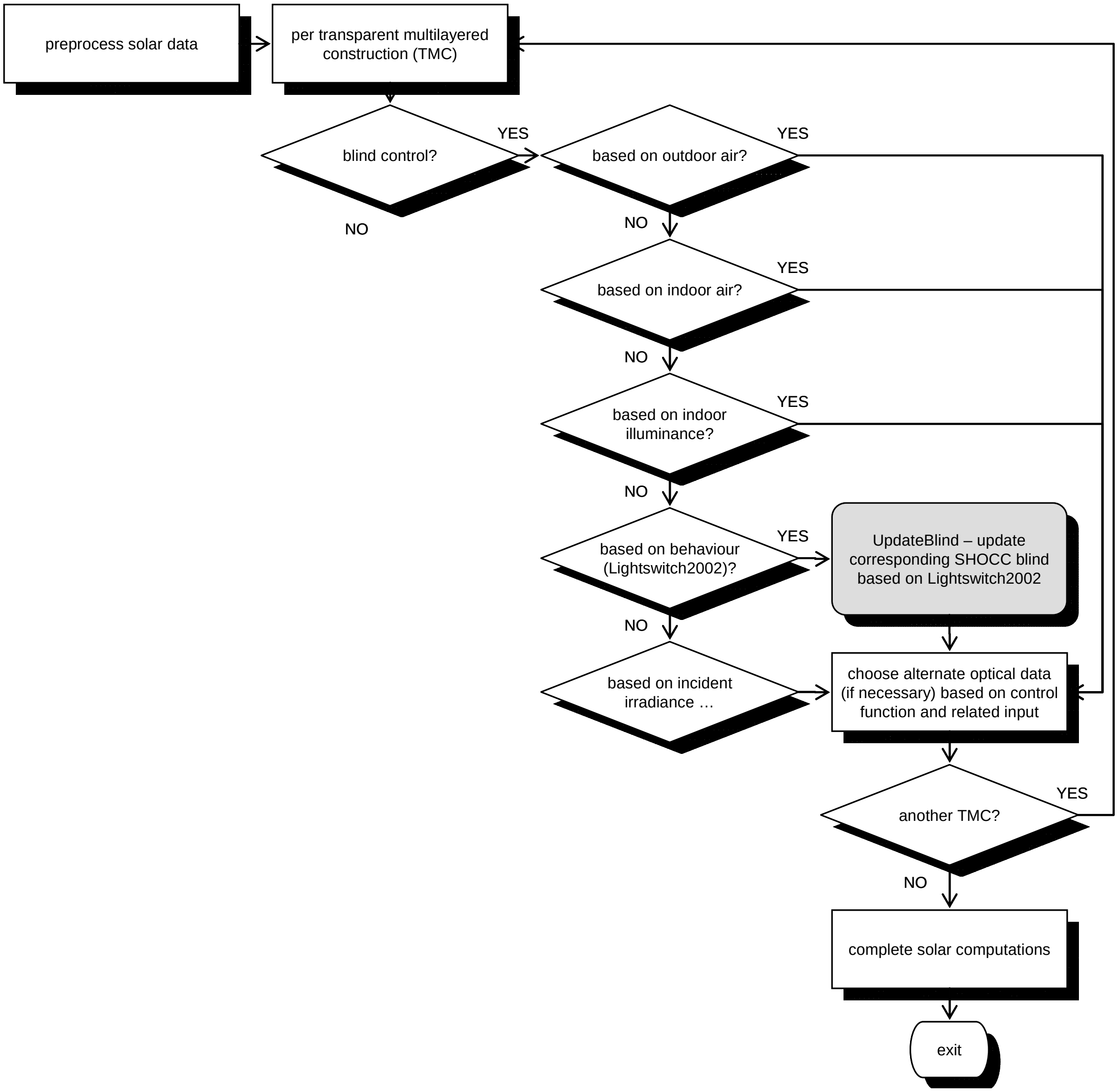

Figure 49 ESP-r's blind/shutter control (SHOCC'ed)

Updating SHOCC equipment and lighting

It is within the *MZCASI* routine, cited in Figure 44, that *controlled* and *uncontrolled* gains, regardless of their emitting source (e.g. occupants), are processed and then lumped into a single value for subsequent computations. This is depicted in Figure 50. If a given casual gain is to be *controlled*, then the *INTLUM* routine returns the output fraction of the controlled gain based on a chosen parameter (e.g. sensed illuminance). It is within *INTLUM* that direct coupling with Radiance or access to Radiance-derived daylight coefficients is possible (Janak and Macdonald 1999, Janak 1997).

With SHOCC enabled, the process remains familiar yet with a few additional embedded processes. First, the previous time-step SHOCC loads are retrieved for ESP-r's own computations before calling SHOCC's *UpdateEquipment* function; a higher-level call to the function described in Figure 34 in the preceding chapter. This renews equipment status based on revised occupancy status. Within the *INTLUM* routine, where sensed illuminance is processed for instance, SHOCC lights are updated following the process described in Figure 38 in the preceding appendix. At this point, the status of all SHOCC occupants, equipments and lights are updated, allowing the subsequent retrieval of all SHOCC gains through the *FetchLoads* function, as depicted in Figure 51.

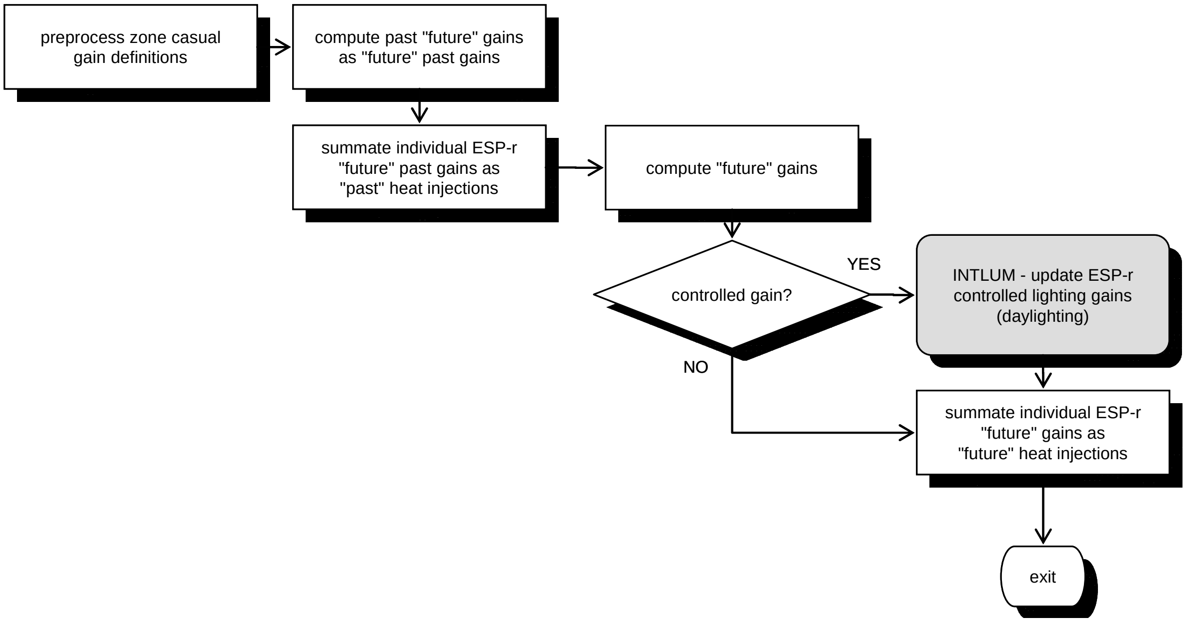

Figure 50 ESP-r's *MZCASI* routine (unSHOCC'ed)

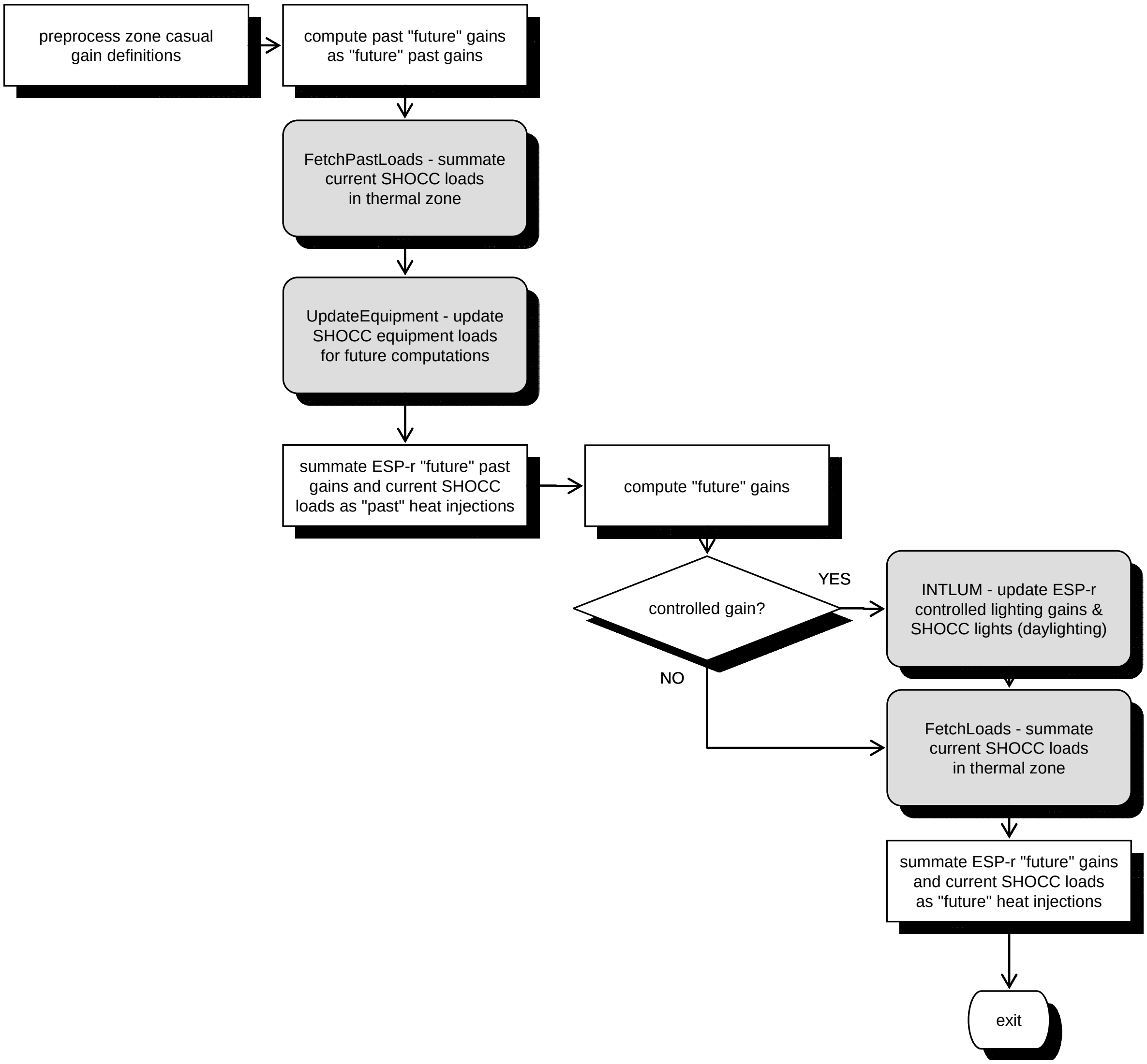

Figure 51 ESP-r's *MZCASI* routine (SHOCC'ed)

References

ASHRAE 55 (1992) "Thermal Environmental Conditions for Human Occupancy", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE 90.1 (2001) "Energy standard for buildings except low-rise residential buildings (IESNA cosponsored; ANSI approved; Continuous Maintenance Standard), SI Edition", American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

CIBEUS (2003) "Commercial and Institutional Building Energy Use Survey 2000: Summary Report", Statistics Canada, on behalf of the Office of Energy Efficiency (OEE), of Natural Resources Canada (NRCan).

DGCCB (2002) "Daylighting Guide for Canadian Commercial Buildings", Public Works and Government Services Canada (PWGSC).

DIN 5034 (1999) "Tageslicht in Innenräumen", Deutsches Institut für Normung.

DIN 5035 (1990) "Innenraumbeleuchtung mit künstlichem Licht Richtwerte", Deutsches Institut für Normung.

EE4 (2000) "EE4 CBIP User's Guide, v.1.30", Natural Resources Canada, Ottawa.

EQ (2001) "L'énergie au Québec", Les Publications du Québec: Sainte-Foy.

IESNA (2000) "The Lighting Handbook 9th edition", Illuminating Engineering Society of North America, New York.

ISO 7730 (1994) "Moderate thermal environments: Determination of the PMV and PPD indices and specification of the conditions for thermal comfort", International Standards Organisation.

LEED v.2.1 (2002) "The Leadership in Energy and Environmental Design (LEED) Green Building Rating System for New Construction & Major Renovations (LEED-NC) Version 2.1", U.S. Green Building Council.

MNECB (1997) "Model National Energy Code of Canada for Buildings", National Research Council of Canada, Institute of Research in Construction, Canadian Commission on Building and Fire Codes.

NBC (1995) "National Building Code of Canada", Canadian Commission on Building and Fire Codes, National Research Council of Canada, Institute of Research in Construction.

QCC (2001) "Quebec Construction Code - Chapter 1, Building, and National Building Code of Canada 1995 (amended)", National Research Council of Canada, Institute of Research in Construction, Canadian Commission on Building and Fire Codes.

RRECNB (1992) "Regulation Respecting Energy Conservation in New Buildings, QRR c.E-1.1, r.1", Gouvernement du Québec.

SAS (2001) "SAS release 8.02", SAS Institute Inc., Cary.

SHEU (2000) "1997 Survey of Household Energy Use: National Energy Use Database, Summary Report", Office of Energy Efficiency, Natural Resources Canada.

SHEU (1994) "1993 Survey of Household Energy Use: National Results", 94-R-2-A, Efficiency and Alternative Energy Branch, National Resources Canada.

Abushakra B., Haberl J. and Claridge D.E. (2004) "Overview of existing literature on diversity factors and schedules for energy and cooling load calculations (1093-RP)" *ASHRAE Transactions* 110(1).

Abushakra B., Sreshthaputra A., Haberl J. and Claridge D.E. (2001) "Compilation of diversity factors and schedules for energy and cooling load calculations", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Report RP-1093.

Aggerholm S. (2002) "Hybrid ventilation and control strategies in the Annex 35 case studies", IEA-ECBCS Annex 35 case study report.

Aldrich J.H. and Nelson F.D. (1984) *Linear Probability, Logit, and Probit Models* Sullivan J.L. (ed.) Quantitative Applications in the Social Sciences, Beverly Hills, Sage.

Arens E.A., Tengfang X., Miura K., Zhang H., Fountain M. and Bauman F.S. (1998) "A study of occupant cooling by personally controlled air movement" *Energy and Buildings* 27(1) 45-59.

ASHRAE (2001) *Fundamentals Handbook*, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Baker N. and Standeven M. (1996) "Thermal comfort for free-running buildings" *Energy and Buildings* 23(3) 175-182.

Baker N. and Standeven M. (1994) "Comfort criteria for passively cooled buildings: A Pascool task" *Renewable Energy* 5(II) 977-984.

Banham R. (1969) *The Architecture of the Well-Tempered Environment*, Chicago, The University of Chicago Press.

Bauman F.S., Baughman A., Carter G. and Arens E.A. (1997) "A field study of PEM (personal environmental module) performance in Bank of America’s San Francisco Office Buildings" Berkeley, Center for Environmental Design Research, University of California. Final report submitted to Johnson Controls World Services, Inc.

Beausoleil-Morrison I. (2000) "The adaptive coupling of heat and air flow modelling within dynamic whole-building simulation", Glasgow, University of Strathclyde, PhD thesis thesis.

Bordass W.T., Heasman T., Leaman A. and Perry M. (1994) "Daylighting use in open-plan offices: the opportunities and the fantasies" in *Proceedings of the CIBSE National Lighting Conference*, 251-259.

Borooah V.K. (2001) *Logit and Probit: Ordered and Multinomial Models* Lewis-Beck M.S. (ed.) Quantitative Applications in the Social Sciences, Thousand Oaks, Sage.

Bourgeois D., Haghighat F. and Potvin A. (2002) "On the applicability of hybrid ventilation in Canadian office and educational buildings: Part 1 - Barriers and opportunities stemming from building regulation" in *Proceedings of the 4th International Forum on Hybrid Ventilation: An Integrated Solution for Ventilation, Health and Energy* (Montreal), 18-23.

Bourgeois D., Haghighat F. and Potvin A. (2002) "On the applicability of hybrid ventilation in Canadian office and educational buildings: Part 2 - Implementing Annex 35 pilot study projects in Canada" in *Proceedings of the 4th International Forum on Hybrid Ventilation: An Integrated Solution for Ventilation, Health and Energy* (Montreal), 24-29.

Boyce P.R. (1980) "Observations of the manual switching of lighting" *Lighting Research & Technology* 12(4) 195-205.

Brager G.S., Paliaga G. and de Dear R.J. (2004) "Operable windows, personal control, and occupant comfort" *ASHRAE Transactions* 110(2) 17-35.

Brager G.S. and de Dear R.J. (2001) "Climate, comfort & natural ventilation: A new adaptive comfort standard for ASHRAE Standard 55" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 60 - 77.

Brager G.S. and de Dear R.J. (1998) "Thermal adaptation in the built environment: a literature review" *Energy and Buildings* 27(1) 83-96.

Brown L.R. (2000) "Challenges of the new century" in Starke L. (ed.) *State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society*, New York, W.W. Norton & cie.

Claridge D.E., Abushakra B., Haberl J. and Sreshthaputra A. (2004) "Electricity Diversity Profiles for Energy Simulation of Office Buildings" *ASHRAE Transactions* 110(1).

Claridge D.E. and Abushakra B. (2001) "Accounting for the occupancy variable in inverse building energy baselining models" in *Proceedings of the International Conference for Enhanced Building Operations (ICEBO)* (Austin).

Clarke J.A. and Tang D. (2004) "A co-operating solver approach to building simulation" in *Proceedings of ESIM2004, the bi-annual conference of IBPSA-Canada* (Vancouver).

Clarke J.A. (2001) *Energy Simulation in Building Design*, Oxford, Butterworth-Heinemann.

Clarke J.A. and Maver T.W. (1991) "Advanced design tools for energy conscious building design: development and dissemination" *Building and Environment* 26(1) 24-25.

Clements-Croome D.J. (1997) "Specifying Indoor Climate" in Clements-Croome D.J. (ed.) *Naturally Ventilated Buildings: Buildings for the Senses, Economy and Society*, London, E & FN Spon.

Crown W.H. (1998) *Statistical Models for the Social and Behavioral Sciences: Multiple Regression and Limited-Dependent Variable Models*, Westport, Praeger.

de Dear R.J. and Brager G.S. (2001) "The adaptive model of thermal comfort and energy conservation in the built environment" *International Journal of Biometeorology* 45(2) 100-108.

de Dear R.J. and Brager G.S. (1998) "Developing an Adaptive Model of Thermal Comfort and Preference" *ASHRAE Transactions* 104(1a) 145-167.

de Dear R.J., Brager G.S. and Cooper D.J. (1997) "Developing an adaptive model of thermal comfort and preference: Final report" Sydney, MRL, ASHRAE RP-884.

De Gidds W. and Phaff H. (1982) "Ventilation Rates and Energy Consumption due to Open Windows" *Air Infiltration Review* 4(1) 4-5.

Degelman L.O. (1999) "A model for simulation of daylighting and occupancy sensors as an energy control strategy for office buildings" in *Proceedings of Building Simulation '99, an IBPSA Conference* (Kyoto), International Building Performance Simulation Association. 571-578.

Dunn S. and Flavin C. (2000) "Sizing up micropower" in Starke L. (ed.) *State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society*, New York, W.W. Norton & cie.

ESRU (2002) "The ESP-r system for building energy simulation, user guide version 10 series. ESRU Manual U02/1" Glasgow, University of Strathclyde.

Fanger P.O. and Toftum J. (2002) "Extension of the PMV model to non-air-conditioned buildings in warm climates" *Energy and Buildings* 34 533-536.

Fanger P.O. and Toftum J. (2001) "Thermal comfort in the future - Excellence and expectation" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 11-18.

Fanger P.O. (1972) *Thermal Comfort: Analysis and Applications in Environmental Engineering*, New York, McGraw-Hill.

Farley K.M.J. and Veitch J.A. (2001) "A room with a view: a review of the effects of windows on work and well-being" Ottawa, Institute for Research in Construction, National Research Council of Canada, IRC-RR-136.

Foster M. and Oreszczyn T. (2001) "Occupant control of passive systems: the use of venetian blinds" *Building and Environment* 36(2) 149-155.

Fritsch R., Kohler A., Nygard-Ferguson M. and Scartezzini J.-L. (1990) "A stochastic model of user behaviour regarding ventilation" *Building and Environment* 25(2) 173-181.

Fürbringer J.-M. and van der Maas J. (1995) "Suitable algorithms for calculating air renewal rate by pulsating air flow through a single large opening" *Building and Environment* 30(4) 493-503.

Gagge A., Fobelets P. and Berglund L. (1986) "A Standard Predictive Index of Human Response to the Thermal Environment" *ASHRAE Transactions* 92(2B) 709-731.

Griefahn B., Künemund C. and Gehring U. (2001) "Annoyance caused by draught, the extension of the draught rating model (ISO 7730)" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 135-145.

Haghighat F., Brohus H. and Rao J. (2000) "Modelling air infiltration due to wind fluctuations - a review" *Building and Environment* 35(5) 377-385.

Haghighat F. and Donnini G. (1999) "Impact of psycho-social factors on perception of the indoor air environment studies in 12 office buildings" *Building and Environment* 34(4) 479-503.

Hamilton S.D., Roth K.W. and Brodrick J. (2003) "Using microenvironments to provide individual comfort" *ASHRAE Journal* 45(9) 65-66.

Hand J.W. (1998) "Removing barriers to the use of simulation in the building design professions" PhD Thesis, Glasgow, University of Strathclyde, PhD Thesis thesis.

Hawkes D. (1997) "The User's Role in Environmental Control: Some Reflections on Theory in Practice" in Clements-Croome D.J. (ed.) *Naturally Ventilated Buildings: Buildings for the Senses, Economy and Society*, London, E & FN Spon.

Heiselberg P. ed. (2002) *Principles of Hybrid Ventilation*, Aalborg, Aalborg University.

Hendriksen O.J., Brohus H., Frier C. and Heiselberg P. (2002) "Pilot Study Report: Bang & Olufsen Headquarter", Annex 35, Hybvent, International Energy Agency, Energy Conservation in Buildings and Community Systems.

Hensen J.L.M. and Centnerova L. (2001) "Energy simulation of traditional vs. adaptive thermal comfort for two moderate climate regions" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 78-91.

Heschong L. (1979) *Thermal Delight in Architecture*, Cambridge, MIT Press.

Heschong Mahone Group Inc. (2003) "Windows and offices: a study of office worker performance and the indoor environment", California Energy Commission, 500-03-082-A-9.

Humphreys M.A. and Nicol J.F. (1998) "Understanding the adaptive approach to thermal comfort" *ASHRAE Transactions* 104(1b) 991-1004.

Humphreys M.A. (1997) "An Adaptive Approach to Thermal Comfort" in Clements-Croome D.J. (ed.) *Naturally Ventilated Buildings: Buildings for the Senses, Economy and Society*, London, E & FN Spon.

Humphreys M.A. and Nicol J.F. (1995) "An adaptive guideline for UK office temperatures" in Nicol J.F., Humphreys M.A., Sykes O. and Roaf S. (eds.) *Standards for Thermal Comfort*, London, E & FN Spon.

Humphreys M.A. (1978) "Outdoor temperature and comfort indoors" *Building Research and Practice* 6(2) 92-105.

Humphreys M.A. (1975) *Field Studies of Thermal Comfort Compared and Applied*, Building Research Establishment.

Hunt D.R.G. (1979) "The use of artificial lighting in relation to daylight levels and occupancy" *Building and Environment* 14 21-33.

Inoue T., Kawase T., Ibamoto T., Takakusa S. and Matsuo Y. (1988) "The development of an optimal control system for window shading devices based on investigations in office buildings" *ASHRAE Transactions* 94 1034-1049.

Iwashita G. and Akasaka H. (1997) "The effects of human behavior on natural ventilation rate and indoor air environment in summer : a field study in southern Japan" *Energy and Buildings* 25(3) 195-205.

Janak M. and Macdonald I. (1999) "Current state-of-the-art of integrated thermal and lighting simulation and future issues" in *Proceedings of Building Simulation '99, an IBPSA Conference* (Kyoto), 1173-1180.

Janak M. (1997) "Coupling building energy and lighting simulation" in *Proceedings of the 5th International IBPSA Conference* (Prague), 313-319.

Jeong J.-W., Mumma S.A. and Bahnfleth W.P. (2003) "Energy conservation benefits of a dedicated outdoor air system with parallel sensible cooling by ceiling radiant panels" *ASHRAE Transactions* 109(2).

Jones B.W. (2001) "Capabilities and Limitations of Thermal Models" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 112-121.

Keith D.M. (1997) "Use of peak occupancy data to model the effects of occupancy-sensing lighting controls" Faculty of the Graduate School/Civil Engineering, Boulder, University of Colorado, MSc thesis.

Kernighan B.W. and Ritchie D. (1988) *The C Programming Language, 2nd edition*, Englewood Cliffs, Prentice Hall.

Liao T.F. (1994) *Interpreting Probability Models: Logit, Probit, and Other Generalized Linear Models* Lewis-Beck M.S. (ed.) Quantitative Applications in the Social Sciences, Beverly Hills, Sage.

Lindsay C.R.T. and Littlefair P.J. (1993) "Occupant use of venetian blinds in offices" Watford, Building Research Establishment, PD 233/92.

Love J.A. (1998) "Manual switching patterns observed in private offices" *Lighting Research & Technology* 30(1) 45-50.

Mahdavi A. and Kumar S. (1996) "Implications of indoor climate control for comfort, energy and environment" *Energy and Buildings* 24(3) 166-177.

Mastny L. (2004) "Purchasing for People and the Planet" in Starke L. (ed.) *State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society*, New York, W.W. Norton & cie.

McCartney K.J. and Nicol J.F. (2001) "Developing an adaptive control algorithm for Europe: Results of the SCATs project" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 176-196.

Morgan C.A., de Dear R.J. and Brager G.S. (2002) "Climate, clothing and adaptation in the built environment" in Levin H. (ed.) *Proceedings of Indoor Air 2002, the 9th International Conference on Indoor Air Quality and Climate* (Monterey), 98-103.

Nassar K. and Nada M. (2003) "Discrete-event activity simulation for predicting occupants' movements in buildings" in Flood I. (ed.) *Towards a Vision for Information Technology in Civil Engineering, Proceedings of the 4th Joint International Symposium On Information Technology In Civil Engineering* (Nashville), ASCE Technical Council on Computing Practices (TCCP) and European Group for Intelligent Computing in Engineering (EG-ICE).

Newsham G.R., Marchand R.G., Svec J.M. and Veitch J.A. (2002) "The effect of power constraints on occupant lighting choices and satisfaction: a pilot study" in *Proceedings of the IESNA Annual Conference* (Salt Lake City).

Newsham G.R., Mahdavi A. and Beausoleil-Morrison I. (1995) "Lightswitch: a stochastic model for predicting office lighting energy consumption" in *Proceedings of Right Light Three, the 3rd European Conference on Energy Efficient Lighting* (Newcastle-upon-Tyne), 60-66.

Newsham G.R. (1994) "Manual control of window blinds and electric lighting: Implications for comfort and energy consumption" *Indoor Environment* (3) 135-144.

Nicol J.F. and Humphreys M.A. (2004) "A stochastic approach to thermal comfort, occupant behaviour and energy use in buildings" *ASHRAE Transactions* 110(2) 554-568.

Nicol J.F. (2001) "Characterising occupant behaviour in buildings: towards a stochastic model of occupant use of windows, lights, blinds, heaters and fans" in *Proceedings of the 7th International IBPSA Conference* (Rio), International Building Performance Simulation Association. 1073-1078.

Nicol J.F. and Humphreys M.A. (1972) "Thermal comfort as part of a self-regulating system" in *Proceedings of the CIB Symposium on Thermal Comfort* (Watford), Building Research Establishment.

Ong B.L. and Hawkes D. (1997a) "The Sense of Beauty" in Clements-Croome D.J. (ed.) *Naturally Ventilated Buildings: Buildings for the Senses, Economy and Society*, London, E & FN Spon.

Ong B.L. (1997b) "From Homogeneity to Heterogeneity" in Clements-Croome D.J. (ed.) *Naturally Ventilated Buildings: Buildings for the Senses, Economy and Society*, London, E & FN Spon.

Pallot A.C. (1962) "Window opening in an office building" *Yearbook of the Heating and Ventilating Industry* 4-12.

Parent M. (2002) "Estimation du potentiel technico-économique d'économie d'énergie au Québec: Secteur commercial et institutionnel au tarif L" Québec, Rapport de Technosim Inc. pour Hydro-Québec.

Parsons K.C. (2001) "Introduction to thermal comfort standards" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 19-30.

Pigg S., Eilers M. and Reed J. (1996) "Behavioral aspects of lighting and occupancy sensors in private offices: a case study of university office building" in *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings* (Asilomar), 8.161-8.171.

Principi P., Di Perna C. and Ruffini E. (2002) "Pilot Study Report: I Guzzini Illuminazione", Annex 35, Hybvent, International Energy Agency, Energy Conservation in Buildings and Community Systems.

Raja I.A., Nicol J.F., McCartney K.J. and Humphreys M.A. (2001) "Thermal comfort: use of controls in naturally ventilated buildings" *Energy and Buildings* 33(3) 235-244.

Reinhart C.F. (2004) "Lightswitch 2002: a model for manual control of electric lighting and blinds" *Solar Energy* 77(1) 15-28.

Reinhart C.F. and Voss K. (2003) "Monitoring manual control of electric lighting and blinds" *Lighting Research & Technology* 35(3) 243-260.

Reinhart C.F. (2001) "Daylight availability and manual lighting control in office buildings - Simulation studies and analysis of measurement" Department of Architecture, Technical University of Karlsruhe, PhD thesis.

Roberson J.A., Homan G.K., Mahajan A., Nordman B., Webber C.A., Brown R.E., McWhinney M. and Koomey J.G. (2002) "Energy use and power levels in new monitors and personal computers" Berkeley, Energy Analysis Department, Environmental Energy Technologies Division, Ernest Orlando Lawrence Berkeley National Laboratory, University of California, LBNL-48581.

Rowe D. (2003) "A study of a mixed mode environment in 25 cellular offices at the University of Sydney" *International Journal of Ventilation* 1(February) 53-64.

Rowe D. and Wilke S. (1995) "Perceptions of indoor air quality, symptoms of minor illness and malaise and annual rates of sick leave compared" in Haghighat F. (ed.) *Proceedings of the 2nd International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings* (Montreal), 57-64.

Rubin A.I., Collins B.L. and Tibott R.L. (1978) "Window blinds as a potential energy saver - a case study." Washington, NSB Building Science Series, National Bureau of Standards, 112.

Santamouris M.J. and Asimakopoulos D.N. eds. (1996) *Passive Cooling of Buildings*, London, James & James.

Sawin J.L. (2004) "Making Better Energy Choices" in Starke L. (ed.) *State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society*, New York, W.W. Norton & cie.

Schild P.G. (2001) "An overview of Norwegian buildings with hybrid ventilation" in Cauberg H. (ed.) *Proceedings of the 2nd International One-day Forum on Hybrid Ventilation, an Integral Solution for Ventilation, Health and Energy* (Delft), 49-68.

Tjelflaat P.O. (2002) "Pilot Study Report: Media School"", Annex 35, Hybvet, International Energy Agency, Energy Conservation in Buildings and Community Systems.

Toftum J. (2001) "Human response to combined indoor environment exposures" in *Proceedings of the Windsor Conference 2001: Moving Thermal Comfort Standards into the 21st Century* (Windsor), 376-384.

Wahlstrom A., Blomsterberg A. and Sandberg M. (2002) "Natural and hybrid ventilation schools in Sweden" in *Proceedings of the 4th International Forum on Hybrid Ventilation: An Integrated Solution for Ventilation, Health and Energy* (Montreal), 30-37.

Wang D., Federspiel C.C. and Rubinstein F. (2005) "Modeling occupancy in single person offices" *Energy and Buildings* 37 121-126.

Ward G. (1994) *The RADIANCE 2.4 Synthetic Imaging System*, University of California.

Ward Larson G. and Shakespeare R. (1998) *Rendering with RADIANCE. The Art and Science of Lighting Visualization*, San Francisco, Morgan Kaufmann.

Warren P.R. and Parkins L.M. (1984) "Window-opening behaviour in office buildings" *ASHRAE Transactions* 90(1B) 1056-1076.

Winkelmann F., Birdsall B.E., Buhl W.F., Elllington K.L., Erdem A.E., Hirsch J.J. and Gates S. (1993) DOE-2 Supplement, Version 2.1E, Springfield, Lawrence Berkeley National Laboratory.