ENERGY EFFICIENCY IN LOW INCOME TROPICAL HOUSING

A Study into Improving Thermal Comfort in Low Income Housing Designs in Thailand through the Effective Incorporation of Passive Design Strategies

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DECLARATION

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university of institution for any degree, diploma, or other qualification.

In accordance with the Department of Engineering guidelines, this dissertation is does not exceed 15 000 words, and it contains less than 150 figures.

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ABSTRACT

As part of the University of Cambridge's Energy and Low Income Tropical Housing (ELITH) project, this research investigation focused on identifying and analysing potential areas for improving the thermal performance of low income, government-provided housing designs in Bangkok, Thailand. In a country that experiences hot and humid temperatures throughout the year, buildings need to be adaptable to the climate in order to improve the thermal comfort of inhabitants.

The current housing typologies include a prevalence of high density, low-rise condominiums with a large brick and concrete composition. As an initial step, the performance of the building was determined according to adaptive comfort standards using the software IES VE. The results from the baseline model were analysed according to the adaptive comfort CIBSE TM52 guideline and were observed to exceed the acceptable limits of what is deemed appropriate for naturally ventilated buildings. The main sources of the low thermal performance were identified as resulting from: thermal storage effects, the lack of sufficient natural ventilation through the living zones heat gains through the roof.

Based on these findings five representative passive design parameters were selected to be analysed for sensitivity in order to understand the influence of passive design strategies on thermal comfort within these buildings. Theses parameters are external wall material; shading of windows; the presence of a balcony; the openable area of the windows and the incorporation of insulation into the roof. Once the baseline conditions were identified the software SimLab2.2 and RStudio were used to carry out the sensitivity analysis. These results indicated that roof material and the presence of a balcony have the greatest influence on the system. Incorporating insulation into the roof reduced the mean number of days of overheating by 21.43%. Removing the balcony increased the number of days of overheating by 19.94% due to significant reductions in internal ventilation.

The conclusions to this study show that in low income, naturally ventilated buildings in Thailand the incorporation of measures to reduce heat gain in the roof and the maximisation of ventilation through the living areas should be prioritised in the planning and design stages of low income housing projects.

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LIST OF ABBREVIATIONS AND ACRONYMS

ELITH	Energy and Low Income Tropical Housing
NHA	National Housing Authority
CBO	Community Based Organisation
ASHRAE	Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institute for Building Services Engineers
DOE	Design of Experiments
NVB	Naturally Ventilated Buildings
BES	Building Energy Simulations
DTS	Dynamic Thermal Simulations
SA	Sensitivity Analysis
We	Weighted Exceedance
WM	External Wall material
SW	Shading of Windows
BA	Balcony
WA	Window Openable Area
RM	Roof Material
WM	External Wall Material

LIST OF APPENDICES

1 INTRODUCTION

The consequences of rapid population growth and urbanization in the context of the limited availability of resources have exposed the immediate need to address underlying social circumstances which are attributed to the prosperity of both individuals and the natural world (Golubchikov and Badyina, 2012; Hannula, 2012). In the developing world the inadequacies of the current housing systems have been exposed. The accessibility of affordable housing is limited by the socio-economic status of those who need it (French *et al.*, 2011) and the quality of the current stock of low income housing is characterised by technical inefficiencies and inappropriate design elements thus rendering it inadequate for day to day living. With concerns growing over urban liveability in these regions, priorities need to be placed on planned future development (Hannula, 2012). This involves a shift towards the provision of housing that not only make use of environmentally sensitive construction materials, processes and technologies, but also considers how housing performs under the effects of both internal and external climatic factors (Golubchikov and Badyina, 2012). This results in housing that promotes equity and social inclusion amongst communities and the poorest residents. Essentially advances need to be made in the supply of dwellings that reduce the vulnerabilities of inhabitants to future hazards and contribute to resilience, while remaining affordable (French *et al.*, 2011).

2 Literature Review & Research Objectives

This chapter provides an introduction into the various concepts and that are investigated and evaluated within this dissertation. A detailed literature review is first presented. This introduces the motivation for investigating concepts of thermal comfort in low income housing in tropical regions under the ELITH project, which serves as the focal point for this research. The context of low income housing provision in Asia and specifically Thailand is investigated, followed by a review of existing means of measuring thermal comfort in tropical regions and applicable passive design strategies have been used in these regions to overcome these problems. Analytical topics, which were used for data processing within this investigation, are then outlined. The chapter concludes with an outline of the specific research objectives for this investigation.

2.1 Energy and Low Income Tropical Housing Project (ELITH)

The University of Cambridge is currently involved in The Energy and Low Income Tropical Housing (ELITH) project which forms part of a research collaboration between various academic institutions and International Development organisations within the United Kingdom, China, Uganda, Tanzania and Thailand. This project is aimed at facilitating methods of reducing energy consumption in low income housing within tropical regions.

The housing industry is characterised by large amounts of energy consumption both in the construction and utilisation phases. Thus, the programme is structured to look at elements of sustainable design that alleviate energy dependency in both these areas. The research that has been initiated under this programme follows two distinct paths, namely analysing current housing stocks within Asia and East Africa in order to design low income housing that:

i. Contains fewer materials with a high embodied energy and makes use of less energy intensive construction methods and technologies.
ii. Incorporates building physics and structural design features in a manner that is appropriate to the relevant climate (Hannula, 2012).

The research contained within this report follows the second path. This study serves as a component of the continued research into identifying low cost methods of improving thermal comfort through passive design techniques, less energy intensive building materials and adaptive construction techniques (University of Cambridge, 2015).

2.2 Low Income Housing in Bangkok: 1950-Present

Presently the provision of low income housing in Bangkok is the responsibility of two government organisations namely the National Housing Authority (NHA) and Community Organisations Development Institute (CODI) (Kritayanavaj, 2012). While these two organisations are both responsible for ensuring the provision of adequate and affordable housing, the NHA and CODI take two different approaches to reaching the goal of the Thai government of improving the conditions of housing for the lower income bracket of the population (Kritayanavaj, 2012; Usavagovitwong *et al.*, 2013).

The NHA is a state enterprise founded in 1973 which is responsible for public housing through a "supply-driven" approach (Kritayanavaj, 2012). On the other hand CODI was established in 2000 and forms part of a national shift in policy towards creating more self-reliant communities through Community Based Organisations (CBO's) (Usavagovitwong *et al.*, 2013). In 2003 the Thai government initiated two housing programmes focusing on delivering one million affordable homes for urban citizens in five years (Archer, 2010). The NHA established the Baan Ua-Arthorn programme, which is concerned with providing subsidised housing aimed at the lower-middle-income sectors, while the Baan Mankong programme was instituted through CODI as a method of upgrading the urban slums through community-driven methods (Archer, 2010; Usavagovitwong *et al.*, 2013).

2.2.1 Baan Ua-Arthorn Low Cost Housing Programme

The Baan Ua-Arthorn programme is an example of a top-down governmental approach to the affordable housing crisis in Thailand. The low cost housing development programme was implemented in 2003 as a means to enhance economic growth in the country, with the intention of constructing 600 000 homes (Kritayanavaj, 2012) within a five year period. This figure has not been attained however, and during an eight year period of implementation the NHA has only completed just over 250 000 housing units. These units range in design from low-rise condominiums and single detached houses to semi-detached houses and townhouses (Figure 1).

Figure 1 Typical types of low income houses supplied by the NHA under the Baan Ua-Arthorn programme (Chiarakorn *et al.*, 2014)

The breakdown of the number of housing units according to model type is shown in Figure 2. This data shows that during the period of the project implementation over 180 000 of the 253 164 houses constructed included low-rise condominiums. The average construction cost of one of these low income condominiums equates to 8000 THB per m² (Suenderman, 2005). Due to the low cost nature of these housing estates, the units are characterised by their use of inadequate materials (Chiarakorn *et al.*, 2014), the inferior quality of the design and the construction, and located in hard to reach urban zones (Archer, 2010).

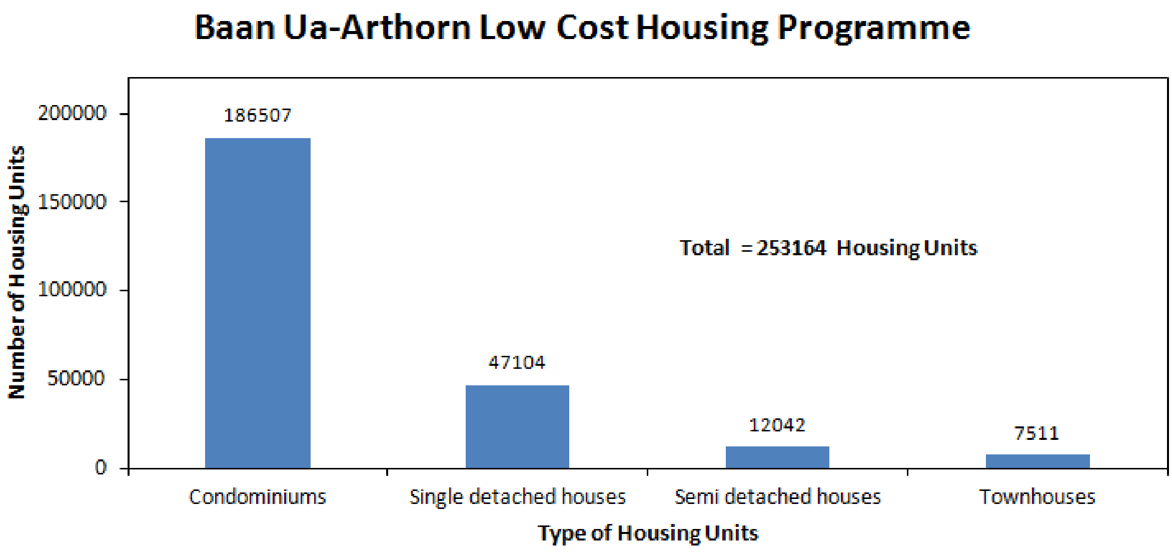


Figure 2 Breakdown of housing unit types under the Baan Ua-Arthorn Housing Project

While the Baan Ua-Arthorn housing programme was discontinued and replaced with preferred bottom-up or "community-based development" (Archer, 2010) initiatives, the programme highlights the concern over sustainable housing standards for the poorer sectors of society.

2.3 Design Considerations for Tropical Climates

The Baan Ua-Arthorn project is an example of the continued implementation of capital intensive methods of "providing large-scale housing to as many people as possible" (French *et al.*, 2011, p. 5). In trying to overcome challenges of demand and to optimise land usage, low income housing designs in tropical regions designs *were* produced and are *continuing* to be produced according to western standards (French *et al.*, 2011). The incorporation of architectural specifications which are incompatible with both the prevailing climatic conditions is found to exacerbate issues associated with extreme indoor temperatures and comfort, adequate natural ventilation and low levels of indoor air quality in these dwellings (Santamouris *et al.*, 2007). This has induced a dependency on mechanical forms of cooling once individuals can afford it (Antarikananda *et al.*, 2006) and the residential energy consumption in Thailand set to increase more than twofold by 2030 (Suenderman, 2005). The construction of housing that can adapt to dominant climatic conditions is a key element of providing appropriately sustainable housing and reducing energy consumption in an urban context (Hannula, 2012).

2.3.1 Thermal Comfort in Residential Buildings

The concept of thermal comfort in residential buildings is recognized as obtaining a state whereby the internal thermal environment is optimally suited to an inhabitant's physical and psychological preferences ("ASHRAE 55-2004," 2004). The possible internal design conditions of a typical house require some flexibility since there is a wide range of temperatures where people typically feel comfortable. In developing an index for thermal comfort (Santamouris, 2003) there are various mathematical models that have been used to define this state of which Fanger's steady-state Comfort Model (Fanger, 1970) is the most renowned.

Fanger (1970) performed tests on human subjects in various environments in a controlled climate chamber, assuming the test subjects are in a condition of steady state with their surroundings. The results from these experiments have formed the basis of international building services standards, with the experimental data relationships having been assumed to be universally applicable across all building types, all climate zones, and all populations (de Dear and Schiller Brager, 2001).

Due to the steady-state basis of the Fanger model, these standards disregard how people adapt to their environments by changing the conditions to become more accommodating (Nguyen et al., 2012a). This is of particular concern in hot and humid tropical climates as the application of these thermal comfort indices has been shown to inadequately predict levels of thermal comfort in these regions (Hwang et al., 2009; Nicol, 2004). In the tropics people have adapted to being comfortable at higher temperatures for longer periods of time (Nicol, 2004). In Thailand, field studies have shown that in naturally ventilated buildings, individuals remain a state of reasonable comfort at 28°C (Rangsiraka, 2006) with an upper limit for thermal comfort reaching 31.5°C (Tantasavasdi et al., 2001).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Chartered Institute for Building Services Engineers (CIBSE) have developed guidelines for assessing thermal comfort that incorporates this adaptive approach. These standards are both based on the concept that external temperatures influence internal comfort because individuals can adapt to seasonal temperature changes (The Chartered Institution of Building Services Engineers, 2006). In this way the adaptive thermal comfort index more adequately accounts for those aspects of human comfort based on social, cultural and climatic circumstances (de Dear and Schiller Brager, 2001).

2.3.2 Thailand Climate

Thailand falls within the tropical wet-dry climate (Aw) characterised by hot and humid conditions throughout the year (Figure 3).

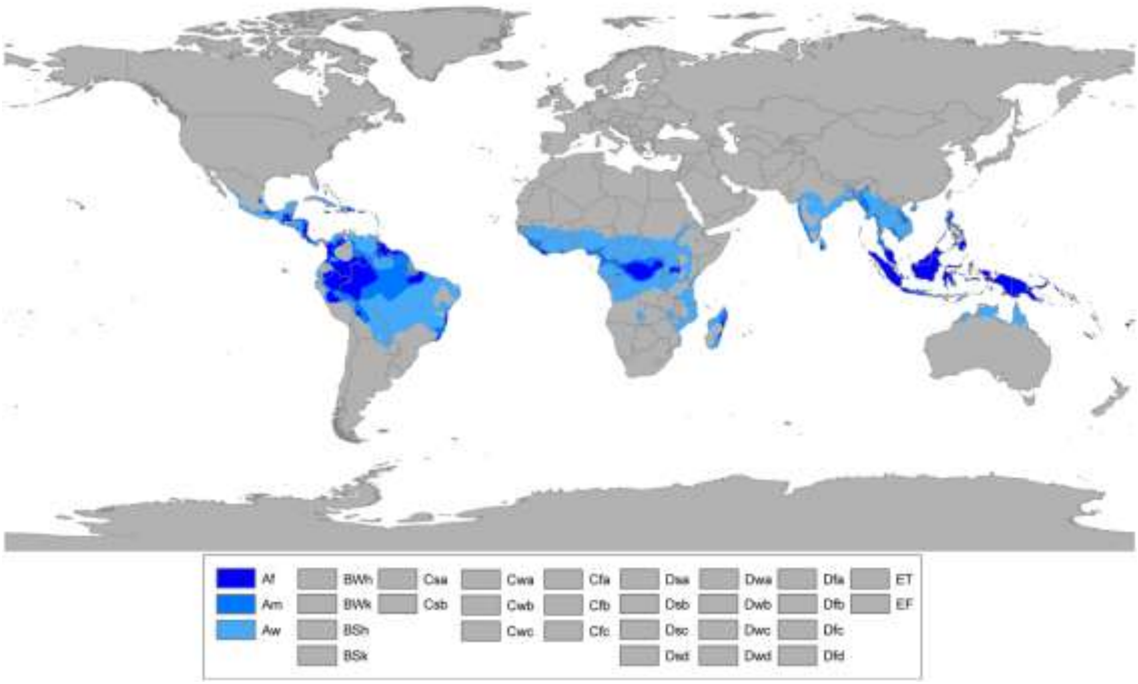


Figure 3 Köppen Climate Map of the world showing the distribution of tropical weather zones (Peel *et al.*, 2007)

Three distinct climatic periods exist in Thailand. Figure 4 shows that the hottest temperatures are experienced from March to May, the rainy season consisting of elevated levels of relative humidity occurs from June to October and a relatively colder period occurs from November to February (Antarikananda et al., 2006). The mean daily temperature ranges from 26°C-36°C with the average minimum temperature falling to 21°C in the 'winter' months with the annual average temperature reaching 28°C ("Bangkok Climate & Temperature," 2015). The relative humidity remains high throughout the year averaging 74%-85% and peaking during the rainy months (Figure 4). Daytime temperatures are found to exceed those temperatures deemed thermally comfortable throughout the year (Suenderman, 2005).

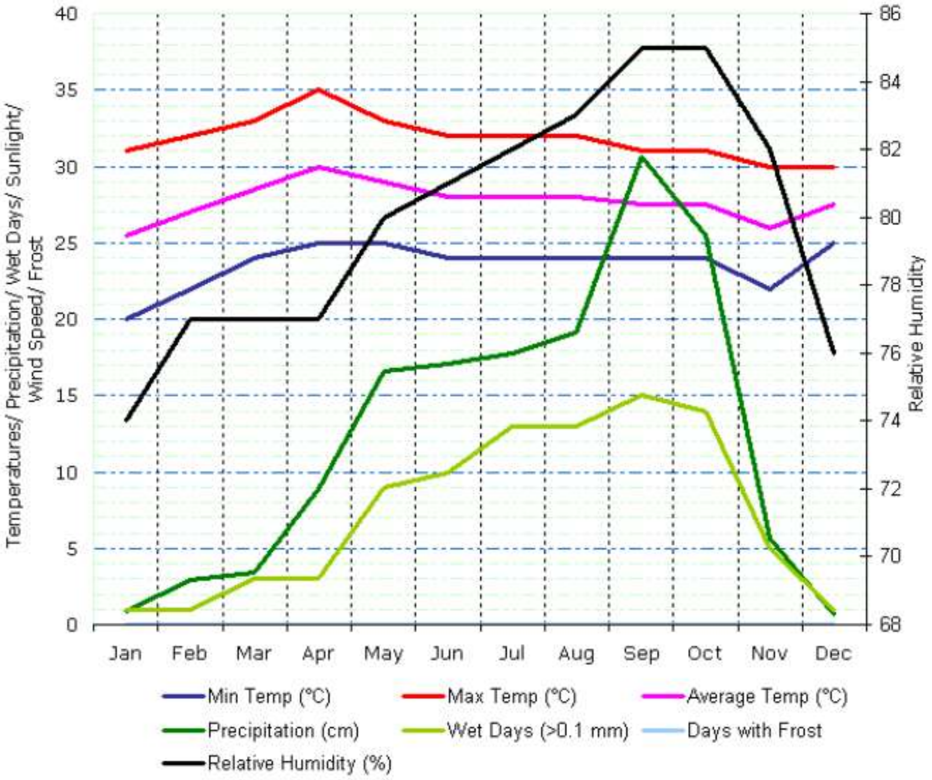


Figure 4 Annual climate graph for Bangkok, Thailand ("Bangkok Climate & Temperature," 2015)

2.3.3 Passive Design Strategies in Tropical Regions

The distinct nature of the tropical climate means that housing design in these regions needs to incorporate strategies that exploit the benefits from the outdoor climate to achieve thermal comfort inside (Jayasinghe et. al, 2002). Passive design strategies have been proposed as an adequate method to achieve optimum indoor environmental conditions in residential buildings and thus reduce energy consumption in numerous tropical regions. The main design consideration is incorporating elements that minimise internal heat gains and maintain thermal comfort of inhabitants during periods of high solar radiation and relative humidity.

2.3.3.1 Ventilation and Heat diffusion

In tropical climates, sufficient air movement through buildings has the capacity to reduce thermal discomfort. The high outdoor temperatures and elevated levels of relative humidity mean that indoor comfort is promoted through both the number of air exchanges that occur as well as the speed of the air (Prianto and Depecker, 2002) Studies have shown that air movement of up to 1m/s can reduce internal operating temperatures by 3.5°C (Nicol, 2004; Tantasavasdi et al., 2001).

In order to take advantage of ventilation cooling strategies, the distribution, size and number of openings needs to be maximised. Openings in each room are critical to aid in the air flow. The internal layout should be designed to allow for air flow through principal rooms and from the front to the back of the building (Garde et al., 1999). The incorporation balconies induces the free movement of air into tropical housing designs have been found to accelerate airflow into a dwelling (Prianto and Depecker, 2002). A balcony acts like a "wind scoop" enhancing the rate of air movement through its opening (Prianto and Depecker, 2002).

Stack ventilation is a common form of heat dissipation that uses physical concepts of air density or the stack-effect to drive warm air upwards. The incorporation of a solar chimney on the roof removes the warm, humid air and entrains cooler air into the internal environment. These design parameters have been found to increase the rate of natural ventilation in areas with limited wind speeds (Santamouris et al., 2007).

In tropical regions, nighttime temperatures remain relatively high. This makes night cooling of buildings a challenge. The utilisation of ventilation and heat diffusion techniques can help compensate for this climatic restriction and assist in the reduction of internal operating temperatures at night (Suenderman, 2005).

2.3.3.2 Solar Protection of the Building Envelope

Radiant gains from sun exposure and conduction gains through the building envelope account for 80% and 20% of external heat gains in tropical climates respectively (Garde et al., 1999). Passive design means incorporating efficient mechanisms of solar protection to reduce direct solar exposure. The strategy is to optimise the effects of shading by orientating openings with overhangs (horizontal shades) to the north or south to maximise shading when the sun is at its peak. This provides optimum shading of windows and walls over the year (Suenderman, 2005). Vertical shading elements should be used on the east and west facing openings to obstruct direct sunlight.

2.3.3.3 Materials Characteristics

The thermal characteristics of materials have a significant influence on the induction of passive cooling in buildings. The optimisation of materials with high thermal resistance (low U-values) means that the building envelope will have greater insulating properties, thereby reducing conduction heat into a dwelling. Thermal insulation in the roof and the walls induces the same effects by reducing the heat gain through the structural elements. Conversely, the insulation will restrict heat loss from the interior space at night creating discomfort (Suenderman, 2005). Materials with high surface emissivity can easily absorb and release radiant heat which could also induce discomfort (The Concrete Centre, 2015). The utilisation of materials with low thermal storage capacities are optimum for improving the thermal comfort at night as they cool down rapidly (Eyre, 2015; Suenderman, 2005).

2.3.3.4 External Finishes

The colour of structural elements exposed to the external environment impacts the internal temperatures of a dwelling. This is due to a higher rate of absorption of solar radiation by dark colours. Darker coloured walls, floors and roofs can increase the temperatures of "well-sheltered rooms" by up to 4°C (Jayasinghe et al., 2002).

2.4 Building Energy Simulations

Dynamic Thermal Simulations (DTS) are used to analyse energy performance of buildings in terms of energy consumption and indoor temperatures (Clarke, 2001). In a DTS model a series of design factors are used to create a virtual environment which can then be used to analyse the time-dependant flow of energy within a building and through the building envelope. These models are based on integrative and complex heat transfer phenomenon and building physics concepts (Clarke, 2001).

In dynamic models a building is analysed through a process of thermal zoning. Zones represent spaces that are thermally identical. The allocation of rooms into zones is determined based on their usage (periods of time that a space is occupied), solar gains (heat gain resulting from solar radiation), location (whether a space is situated on the perimeter or interior of a building) and distribution system types (energy distribution systems in the form of mechanical means of heating and cooling) (International Building Performance Simulation Association, 2012). An adiabatic zone is composed of adiabatic walls which do not allow for the transfer of heat and thus has no influence on thermal performance of other zones

In naturally ventilated buildings the accurate classification of thermal zones is important as this allows for the airflow rates based on the aforementioned input factors from one zone to another to be determined.

2.4.1 IES Virtual Environment

Virtual Environment is a software package created by Integrated Environmental Solutions which is used for building energy analysis and sustainable design. IES-VE consists of a range of built-in analysis tools, which facilitate the ease of modelling and analysing the "performance of a building either retrospectively or during the design stages of a construction project" (Booth, 2015). The interface makes use of a graphical user interface (GUI) or "black box", which produces graphical results based on a series of user specified inputs. For the purpose of this study the ease of the interface and geometry building, the speed with which results can be produced and the scale of the models needed to be simulated makes it ideal.

2.5 Design of Experiments (DOE)

A fundamental part of the research process involves the planning of experiments or the simulation process. Typically, one is presented with a large combination of parameters (the factors that have a direct effect on the solution) each with a possible setting (referred to as a level). When the purpose of the investigation is to identify the controlling parameter, a critical concern is the interaction between the different parameters and how they affect a desired outcome (Park, 2007). Fractional factorial designs are a subset of DOE techniques that allow for the adequate study of parametric effects from conducting the least amount of simulations (Telford and Uy, 2009). These designs allow for the sensitivity of each parameter as well as the interaction between parameters to be assessed.

2.5.1 Sensitivity Analysis

The purpose of a sensitivity analysis (SA) is to ascertain how the uncertainty associated with the individual inputs into a model affects the uncertainty of the outputs of the model (Tarantola *et. al*, 2002). The implementation of a sensitivity analysis is composed of two phases, namely screening experiments and optimisation (Telford and Uy, 2009).

2.5.1.1 Screening

Screening refers to the identification of the main factors that have an effect on a desired outcome or system. This involves establishing the critical factors and not the interaction between the factors. The applications of SA techniques are useful for assessing thermal responses of building and data variability. Screening experiments are performed in the early stages of the process, when it is likely that many of the design variables initially considered have little or no effect on the response. The purpose is to identify the design variables that have large effects for further investigation. The experimental planner SimLab2.2 was used to perform the screening process. A sequence of results was generated using the Morris Method. This method was selected for this study as it was designed for the screening of a large number of input factors with the outputs incorporating only "elementary effects" (Morris, 1995) of the inputs i.e. those factors with a profound effect on the output and those with a minimal effect. The number of permutations is calculated by the formula $r \times (k+1)$, where *r* is the number of levels and *k* the number of independent input factors (SimLab2.2, 2015).

2.5.1.2 Optimisation

Optimisation refers to the assessment of factor interaction and a system's variance from a statistics perspective. RStudio was used to carry out the optimisation analysis. R is an open source programming language for the statistical analysis. The programme enlists the use of 'command-line scripting' for the creation of functions for statistical modelling.

2.6 Scope and Research Objectives

The scope of this study it is to quantify the thermal performance of a single condominium housing unit under the Baan Ua-Arthorn programme. Under the long term outcomes of the ELITH project, this study aims to analyse elements of the building envelope that influence building performance and thereby make recommendations on viable options to solve the inadequacies. The literature review has shown the vastness of this field with continued research into thermal comfort measures in tropical regions as well as the continued study of passive design features. This study does not to propose a redesign or new concept design of low income housing for the NHA, but to indentify the dominant passive cooling strategies and areas of concerns that should be incorporated into low income housing design in this region.

The specific objectives for this dissertation are as follows:

i. Develop a detailed analysis on the performance of key design and material elements of government provided low income housing in order to understand contextual aspects of thermal comfort and cooling.

ii. Assess the sensitivity of the elements in **(i)** using representative passive design parameters in order to contribute to the discussion around the use of passive design techniques as a low cost design strategy for more sustainable housing supply.

iii. Make recommendations based on the adequacy of the design strategies in Naturally Ventilated Buildings (NVB) in consideration of the Thai context.

3 Methodology and Case Study Profile

This chapter covers the type of study that was adopted in order to address the research questions. The justification for the case study the housing model to be analysed is presented. The building dimension and layouts are derived, typical construction methods and material composition listed and material characteristics are discussed. The outcomes of the identified case study profile in this section are used in the next chapter to conduct the thermal performance analysis.

3.1 Research Methodology

The purpose of this study is to assess the performance of low income housing in terms of material composition and design strategies under specific macro climate conditions. The planning of experimental procedures is a fundamental process for undertaking research and in consideration of the research objectives (section 2.6), this dissertation will take the form of a proof of principle study. In order to facilitate any advances made in this area an array of parameters needs to be assessed to determine how they will affect a desired outcome. The proof of principle study will enable the feasibility of certain methods of modelling to be tested and furthermore to ascertain whether these concepts can be used to critically analyse the research variables (Janssen and Janssen, 2010).

The methodological approach to answering the research objectives within the outline of the scope incorporates the use of energy modelling software to obtain data about the thermal performance of a ‘typical’ housing unit in Thailand. The four primary processes involved in this study include:

1. Establish a housing design to be used as a baseline example for assessment.
    a. Identify material compositions and geometric design aspects of the condominium housing models.
2. Generate a 3-D model incorporating construction and thermal properties of the condominium housing models in IES VE.
    a. Carry out building energy simulations for the standard housing design using IES VE software.
    b. Validate the results of the thermal performance of the baseline model according to adaptive thermal comfort standards.
3. Identify passive design techniques in the form of key material and design parameters that influence thermal comfort in low income housing in tropical regions.
    a. Develop permutations of design parameters using SimLab2.2 Sensitivity Analysis Software
    b. Run building energy simulations incorporating of the permutations of the standard baseline housing model that incorporate the various design and material changes in IES VE software.
    c. Compare the results to those obtained for the baseline model in order to assess variances in the thermal performance of the housing model.
4. Identify the parameters that have the most effect on the thermal performance.
    a. Undertake a sensitivity analysis based on the results of running simulations for each permutation using SimLab2.2 Sensitivity Analysis and RStudio statistical software.

Once the effects of the parameters, with regard to a given response such as thermal comfort have been identified, recommendations can be built around future housing projects. Specifically how passive design aspects can be incorporated into and considered in the provision of low income housing in Thailand and perhaps other tropical regions with similar climatic characteristics.

3.2 Selection of Housing Typology for Analysis

The Baan Ua-Arthorn low cost housing Programme portion of the literature review (section 2.2.1) explained the current situation regarding low income housing typologies in Thailand and specifically Bangkok. The housing typology to be assessed for this study was based on the figures from the NHA, indicating a prevalence of high-density, low-rise condominiums containing single-storey units of $33m^2$ (Figure 5).

Figure 5 Condominiums under the Baan Ua-Arthorn Programme (Usavagovitwong *et. al*, 2013)

3.2.1 Construction Method and Material Composition

The ELITH Project Thailand group provided a Bill of Quantities (BOQ) that defined the material composition of one condominium (Appendices). The standard method of construction for housing under the Baan Ua-Arthorn Housing project included a skeleton composed of reinforced concrete columns and beams for structural stability and infill brickwork walls for the bracing (Suenderman, 2005). The roof has been constructed with a pitch of 30° and does not provide significant shading of the building through overhangs.

Figure 6 External views of typical condominiums

The various material components of an individual five-storey apartment block are presented in Table 1. The construction methods and material choice allowed the NHA to lower costs in order to deliver these projects en masse. The roof cover (tiles), the steel frame and glass louvre windows and the mass concrete are indicative of low income NHA housing, whereas clay brick is a material characteristic of more middle income NHA housing (Suenderman, 2005). The influence of material properties on the thermal performance and thus the capacity for passive cooling to occur is presented in Section 2.3.3.3. The U-value is a function of the thermal conductivity of each material as well as the thickness of the element. The elements with the most significant heat transfer values are the external walls, the floor slab and the roof cover. The concrete floor slab and the clay brick composition of the external walls have a dense material composition as well as a high heat storage capacity. This indicates that the thermal mass effects in these apartments will be pronounced. The roof tiles have the lowest thermal resistance (highest U-value) and will thus be significantly affected by continued exposure to intense solar radiation.

Table 1 Material description of typical housing unit

Construction Element	Material	Thickness	U-Value (W/m^2k)	External Absorptivity (α)	Surface Emissivity
Roof	tiles	5mm	6.266	0.7	0.51
External Walls	Clay brick and cement rendering	200 mm	2.246	0.7	0.75
Internal Partitions	Concrete Block	100 mm	3.384	-	0.90
Windows	glazing	6 mm	2.7465	0.49	0.90
Ceiling	Gypsum	90 mm	1.255	-	0.85
Floor	Reinforced concrete	250 mm	3.618	-	0.90

3.2.2 Details of a Typical Housing Unit

The internal layout of one of these condominiums is shown in Figure 7 and Figure 8. These low-resolution floor plans were provided by the NHA and show the typical dimensions and arrangements of the various rooms and structural elements. The floor plans show a set of nine apartments on each level, with each condominium containing five levels. A central hallway separates the two rows of flats with a fire escape situated at one end of the hall and a flight of stairs providing access to other levels is situated at the other end. There are two windows situated at the end of the hallway which provide ventilation through the passage areas.

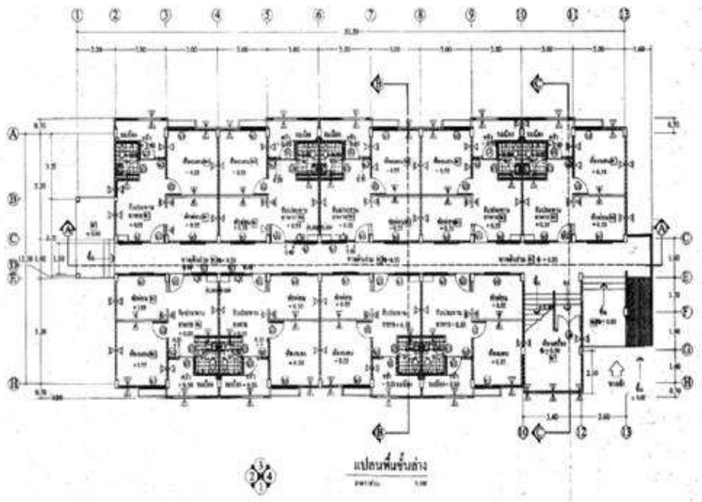


Figure 7 Ground Floor Layout of Typical Low-Rise Condominium

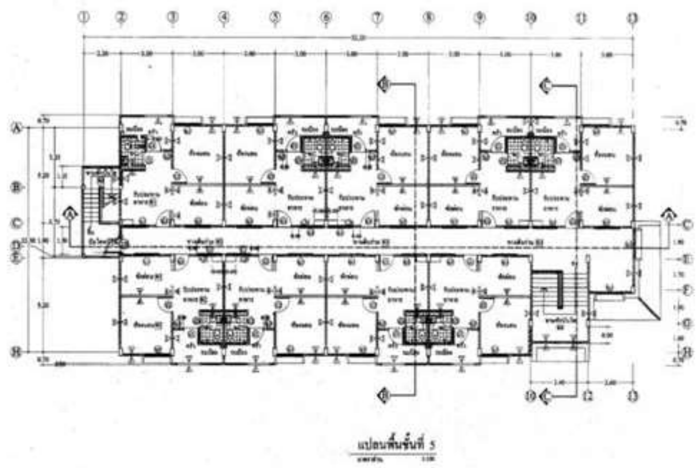


Figure 8 Top Floor Layout of Typical Low-Rise Condominium

3.2.3 Details of typical Individual Apartment

The apartments have been designed in such a way that two adjacent apartments are mirrored constructions of each other. Each of the apartments is composed of five rooms, namely: a balcony, a toilet, a living room, a bedroom and a kitchen (Figure 9). The bedroom is the only room with an outside facing window, while the kitchen and the living room both contain windows overlooking the internal hallway. The balcony is accessed through a door from the living room. The architectural drawings of the floor plans have been reduced into a typical plan view of two adjacent apartments. The layouts show the relevant dimensions and the respective floor areas of each room. The layout also shows the location and dimensions of the windows and doors. The windows are set at dimensions of 1.5 m x 1.5 m and are situated 1 m above the base. The doors are set at 0.9 m x 2.5 m.

Room Type	Floor Area (m^2)
Balcony	5.25
Toilet	3.0
Living Room	12.75
Bedroom	10.5
Kitchen	7.5

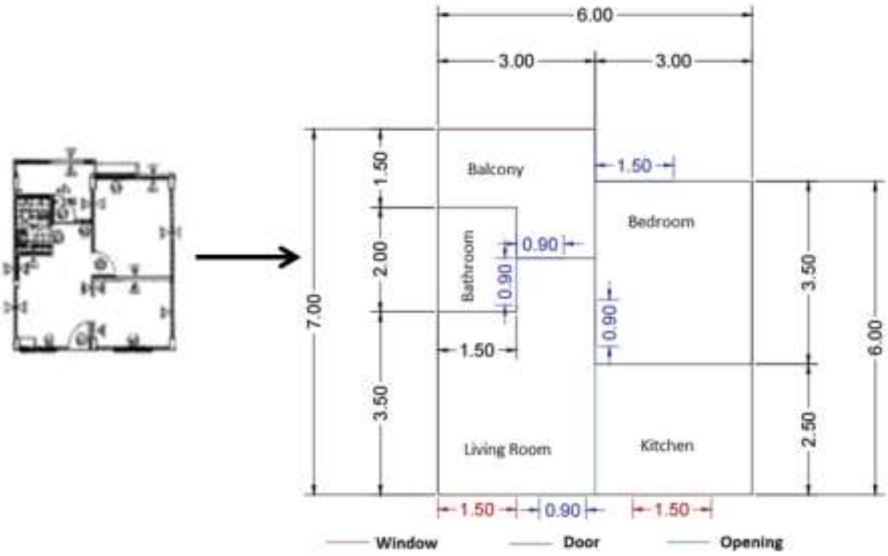


Figure 9 Plan layout of individual apartment with floor area of rooms

4 Dynamic Thermal Simulations of the Case Study House

This chapter covers the Building Energy Simulation (BES) model for the case study apartment in order to establish a baseline condition. An introduction into Dynamic Thermal Simulations (DTS) is given. An overview of the setup of the model is given including the conditions considered for the simulations and the thermal performance of the apartment is shared and discussed. All of the simulations were performed using IES Virtual Environment energy modelling software. The results obtained from this analysis are used in latter chapters for conducting a sensitivity analysis on key design and material parameters.

4.1 Setup of Baseline Model

This section provides an overview of the setup procedure of the model in IES VE in order to assess the building performance. The practical and theoretical foundations of building modelling and simulation are presented in section 2.4 and a review of the software is presented in the Design of Experiments portion of the Literature Survey (Section 2.5). When a new model is created in IES VE, the user first needs to specify the location of the project in order to obtain accurate weather data. The user can then assign construction templates and thermal conditions to a 3-Dimensional drawing of the model using the **Building Template Manager**. This incorporates material parameters for each structural element and defines energy inputs within the building respectively. Once these initial inputs are complete, IES VE gives the user access to the five distinct components of the DTS process: ModelIt, MacroFlo, SunCast ApacheSim and VistaPro. The specific set up of the baseline model under each of the modules in now explained.

4.1.1 Construction Template

IES VE contains a database of materials which can be used to create a construction template for the relevant model. This application allows the user to specify the relevant dimensions of the construction elements with assigned thermal properties including roof, external walls, internal partitions, floor, glazed surfaces and door. The construction template was set up using the extracted information from the table of material parameters (Section3.2.1, Table 1).

4.1.2 Thermal Conditions

The thermal conditions refer to the heating and cooling requirements for the building. These are assigned by creating a thermal profile for each room, which accounts for all of the auxiliary heat gains which do not come from external sources i.e. the weather. The thermal conditions are dependent on whether a room is mechanically or naturally heated and cooled; internal causal gains from occupancy, lighting and/or appliances and the number of air exchanges within a room.

For the basis of this research the buildings are considered as naturally ventilated with no forms of mechanical cooling due to the socio-economic status of the home owners (Suenderman, 2005). The number or air exchanges per room relates to the amount of air that can infiltrate the building through openings in the building envelope. This value was set to 4 ac/hr to account for the lower quality standards of the condominiums considering the low income context (Archer, 2010). The only sources of internal heat gain within the apartments are due to occupant behaviour and mechanical gains from cooking appliances.

4.1.2.1 Project Profiles and Internal Gains

IES VE allows the user to explicitly state the times at which a building is occupied or when appliances are switched on by allowing the user to specify an **Activity Profile**. This profile is specific to every DTS project and describes the period and measurement of occupant activity. This profile incorporates a modulating value for each time of the day, in order to inform the programme when heat gains from people or appliances need to be considered. This modulating value ranges from 0 to 1. A value of 0 indicates that the room is unoccupied or an appliance is off and a value of 1 indicates that a room is 100% occupied or an appliance is switched on.

The typical occupancy pattern for the apartment was adapted using information about an average Thai family from the National Statistical Office of Thailand (Ministry of Information and Communication Technology, 2004). An average of four people is assumed to be living in the apartment with working hours spanning from 8 am to 6 pm during the week. The apartment is considered as occupied during all other hours. The internal gain associated with sedentary person is 90 W/person/day and the gains associated with appliances include 106 W/m² from a gas cooking stove (Ministry of Information and Communication Technology, 2010; The Chartered Institution of Building Services Engineers, 2006). The buildings are free-running and include no forms of mechanical cooling (Suenderman, 2005). The project profiles are presented in the Appendices.

4.1.3 ModelIt

This function allows the user to build the model in 3-D incorporating the solid building elements and specified building geometry. Once the construction template and thermal conditions are set up, the first step is to define the plan layout of the housing model incorporating the relevant dimensions as well as the positions of the windows and the doors. Based on the concepts of zoning discussed in section 2.4, each room in the apartment was identified as an individual zone. Figure 10 shows the adaptation of the architectural drawings into a zoned layout for the purpose of conducting simulations. The numbers in each space correspond to an independent zone.

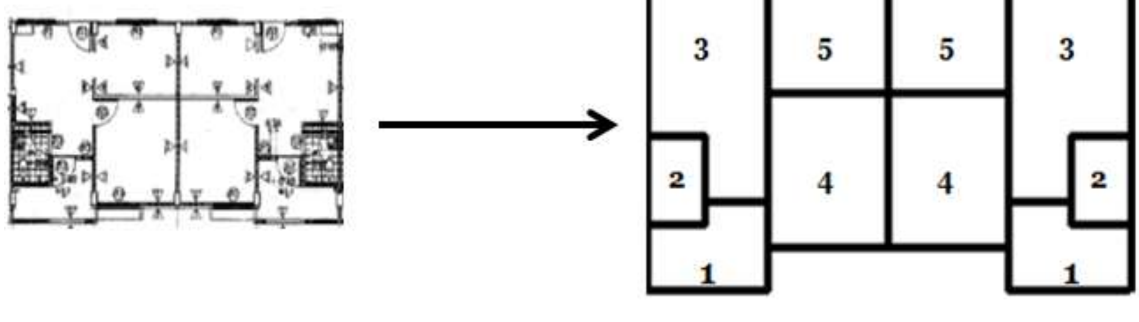
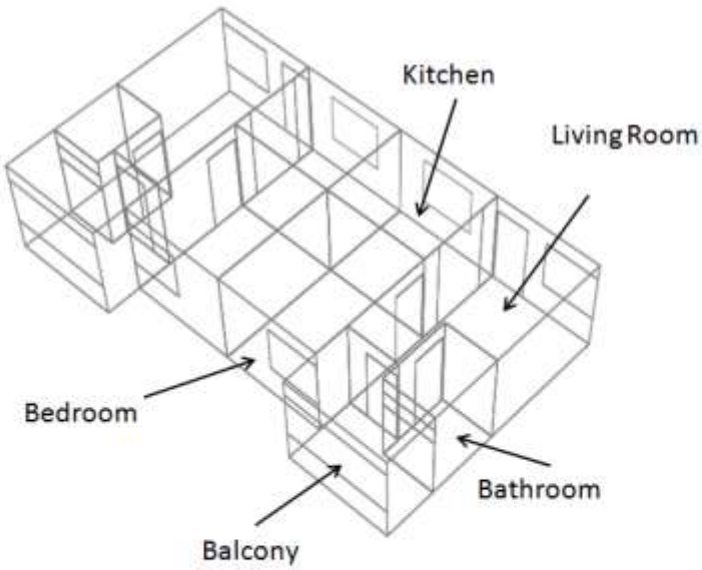


Figure 10 Layout of zones for simulations for two adjacent apartments

In the architectural drawings the kitchen and the living room are shown as interleading spaces. In order to maximise the number of zones, these two rooms were constructed as two separate zones (3 and 5) connected by a virtual partition. This means that although these spaces are represented as separate zones, the internal heat gains and resulting thermal performance are representative of both of these zones. The next and final step in the ModelIt process is to define the location and sizes of all the openings. The internal isometric rendering of two adjacent apartments for simulation with the corresponding zones is shown in Figure 11.



Zone	Room Type
1	Balcony
2	Toilet
3	Living Room
4	Bedroom
5	Kitchen

Figure 11 Isometric layout of typical apartment layout with zone classification

4.1.3.1 Simulation Strategy

The study is focused on improving the living areas within the apartment. Thus for the purpose of the simulations, the ‘living zones’ were considered for assessment of their thermal performance. This included the living room, the bedroom and the kitchen.

The model was set up in order to assess the performance of the dwelling under the ‘worst case scenario’ conditions. The building was orientated towards the south in order to incorporate the effects of maximal solar gains and each level was reduced to a representative five zone layout as shown in Figure 12. The simulations were carried out on two of the apartments on each of the levels. The apartments were strategically selected according to their position on the level as well as their structural boundary conditions. The position of the apartments means that they will receive minimal cross ventilation (blue arrow) effects from the central hallway windows compared to the those situated adjacent to the window (red arrow). This is because the air will follow the path of least resistance.

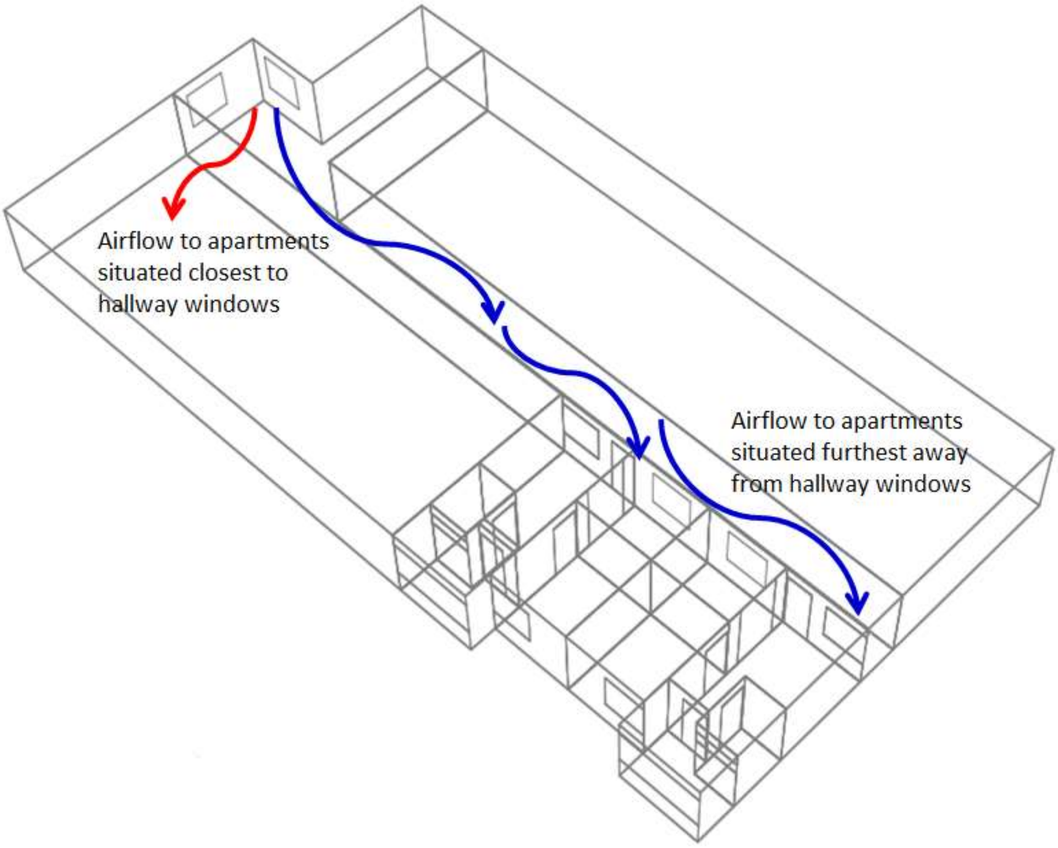


Figure 12 Graphical representation of airflow through the condominium

The basic assumption before simulations were performed was that the thermal performance of apartment 1 would be worse than that of apartment 2. This is due to the different structural compositions of the two apartments. Apartment 1 is constructed with two external walls (Figure 13) this means that the rate of heat transfer through this material is more rapid than that of the internal partitions due to their respective thermal resistances (Section 3.2.1). In order to test this assumption apartment 2 was included in the simulation to compare the magnitudes of operating temperatures and thus draw conclusions about the significance of the effect of location and boundary conditions on thermal performance. In order to ensure that the model was accurately simulating the heat transfer between these two apartments only, the adjacent zones were modelled as adiabatic or what IES defines as ‘adjacent buildings’. The significance of adiabatic zones in building energy simulations is explained in Section 2.4.

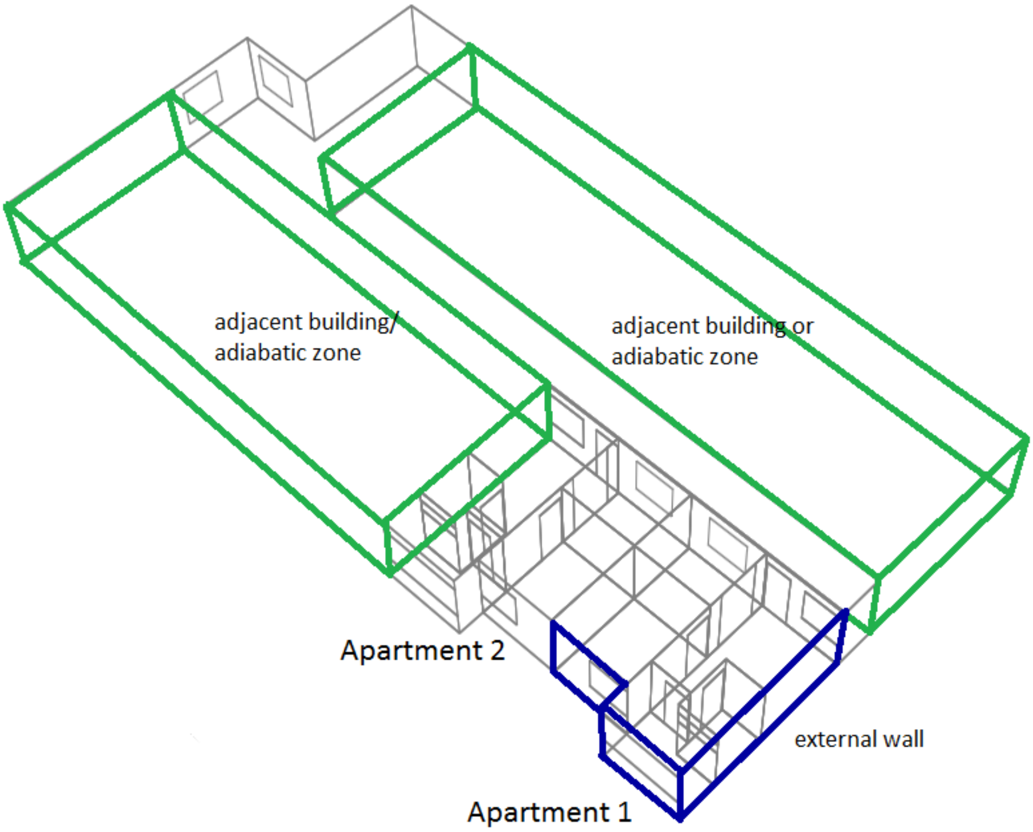


Figure 13 Rendering of zonal boundary conditions for simulation

The final rendering of a condominium under the Baan Ua-Arthorn housing programme is shown in Figure 14.

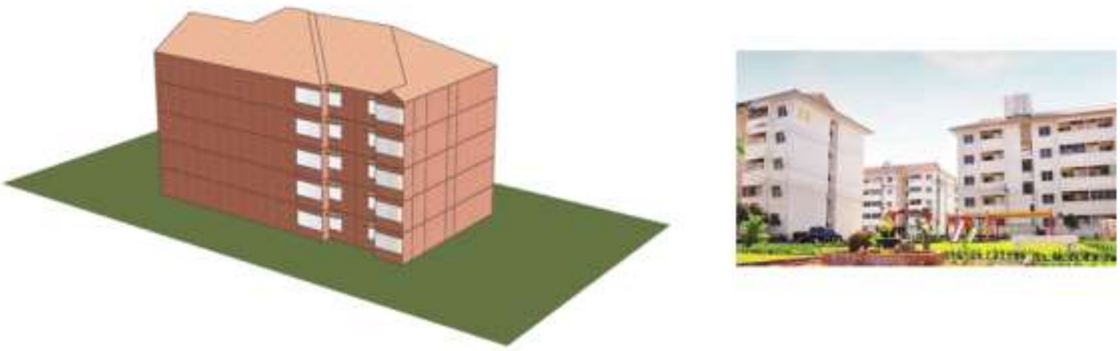


Figure 14 Rendering of case study dwelling

4.1.4 MacroFlo

This module is used in order to investigate the efficiency of ventilation through the building. Through the creation of an **Activity Profile**, the user can set up a schedule of window and door openings based on the duration and the degree of the opening. This module also allows for the type of window openings to be described. MacroFlo incorporates the information from the external weather conditions in accordance with the dimensions and location of the openings to calculate the volumetric air flow rate (l/s or m^3/s) through the openings (Booth, 2015).

4.1.4.1 Baseline MacroFlo Conditions

The schedule of openings for the baseline model was created on the basis that windows are all open during the day and closed during the night. This stems from the overarching social factor of security. The house windows are all defined as louvre windows based on the BOQ and the window openable area is 25% (percentage of entire window area that the windows can open). The openable area for the doors was set to 50%. The balcony was modelled as a window that is continuously open at 100%.

4.1.5 Definition of Virtual Environment

The final step in the setup of the model is the definition of the external environmental factors that influence the indoor temperatures. The theoretical basis of this process is presented in section 2.4 of the Literature Review. The virtual environment includes the definition of the geographical location of the building and the associated climatic and weather data for that region. The IES VE package contains weather data on hundreds of locations globally under the **APlocate** tool. The user is granted access to these weather files once a location is selected. IES will then incorporate this data once the simulation is run. For this case the weather data over a twelve month period for the Bangkok Metropolis (13.73°N, 100.57°E) was selected.

4.1.5.1 SunCast

The SunCast module is used to calculate the solar gains that the building will experience. The solar gains for a particular location and building are defined as the amount of energy gained (Watts) within the building as a result of solar radiation i.e. the amount of energy gained from solar exposure. IES VE uses the sun path at the user-defined location to determine the position of the sun relative to the building for the every hour within a 12 month period. The output is the maximum solar gain experienced at a specific time during the day.

The orientation of the building needs to be considered as it determines how much light and solar radiation enters a zone. The proximity of Thailand to the equator means that there is not a great variation the angle of the sun between summer and winter (Figure

15). The sun is situated either north or south of the building for ten months of the year (five months each respectively). During the remaining two months, the sun is basically overhead the building (Jayasinghe and Priyanvada, 2002). The orientation for the baseline model was set to south facing. This was to simulate the worst case scenario for solar gains and to maximise the effect of the local shading devices over the bedroom windows.

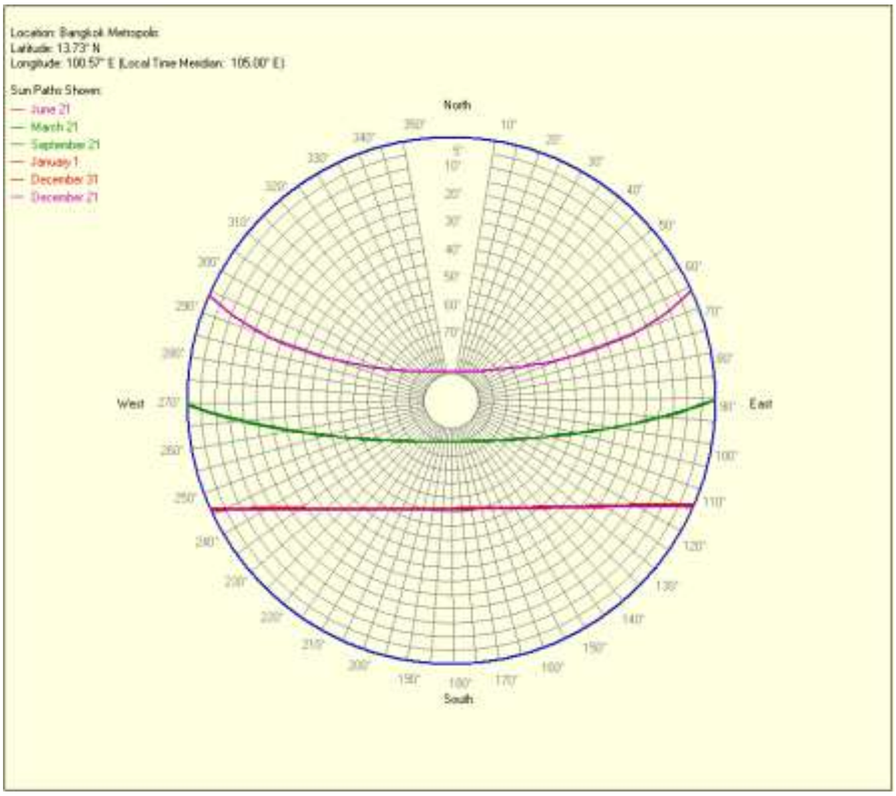


Figure 15 Sun path for Bangkok metropolis: January-December

4.1.6 ApacheSim

Once the ModelIt, MacroFlo and SunCast modules have been completed, the thermal calculations can be run. The ApacheSim module performs the dynamic simulations in order to determine the air temperature, air flow and internal thermal conditions of a building for every hour of the simulation period.

4.2 Adaptive Thermal Comfort Criterion

In section 2.3.1 of the literature review the technical concepts of thermal comfort in residential buildings were explained. The choice of guideline for measuring house performance is a key part of the study as it is effectively a statement of the definition of thermal comfort used. The adaptive thermal comfort standard chosen for assessment in this study was CIBSE with the specific guideline CIBSE TM52.

4.2.1 Predicting Discomfort with CIBSE TM52

The comfort parameter that forms the basis of the CIBSE TM52 adaptive thermal comfort assessment in free-running buildings is Operating Temperature (T_{Op}). This variable incorporates the combined effect of radiant temperature and air temperature.

$$\mathrm{Top} = (\mathrm{Tr} + \mathrm{Ta}) / 2 \qquad (1)$$

The CIBSE TM52 guideline assesses performance against three criteria. A zone is classified as overheating if it fails any two of the three criteria (Nicol, 2013). The criteria are defined in terms of ΔT. This is the difference between the actual operative temperature in the room at any time (Top) and Tmax the limiting maximum acceptable temperature (Appendices). This is rounded to the nearest whole degree.

$$\Delta\mathrm{T} = \mathrm{Top} - \mathrm{Tmax} \qquad (2)$$

4.3 Performance of Baseline model of Case Study Housing Unit

4.3.1 Hours of Exceedance (He)

The first criteria of assessment sets a limit for the number of hours that the Operating temperature of a zone exceeds the Maximum Temperature by 1°C or more during occupied periods.

$$\Delta T \geq 1℃\ must\ be\ less\ than\ 3\%\ of\ occupied\ hours$$

In Figure 16, the percentage of hours of exceedance is shown for the living zones on the ground floor and the fourth floor. The initial observation is that the apartments greatly exceed the limiting factor of 3%. The apartments on the fourth floor are shown to have worse thermal performance than those on the ground floor. The worst performing apartment is the edge unit on the top floor (two exposed external walls). The living room in this unit is the worst performing zone with a performance that exceeds the limiting factor by over five times at a value of 16.14%. The bedroom exceeds the limiting factor by over three times with a value of 10.06%.

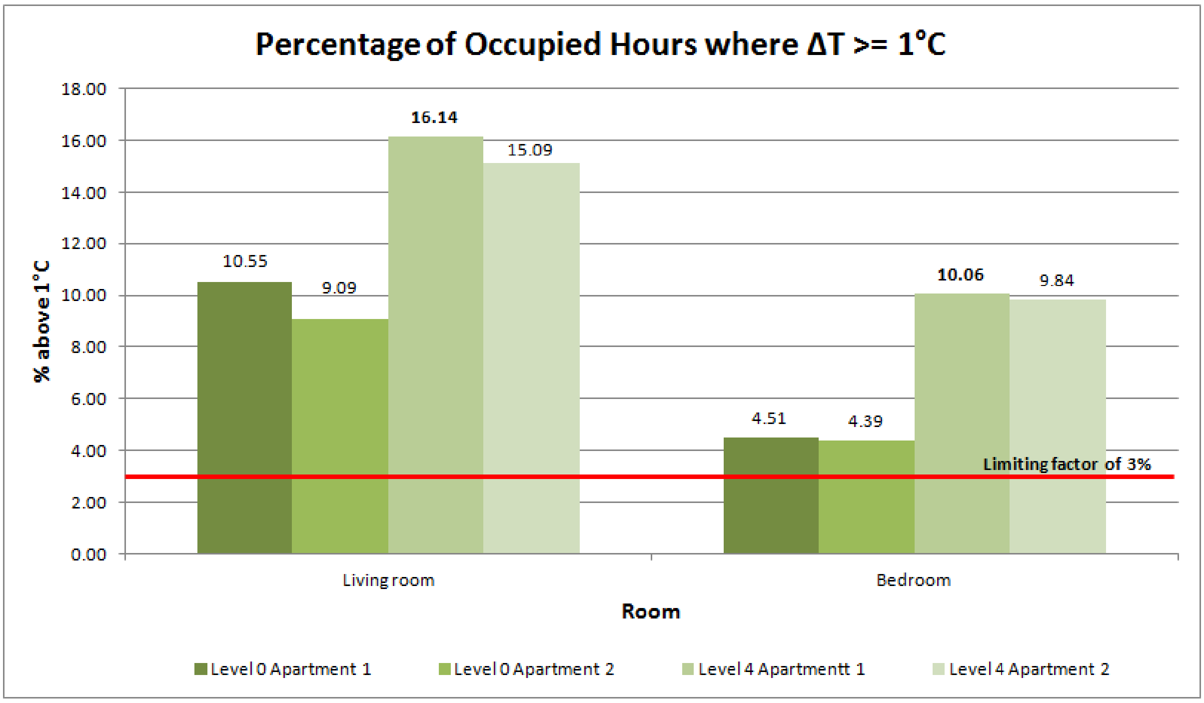


Figure 16 Performance of apartment according to criteria 1

4.3.2 Daily Weighted Exceedance (We)

This criterion assesses the severity of overheating in a zone. The length of overheating during a single day (number of hours) is weighted against **ΔT** (magnitude of exceedance). This value is limited to 6°CHr in any one day.

$$Daily\ Weighted\ Exceedance \leq 6°CHr$$

This criterion was assessed by counting the number of days in a calendar year where the **We** exceeds 6°CHr while that zone was occupied. In compliance with criteria 2, a zone should exceed this value for no days. The results for the baseline case are shown in Figure 17. As with criteria 1, the apartments are shown to exceed the limits of failure with the corresponding top floor apartment showing the greatest signs of overheating. Within this apartment the living room surpasses 6°CHr for 115 days and the bedroom surpasses 6°CHr for 77 days out of 365 days respectively. This indicates that the zones within the apartment spend a large percentage of time at very high temperatures throughout the year.

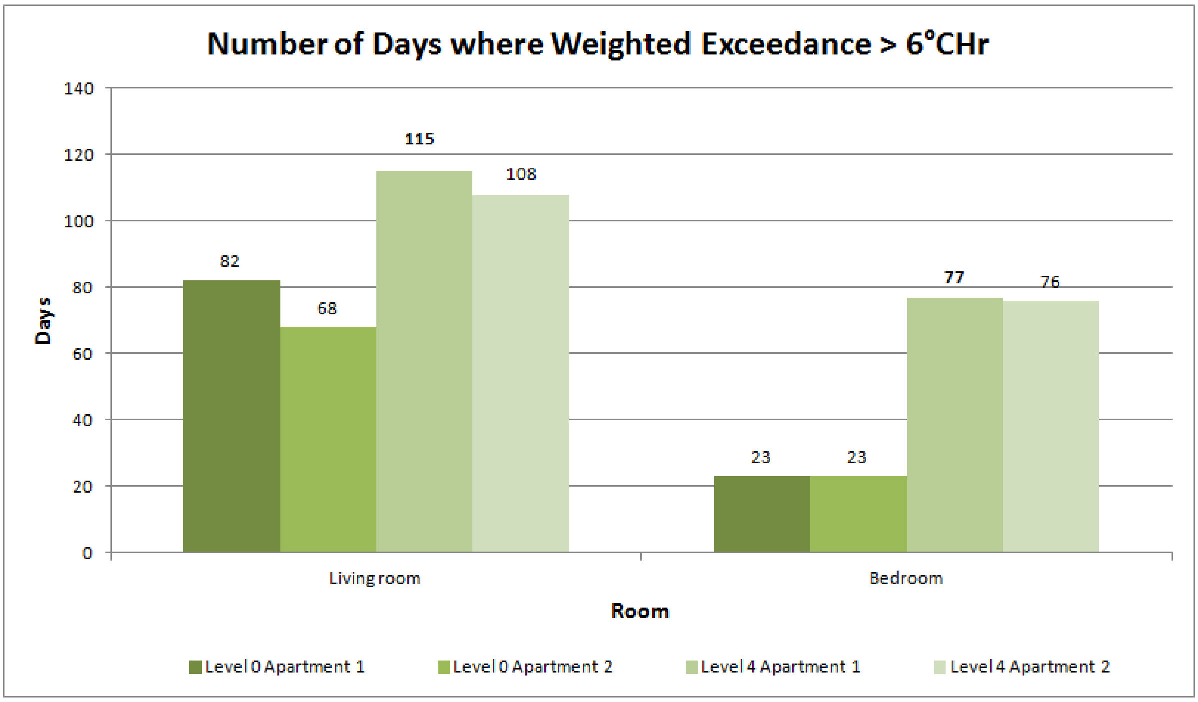


Figure 17 Performance of apartment according to criteria 2

4.3.3 Upper Temperature Limit for Overheating

This criterion sets an absolute upper temperature limit (**Tupp)** for which the Operating Temperature in a zone can reach. This is the temperature adaptive measures cannot alter an individual's sensation of feeling 'too hot'.

$$\Delta T \ < 4°\mathrm{C}$$

The apartments on the lower ground are again found to perform better than those on the top floor. The living room is observed to be the critical zone within the apartments as it fails criteria 3 for three of the four apartments (Figure 18). The differentiation in the performance of the apartments on the lower floor is attributed to the location of the apartments. The unit with two exposed walls (apartment 1) has reduced capacity for providing thermal comfort within the adaptive comfort limits. The living room in apartment 1 on the ground floor and top floor exceed 4°C by 4 hours and 11 hours annually, respectively.

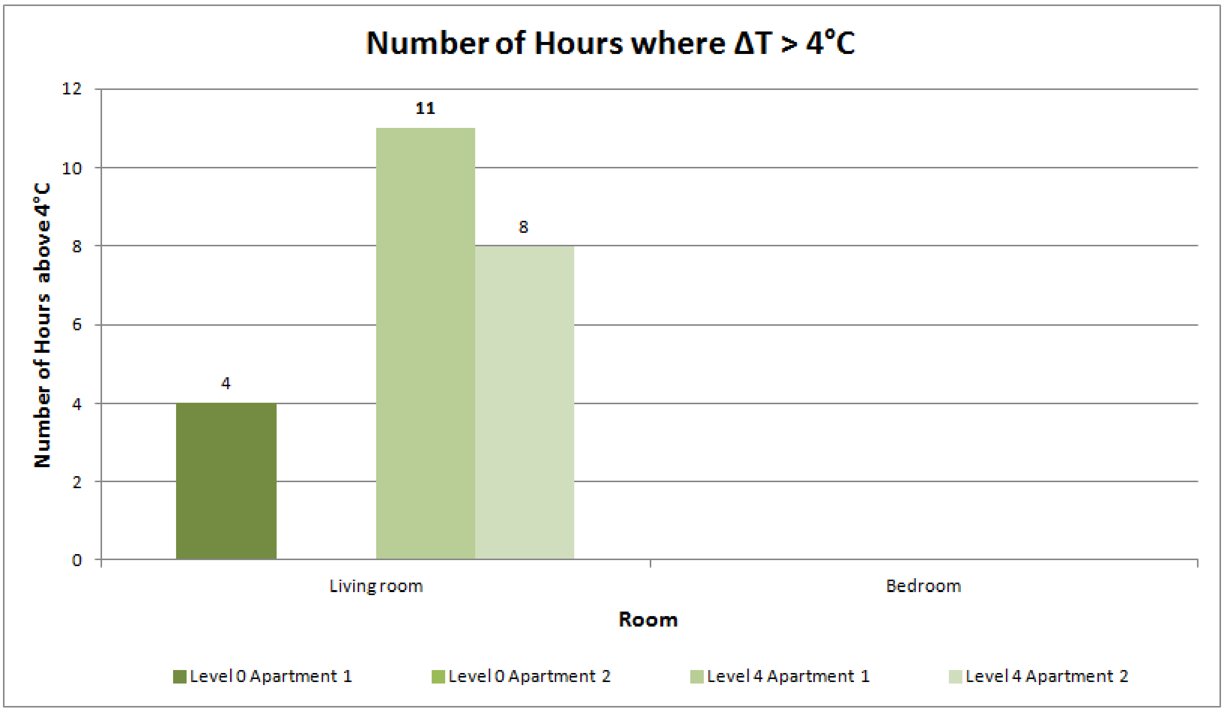


Figure 18 Performance of apartment according to criteria 3

In terms of adherence to the CIBSE TM52 criteria, the zones under consideration within the case study housing unit are found to exceed the acceptable limits of two or more of the criteria. The critical zone of concern is the living room. The living room incorporates the internal heat gains from the kitchen in the form of cooking as these are interleading rooms.

The apartment with the poorer thermal performance was shown to be apartment 1 on the top and ground floors. This is attributed to the material properties of the structural features of the building envelope. This apartment is constructed with two exposed external walls (Figure 19). The material properties of the external walls allows for a higher rate of heat transfer and thus the presence of two of these walls induces a more rapid build-up of heat within the apartment at a faster rate compared to containing only one external wall.

In conjunction with the location of the apartments on a level, the height of the condominium influences the thermal performance of the apartments. The building is subjected to effects from 'buoyancy-driven air movement' (Suenderman, 2005). Hot air from the lower levels rises up through the building and with no means of escaping the living zones, accumulates on the top levels. Combining this with the effects from the building envelope corresponds to the inadequate thermal performance of apartment 1 on level four for all 3 criteria.

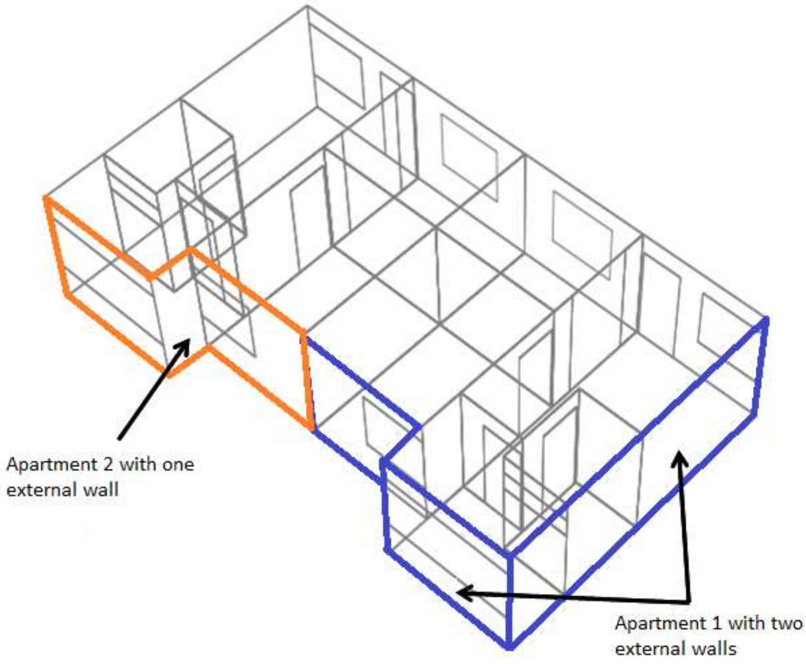


Figure 19 Location of case study apartments

In terms of criteria 3, the bedrooms in each of the apartments do not show exceedance of 4°C over the year. This can be attributed to the classification of the bedroom as a 'night-zone' (Garde et al., 1999) which means it is only occupied at night. These criteria are assessed based on when the zone is occupied. This means that the external night time temperature drop below a certain point whereby the addition of internal gains from people is not significant enough to raise the temperature above T_{upp}. In comparison, the living room is either partially or fully occupied at all times. This incorporates those periods where external daytime temperatures reach their maximum.

While these results show that this housing model far exceeds what is deemed acceptable for TM52 it is important to note that TM52 is designed as a tool for mainly assessing overheating in summer in Europe and the UK. Thus its application to tropical climates tends to underestimate the amount of time spent at high temperatures (which in these regions is most of the day). This is particularly significant for the application of criteria 2. While this level of severity of overheating may be more unacceptable in temperate zones, inhabitants in Thailand are less critical of these conditions. These observations also correlate with those made by Eyre (2015) for low income housing in Tanzania and should be incorporated into continued research into establishing adequate thermal comfort criterion for tropical regions (Nguyen *et al.*, 2012)

4.3.4 Diurnal Temperature Fluctuation

The 24-hour temperature profiles of the living room, the bedroom and the kitchen for the hottest day of the year (29 April) are shown in figures Figure 20, Figure 21 and Figure 22 respectively. The internal temperature patterns correlate to the external temperature changes. The variation of room temperature with time shows a low diurnal temperature swing. The temperatures reach the lowest point in the morning about 7:00-8:00 am and reach the highest point in the afternoon at about 3:00 pm. The peak in operating temperature in the kitchen at 6:00 am and 7:00 pm can be attributed to internal gains from cooking. The internal operating temperatures remain relatively high throughout the day and night, fluctuating between the maximum acceptable temperature and the upper limit for overheating. The temperature reaches a night time maximum of 30°C dropping to a minimum of 27°C. This indicates that the external night temperatures do not drop significantly enough to induce rapid cooling of the indoor environment.

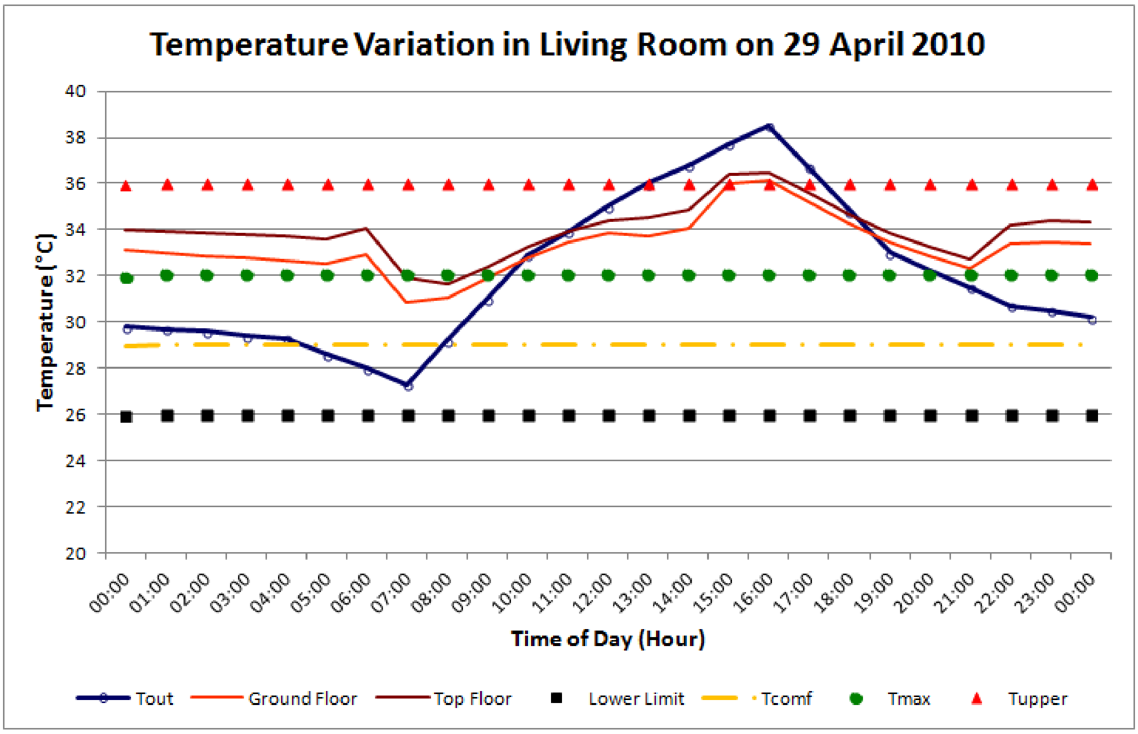


Figure 20 Diurnal temperature variation of living room

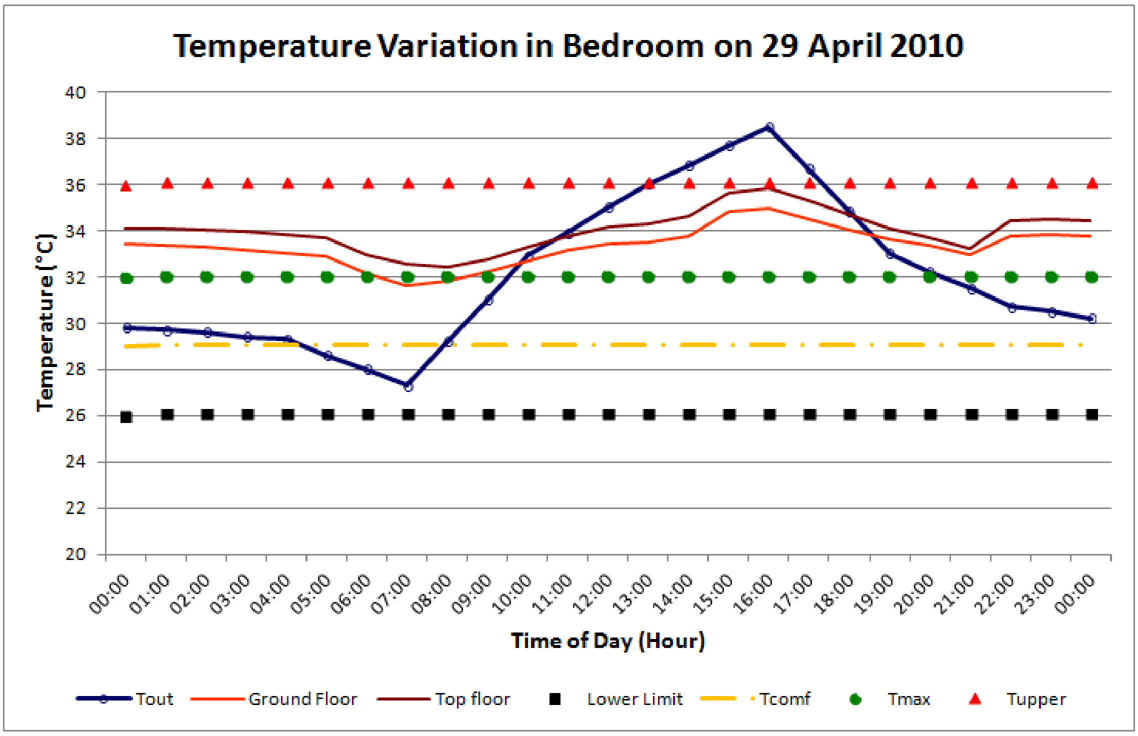


Figure 21 Diurnal temperature variation of bedroom

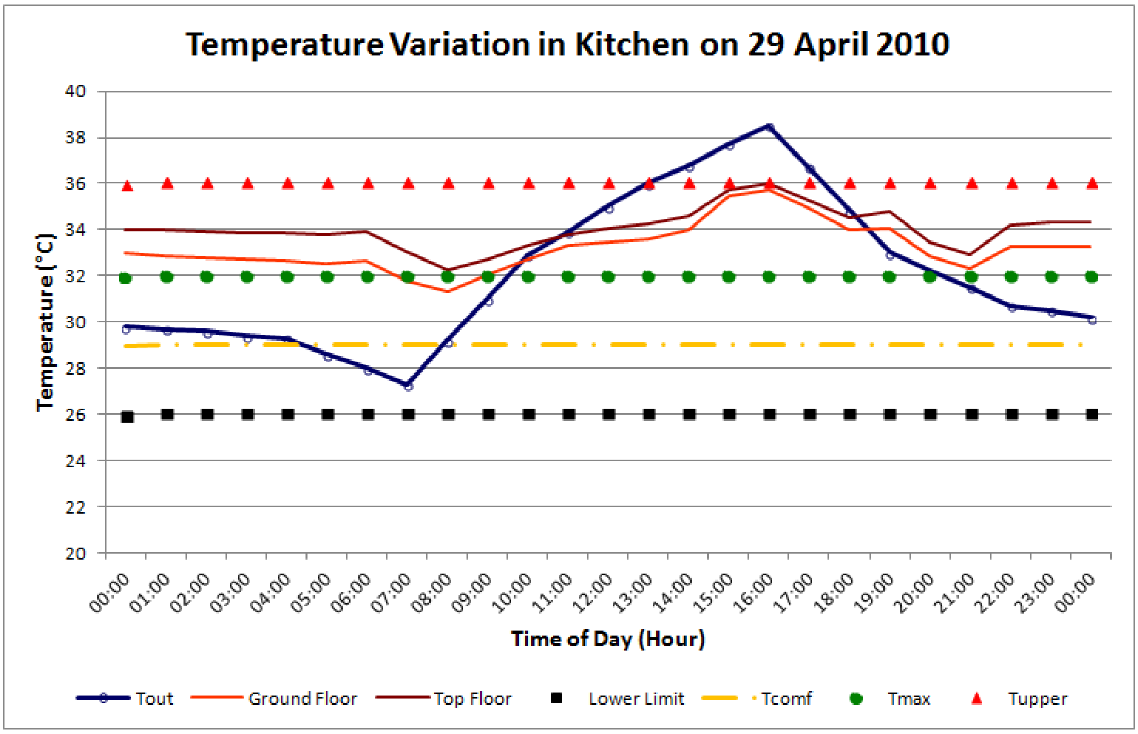


Figure 22 Diurnal temperature variation of kitchen

4.3.4.1 Influence of Building Envelope on Thermal Performance

As was explained in Section 3.2.1, the thermal mass has a significant influence on the cyclical nature of the temperature changes within the apartment units. As the external air temperature rises, the external walls and floor slab will absorb and store the heat.

Once the external temperatures start to drop (7 pm) the heat within these materials rises to the surface and is released into the internal environment. This accounts for the elevated internal temperatures of the living zones during the night. This process is represented in Figure 23, where the fluctuations in the conduction gains of the external walls are influenced by changes in the outdoor temperature. This has the resultant effect of moderating the operating temperatures of the living zones. The critical issue is that this effect keeps the operating temperatures at high levels throughout the day, inhibiting sufficient cooling to occur.

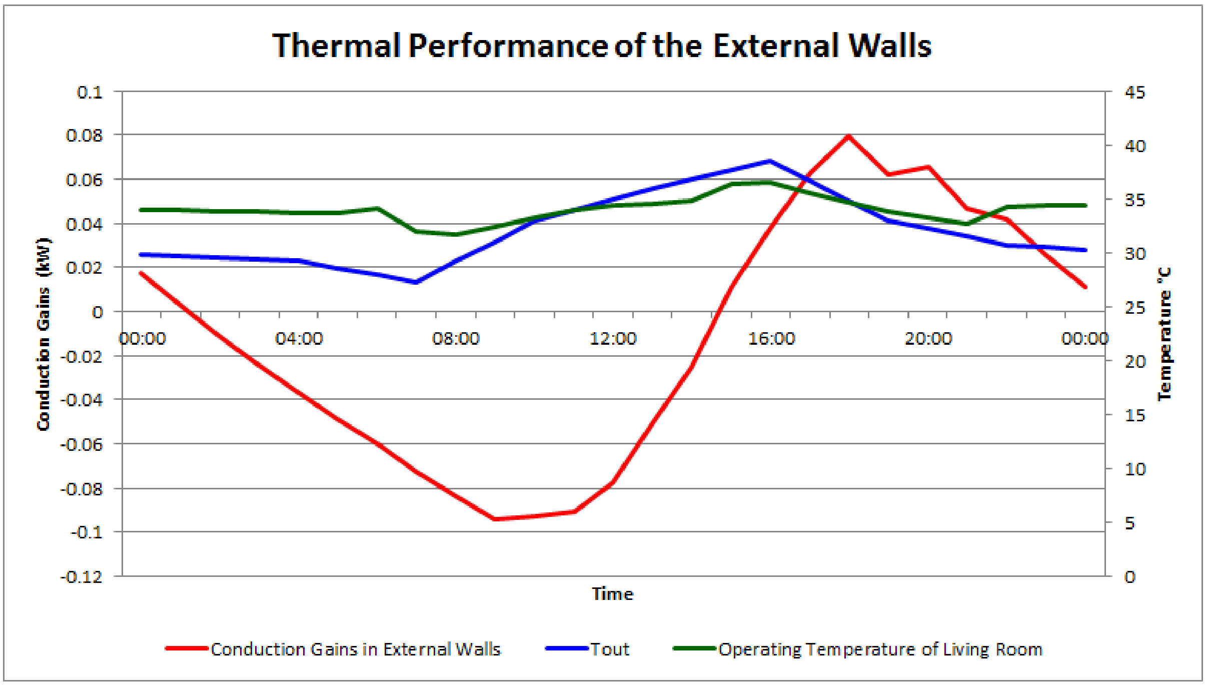


Figure 23 Thermal storage effect of external walls

While increasing a building's thermal mass can allow for the reduction of internal daytime temperatures through heat absorption, a lack of sufficient ventilation at night can elevate temperatures and cause further discomfort. In this study the windows were assumed to be closed at night due to security and social reasons. This limits the amount of airflow in the apartment at night, particularly in the bedroom which has only one window. With insufficient mechanisms to abate excess heat that is released into the zone at night, the operating temperatures of the apartment remains elevated. Figure 24 shows that about a 2°C reduction in the operating temperature is induced in the bedroom if the window remains open at night and airflow is improved.

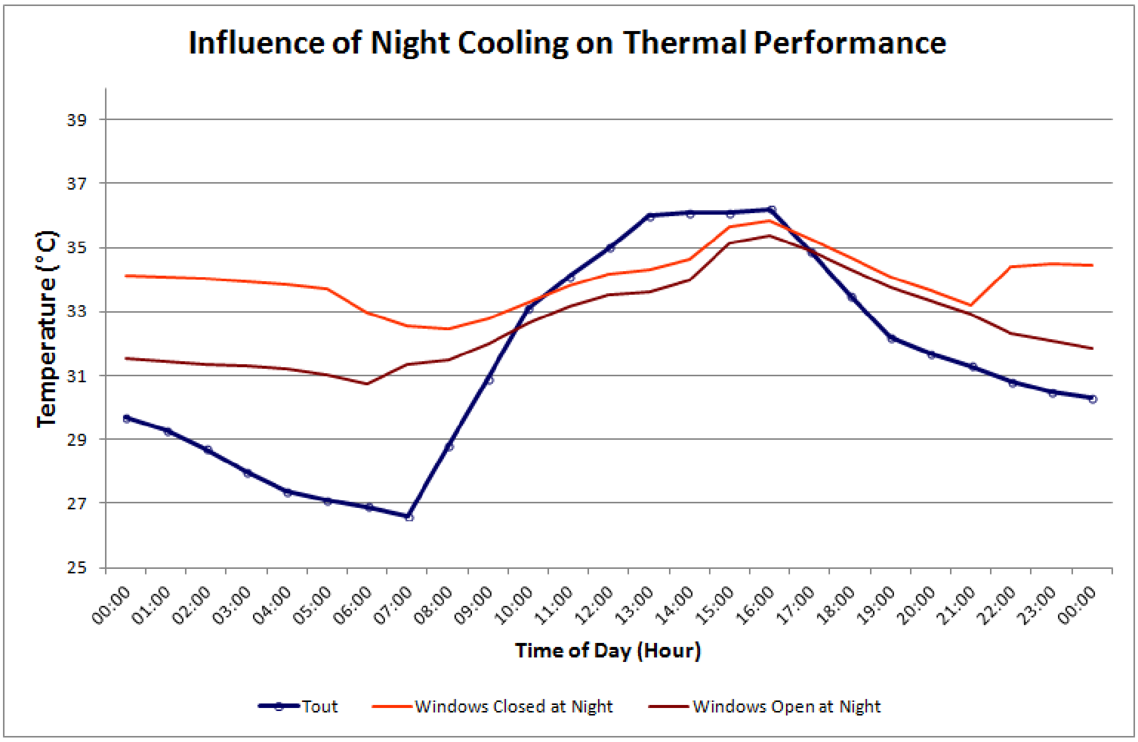


Figure 24 Improvement of ventilation with night cooling

4.3.4.2 Influence of Natural ventilation on Thermal Performance

The high internal operating temperatures are a result of both convection and radiation heat which build up over the day. Without any form of mechanical cooling natural air exchanges are responsible for the removal of this heat; however the current construction of the building and each apartment has a significant influence on the ventilation. While the narrow layout may aid in the circulation of air, the number and type of openings, the layout of the rooms and the restrictions of adjacent apartments means that ventilation between rooms is highly restricted. Figure 25 shows the airflow pattern through the apartment and Figure 26 shows the quantity of airflow that enters into each zone. The value W_c refers to the minimum wind speed that is needed to ensure indoor comfort is maintained (Tantasavasdi *et al*., 2001).

The bedroom and living room are positioned to maximise airflow through the openings in the building envelope. The opening in the bedroom is composed of a single louvre window with an openable area of 25%. This means that wind flow through the openings is significantly restricted. Air circulation within the zone is further constrained by the internal partitions demarcating the space. The door and the window are also situated on adjacent walls which makes airflow through the zone difficult. The daytime flow rate ranges from 0.11 m/s to 0.38 m/s. The windows remain closed at night which accounts for this rate dropping to zero overnight.

The front door and balcony door are situated on either end of the living room. The arrow in Figure 25 shows that this should provide some form of cross ventilation. The issue arises in the design of the kitchen-living room area. The open plan nature of the room means that there is no direct flow of air through the living zone if the front door remains closed. This means that the air will be directed through the kitchen. This explains the higher flow rates in the kitchen than the living room. The presence of a door between the two zones would allow for better cross ventilation in the living room but would elevate the kitchen temperature significantly. The maximum airflow rate in the living room and kitchen is 0.81 m/s and 2 m/s respectively. To achieve a comfortable indoor environment, natural ventilation should provide an indoor air velocity of 0.4 m/s.

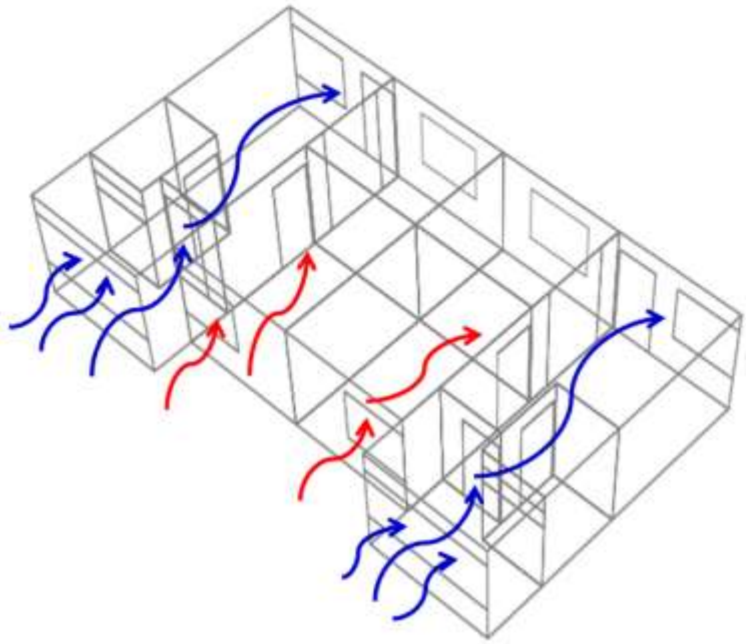


Figure 25 Ventilation through the apartment

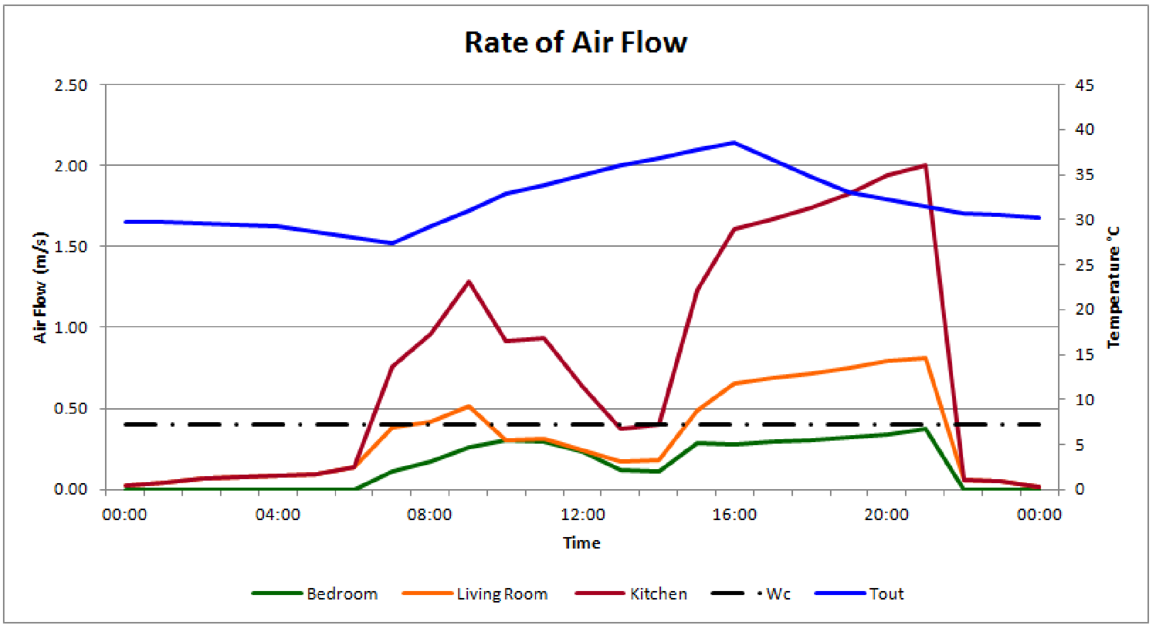


Figure 26 Rate of airflow through the apartment on 29 April 2010

Essentially the amount of cross ventilation that can occur through a single unit is highly restricted by design elements and local climatic conditions. The heat builds up and with no method of removal stagnates to increase the operating temperature as well as the discomfort of the internal environment.

4.3.4.3 Influence of Roof on Thermal Performance

The analysis of the progression of the operating temperature change over the 24 hours showed that the roof is subject to a significant temperature change over the course of the day. The temperature change in the roof is seen to begin at 09:00 as the external temperature rises and the solar radiation increases (Figure 27). The temperature of the apartments is seen to be about 5°C than in those on the ground floor at this time. By 14:00 the roof reaches its highest temperature.

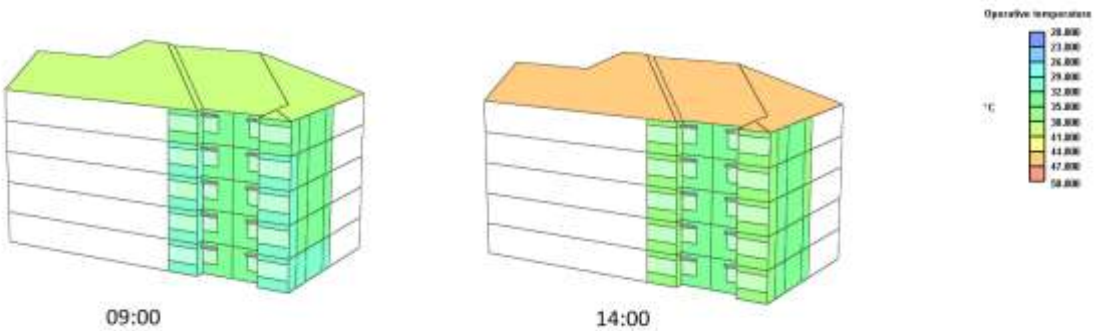


Figure 27 Progression of temperature change in the roof

The corresponding conduction gains in the roof over 24 hours are shown in Figure 28. The conduction values range from a minimum of 1.98kW at 07:00 to a maximum value of 21.86kW at 12:00. This corresponds to the increase in direct solar exposure over the day. The negative gains during the night are associated with reversal in the direction of heat transmission i.e. the roof temperature is higher than the external temperature.

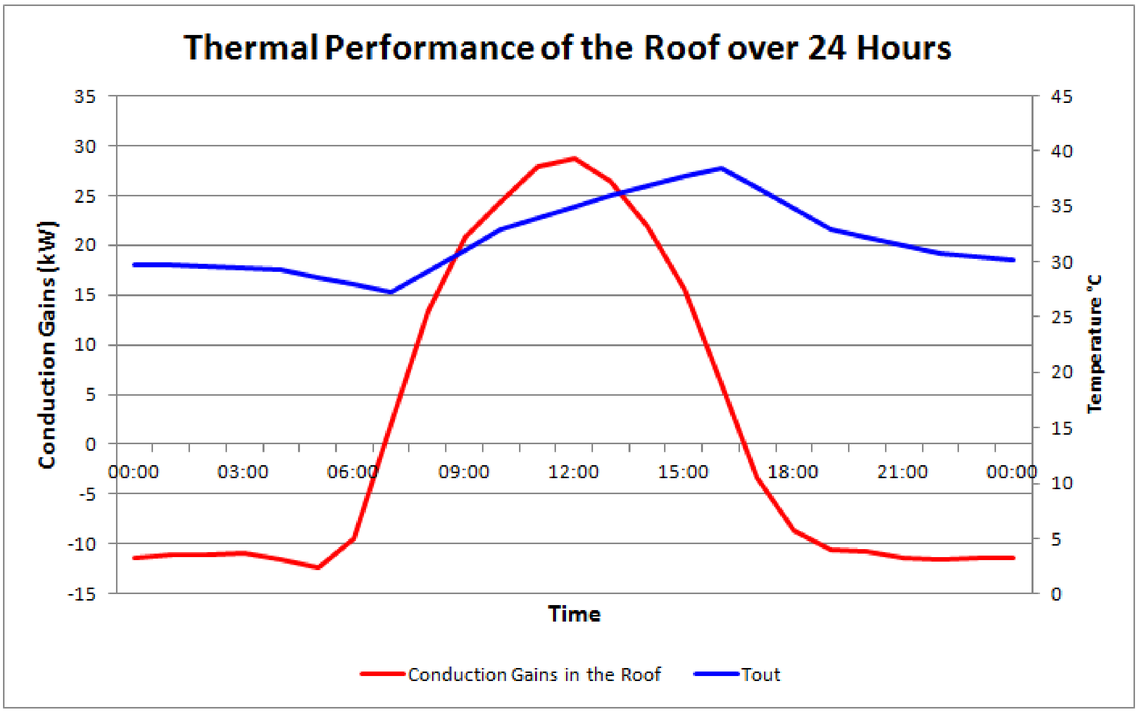


Figure 28 Severity of conduction gains in the roof on 29 April 2010

Various DTS studies that have been carried out on houses in tropical regions have shown that the roof is a key area of concern in terms of thermal performance (Eyre, 2015; Garde et al., 1999; Jayasinghe et al., 2002). The roof is continually exposed to high levels of solar radiation and materials used in roof construction tend to have low thermal storage and low thermal resistance properties. This means that a building remains vulnerable to high levels of heat transmission occurring through the roof. In the case study building, there is a significant difference in operating temperatures between the apartments on the upper level and those on the ground floor. This is partly due to the stack effect of air; however this can also be attributed to the high magnitude and the rapid transmittance of heat energy through the roof.

4.4 Summary of Findings for Baseline model

The findings in this section are drawn from the concepts raised in the discussion.

- Apartment 1 on level four has the worst thermal performance. This is due to its proximity to the roof, the effect of hot air movement into this space and the structural characteristics of the apartment envelope.

- There is a lack of diurnal temperature variation. The internal operating temperatures remain relatively high throughout the day and night, ranging from a maximum of 38.5°C to a minimum of 27.3°C. This is not significant enough to influence night cooling.

- The high storage capacity of the materials used in the construction of this building (brick, concrete) increases the indoor temperatures of the apartments. The levels of heat absorption are not enough to reduce the indoor temperatures during the day significantly. Conversely, this effect negatively influences the indoor nighttime temperatures. This problem is exacerbated due to the low diurnal temperature swing and a lack of sufficient ventilation

- The layout of each apartment is not conducive to inducing adequate levels of ventilation. In an area of low wind speed, the position and the number of openings restricts the amount of airflow through a single unit. The hot air accumulates and stagnates to increase the operating temperature of the internal environment.

- The roof is a key are of concern due to its high U-value, the surface area and the level of exposure to solar gains. This induces a high transmittal of heat into and out of the building. This has a significant effect on the operating temperatures of the apartments on the top floor.

5 Sensitivity Analysis

This chapter covers execution of building energy simulations, based on a range of differing input parameters into the baseline model, in order to assess for system sensitivity. The background to the selection of suitable design and material parameters to be assessed is first presented. The test matrix (DOE) for these parameters is derived and the experimental software is listed. The chapter concludes with the observed experimental data and a discussion around the important considerations that need to be incorporated for implementing passive design strategies into low income housing planning in Thailand.

5.1 Selection of Parameters

The implementation of passive design strategies as a solution to inadequate thermal performance in low income housing in tropical regions was presented in Section 2.3.3 of the Literature Review. In Section 4.4 the critical elements of thermal performance of the apartment were identified. In order to develop specific recommendations about passive design strategies, the study involved assessing the sensitivity of passive design parameters which are representative of mitigating/worsening the effects of the aforementioned elements. The complete set of baseline conditions and alternative conditions are shown in Table 2.

5.1.1 Ventilation

The presence of a balcony allows an opening through which are can flow into and out of the apartment, thus improving air flow and reducing the effects of a high external temperature and humidity. Similarly increasing the amount that a window can open by also improves ventilation.

5.1.2 Material Properties

A change in the wall material to a lightweight material would reduce the high thermal storage effects. Thus the parameter of lightweight concrete was selected. This is also a material that has been suggested in other studies looking at passive design strategies in Thailand (Suenderman, 2005). Similarly the effects of the roof on thermal performance were identified as critical. In order to assess the sensitivity of changes of this parameter to the system, it was chosen to run the simulation incorporating an alternative condition with roof insulation. The insulation was set to 50mm of the most basic type in order to take into consideration the low cost aspect of the design.

5.1.3 Shading

The effects of solar gains are counteracted by incorporating shading devices. In order to assess if this parameter was critical the alternative condition incorporated simulating the model without the presence of shading of the bedroom window.

Table 2 Design options for assessment of sensitivity in condominiums

Construction	Baseline Condition	Alternative Conditions	
Wall Material	Brick and Cement Rendering	Concrete Block And Rendering	Lightweight Concrete And Rendering
Shading of Windows	Local Shading of Windows	No Local Shading of Windows	
Balcony	Open Balcony	Closed Balcony	
Window Openable Area	25%	50%	75%
Roof	tiles	tiles with 50 mm insulation	

5.2 The Simulation Strategy

The results from the execution of the simulations are discussed in Section 4.3.4. These results showed that the worst performing flat in terms of meeting the thermal comfort criteria was apartment 1 on the top floor. In order to assess the sensitivity of the parameters selected in Section 5.1, the simulation strategy incorporated analysing the effects of parameter changes for only this apartment. The motivation behind this step was that improving the thermal performance of the worst case scenario would consequently improve the conditions for all scenarios. The apartment (Figure 29) was set to the baseline conditions (Table 2) with the adjacent and opposite zones set to adiabatic zones (Figure 30). The baseline condition was then modified by incorporating the changes in each of the 60 permutations (Appendices).

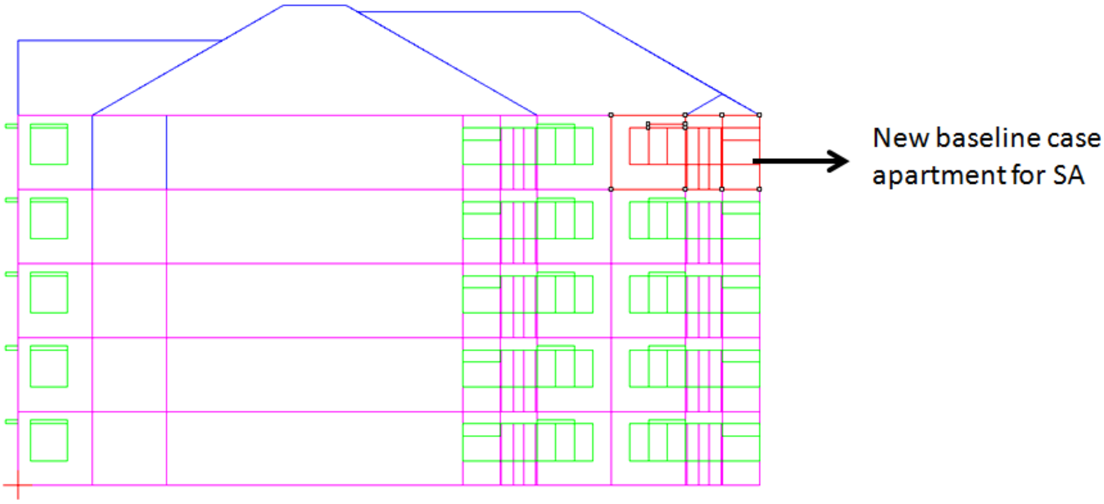


Figure 29 Location of case study flat for Sensitivity Analysis

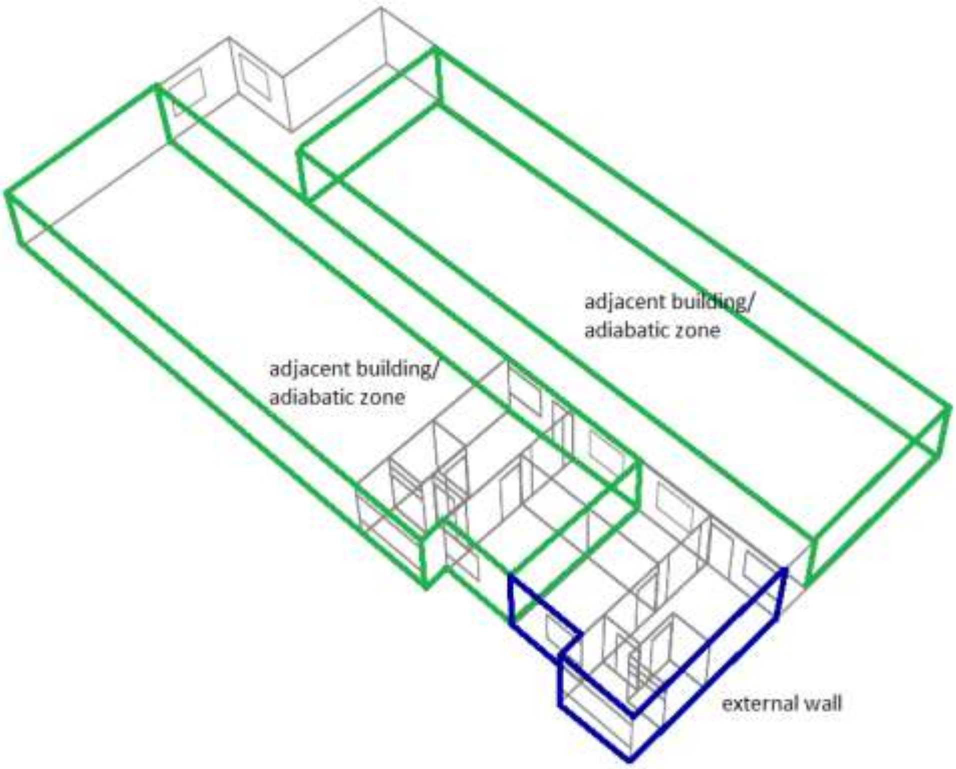


Figure 30 Rendering of internal layout for simulation of permutations

5.3 Design of Experiments

The design of experiments portion of the Literature Review (Section 2) explained the basis for carrying out a sensitivity analysis and the suitability of using the Morris array method as a statistical analysis tool for this research. The practical advantage of carrying out a SA for this research includes the identification of the most influential passive design strategy (Petr et al., 2007) . The variable passive design strategy parameters (factors) to be assessed for this research were external wall material, the presence of shading devices over the windows, the presence of a balcony, the openable area of the apartment windows and the incorporation of insulation into the roof. The levels for each of these variable design parameters are shown in Table 3.

Table 3 Experimental factors and levels

Criterion	Value at 0	Value at 1	Value at 2
External Wall material (WM)	Baked brick	Lightweight concrete	-
Shading of Windows (SW)	shading	No shading	-
Balcony (BA)	Balcony	No Balcony	-
Window Openable Area (WA)	25%	50%	75%
Roof Material (RM)	No insulation	insulation	-

The process of carrying out the SA falls under the "operation of experiments" (Park, 2007) portion of a DOE procedure. The first step was to convert the factors and levels into a set of permutations for the energy modelling purposes. In the **sample generations phase** the parameters were identified as a set of discrete variables with a value of 0, 1 or 2 depending on the alternative condition under consideration. These variables were then passed through the **pre-processor phase** where SimLab converted the independent factors and levels into various permutations. The number of permutations that are carried out is dependent on the number of executions selected by the user. For the purpose of this study the maximum number of executions (60) was selected in order to obtain a higher level of accuracy. The permutations were then converted into an experimental matrix (Appendices) under the **model execution phase**. The complete process undertaken for analysing the incorporation of this data into the energy model represented graphically in Figure 31.

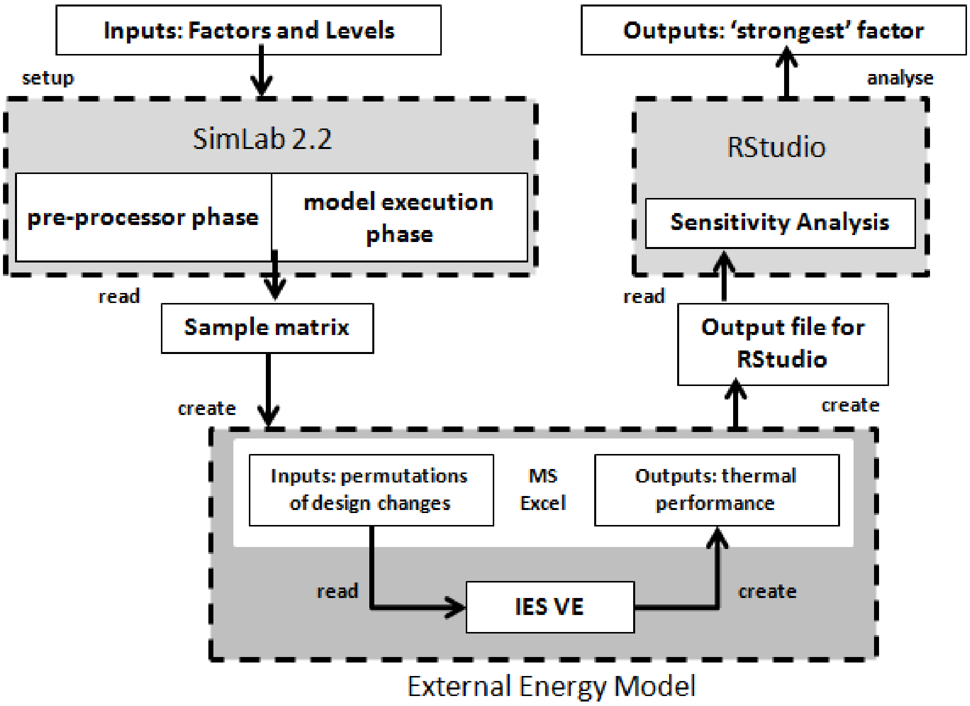


Figure 31 Graphical representation of SA strategy (adapted from Petr *et al.*, 2007)

The baseline energy model was run for different scenarios, incorporating each of the sixty permutations. Once the simulations were completed in IES Virtual Environment the results pertaining to the thermal performance of the model were fed into RStudio. The outputs from RStudio incorporate the sensitivities for each of the independent factors as well as the sensitivities of the factors interacted as pairs.

5.4 Parametric Sensitivity Analysis

The practicality of conducting a sensitivity analysis for this research is explained in the sensitivity analysis portion of the literature review (Section 2.5.1). The sensitivities were calculated based on the variances in the values of the three CIBSE TM52 criteria between the baseline model and each simulated permutation. The linear statistical analysis function was run for the living zones for each of the criteria (Appendices).

The results in Table 4 give an example of the output of the RStudio statistical analysis performed on the energy model output. These results show the coefficients of a fitted model for the living room with regards to Criteria 2 in CIBSE TM52 i.e. the changes in the number of days that **We** exceeds 6°CHr. In this case, the results show only the main effects of the individual parameters on the system (i.e. the effect of a change in one parameter while the others are held steady).

Table 4 Sensitivity of the system due to main effects only – Criteria 2, Living Room

Coefficients				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
Intercept	125.44	3.827	32.775	<2e-16
WM 1	-1.471	2.883	-0.510	0.611975
SW1	2.806	2,982	0.941	0.350988
BA 1	25.011	2.879	8.686	9.11e-12
WA 1	-9.097	3.403	-2.673	0.009970
WA 2	-14. 807	3.737	-3.962	0.000223
RM 1	-26.878	2.885	-9.317	9.41e-13

In the first column, the parameters and their respective levels are listed. The Estimate is the predicted change in the criteria (in number of days) associated with changing a parameter from the baseline (level 0) to the indicated level. The intercept is the modelled value when all the variables are at the level 0. As an example, if wall material is at level 1, shading of windows at level 1, window openable area at level 2, and the rest at level 0, the model predicts that the result should be: $125.435 - 1.471 + 2.806 - 14.807 = 111.963$ days. If there were any interaction effects, the coefficients of the variables would apply when both variables are at the specified level.

The t-value is a statistical test indicating the difference in mean of two groups and is based on the parameter's coefficient estimate and standard error. The Pr value represents the probability of achieving a value of greater magnitude than this observed t-value, if the two groups have the same mean. To say the result is most sensitive to a particular parameter it would need to have a large coefficient (positive or negative) and a low Pr value (<0.1). The Pr Value is also used to determine where the interaction effects should be included and where main effects alone are sufficient.

The results from the first model show that the factors roof material and balcony have the greatest *independent* influence over the performance of the system. An excerpt of the "Main Effects + Two Parameter Interactions" model is presented in Table 5.

Table 5 Sensitivity of the system due to main effects + two parameter interactions – Criteria 2, Living Room

Coefficients				
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
Intercept	113.037	3.749	30.150	2e-16
WM1	-3.941	3.962	-0.995	0.32608
SW1	7.178	3.933	1.825	0.07567
BA1	31.650	4.181	7.571	3.58e-09
WA1	7.061	4.439	1.591	0.11975
WA2	0.149	4.934	0.030	0.97607
RM1	-7.409	3.768	-1.966	0.05639
WA2: RM1	3.440	4.177	0.824	0.41521
WA1:RM1	-14.371	4.087	-3.516	0.0.00113
WM1:RM1	-11.450	3.289	-3.481	0.00125
BA1:WA2	-30.205	4.203	-7.187	1.19e-08

This is not the full model (Appendices), however it is presented to illustrate the effects of changing multiple factors to different levels. In this case, if wall material is at level 1, shading of windows at level 1, window openable area at level 2, and the rest at level 0, the model predicts that the result should be: $113.037 - 3.941 + 7.178 - 0.149 + 5.185 - 1.717 - 10.058 = 109.535$ days. The interaction of WM1:RM1 shows the influence of wall material despite its smaller main effect. In this model the effect of BA1:WA2 appears to be a large improvement, however it is negated by the main effect of BA1 (-30.205 vs. 31.65). The combination of WA1:RM1 ($7.06 - 7.41 - 14.37$) offers a better improvement than WA2:RM1 ($0.15 - 7.41 + 3.44$). This is despite the "Main Effects Only" model suggesting otherwise.

Although the paired interactions are statistically significant and provide more detailed predictions, there are no cases which would change the interpretation of a parameter's effect in isolation. Since the relative importance of factors is required for this study (as opposed to determining a single optimal design), the analysis is primarily restricted to main effects. The results from the analysis of the other zones and criteria showed an equivalent trend in parameter sensitivity (Appendices).

The distribution of the data set for each of the parameters is presented in box plot format. The important values include the median or central tendency measurement, the maximum and minimum number of days on overheating. The most important observations that can be made from these results include the distribution of the number of days of overheating that is experienced based on the parameter and its respective level. A change in a parameter that shows a smaller variability in the data set indicates a closer correlation between the individual values in that set (the mean is more representative of the data set). Although the range and the interquartile range are important to show the spread of the data, these points are determined from only two points in the entire data set. Thus from a statistics point of view, the values of the mean and the median are more adequate indications of the sensitivity of the parameter in the performance of the system

5.4.1 Roof and Wall Material

The impact of the material properties of the roof and walls on the thermal performance of the building was discussed in Section 4.3.4.3. The incorporation of 50mm of insulation in the roof is observed to have the greatest change in thermal performance within the apartment (Figure 32). The mean number of days of overheating is reduced to 98.56 when the wall material is changed to level 1, compared to 124 days at level 0. Insulation reduces the amount of heat gain that can enter into the space between the roof and the ceiling. This means that there is a restriction on the flow of heat in the day and at night. The maximum and minimum number of days of overheating was reduced from 185 to 125 and 115 to 30 days respectively. The spread of data points is greatly improved by incorporating insulation. This means that less variance is seen in the effects of overheating.

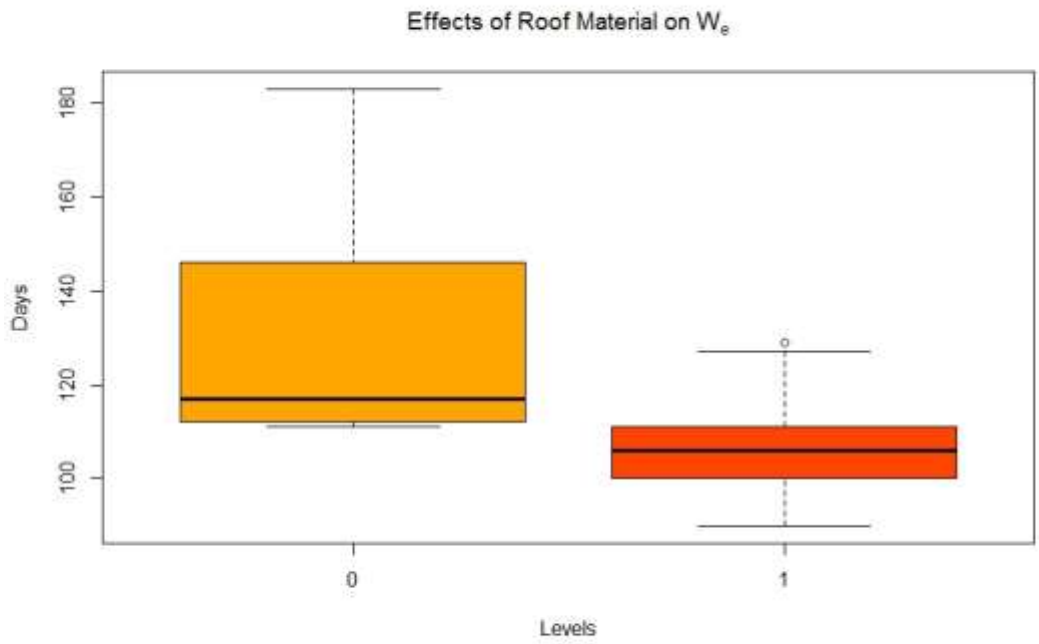


Figure 32 Individual sensitivity: roof material

The change of the wall material from brick (level 0) to lightweight concrete (level 1) is seen to be less critical than changes in the other parameters. Figure 33 shows the reason for this is that the results of the two data sets overlap significantly. A change in wall material resulted in a reduction of overheating to a mean of 123.97 days, with the median value changing from 170 to 160 days. Although the maximum and minimum number of days of overheating was reduced from 175 to 142 and from 115 to 30 days respectively, the value of the median is a better indication of the typical number of days of overheating. The outlying value represents a significant irregularity in the distribution which falls outside 1.5 times the upper quartile rage.

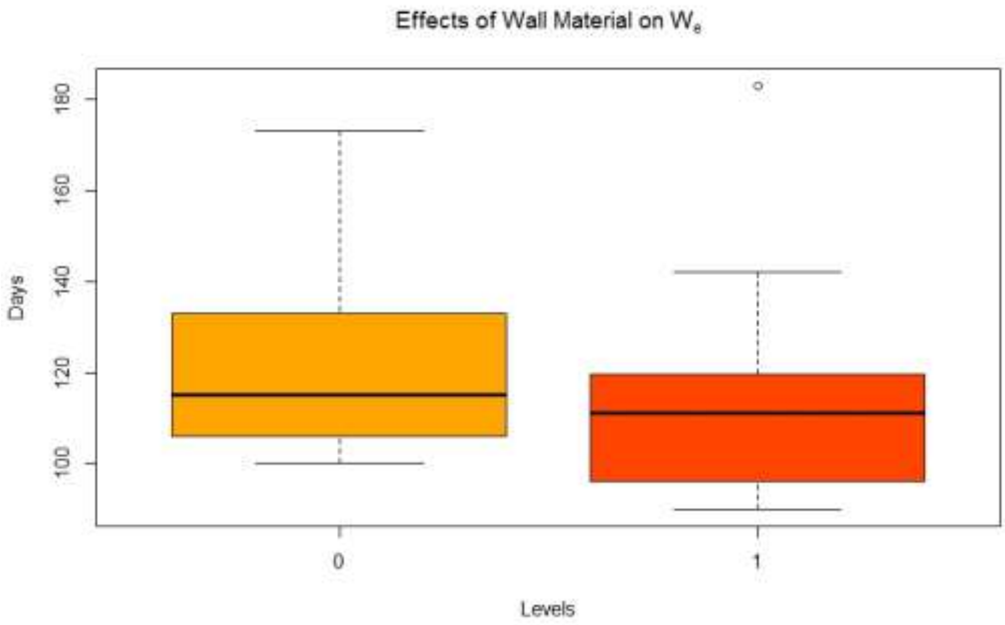


Figure 33 Individual sensitivity: wall material

The total sensitivity effects of the combinations of uncertainty in the distributions of both wall material and roof material are shown in Figure 34. The levels on the x-axis show the effects of changing first the wall material (1, 0), the roof material (0, 1) and then both wall material and roof material (1, 1). The combined incorporation of 50mm insulation and the change of wall material to lightweight concrete reduced the mean number of days of overheating to 101.59 with the maximum reaching 130 days compared to 172 days of the baseline condition. The effects in the combination of the sensitivities can be seen on the graph where the median value has decreased from 135 days at the baseline level to 100 days with both parameters set to level 1. The elementary effects of the incorporation of roof material only, however were shown to reduce the mean number of days of overheating to 98.56. This indicates that although changing the value of these parameters both to level 1 would elicit a decrease in the severity of overheating experienced in the apartment, changing the roof material only has a greater effect in reducing the severity of overheating.

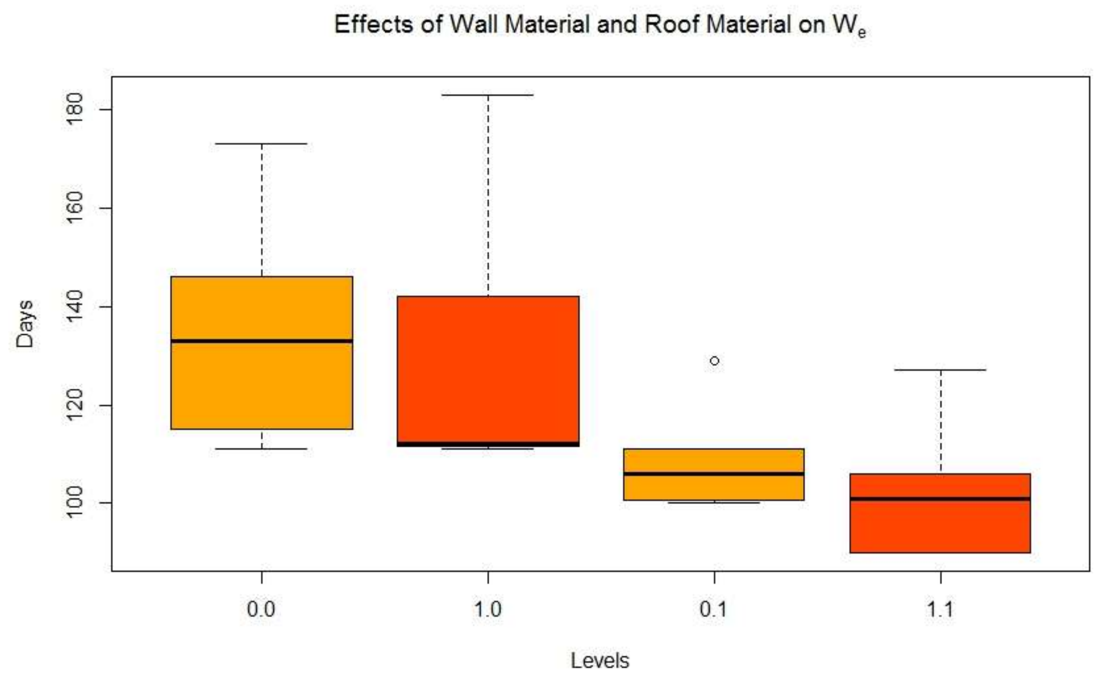


Figure 34 total sensitivities: wall material and roof material

5.4.2 Balcony and Window Openable Area

The impact of ventilation on the thermal performance of the building was discussed in Section 4.3.4.2. The sensitivity of this parameter is essentially assessing for how a decrease in ventilation through the apartment would influence the thermal performance of the design. This parameter was seen to have the second largest effect on the system after the roof material. The graphical representation of these results is shown in Figure 35. At level 1 (the balcony is closed) the maximum number of days of overheating has increased from 118 to 183. The mean was seen to increase to 150.45 days. The already stilted airflow through the living room is further exacerbated once the balcony is removed. This indicates that the temperature of the living zones is staying at elevated temperatures for longer periods without any form of ventilation. This is expected in a region with high humidity as well as low minimal air movement. The presence of the balcony has a profound influence on the natural ventilation through the apartment.

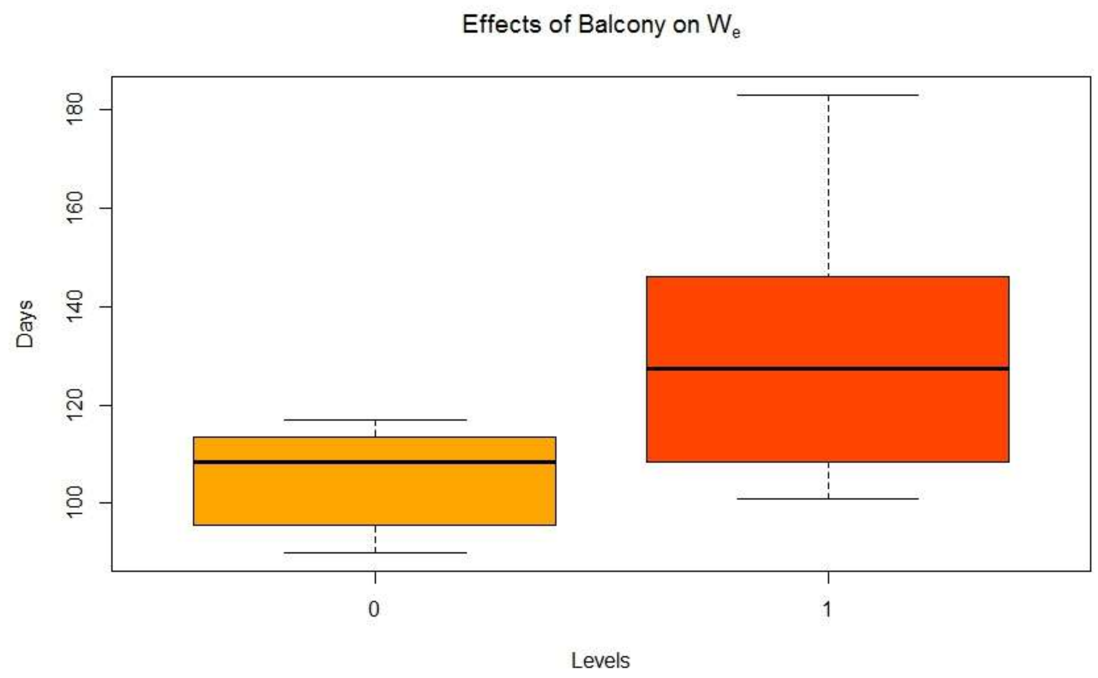


Figure 35 Individual sensitivity: Balcony

In terms of the openable area of the windows, this is also a measure of the amount of ventilation that is generated in the apartment. This parameter was set at three different levels in order to assess the extreme variability of the importance of opening size on ventilation and thus the thermal performance of the apartment (Figure 36). The baseline condition for window openable area is 25% (level 0). The mean number of days of overheating at each level 1 and 2 (50% and 75% openable area) was determined to be 116.34 and 110.63 days respectively. When the openable area is set to 50% the variability of the data set was increased. The nature of the plot can be attributed to single data points that lie further away from the mean, which is why the median (112 days) is a better representation of this data set. At level 2, the variability of the dataset is reduced and the mean is a more adequate representation of how this parameter influences the performance. Essentially the system is shown to be highly sensitive to a change in this parameter.

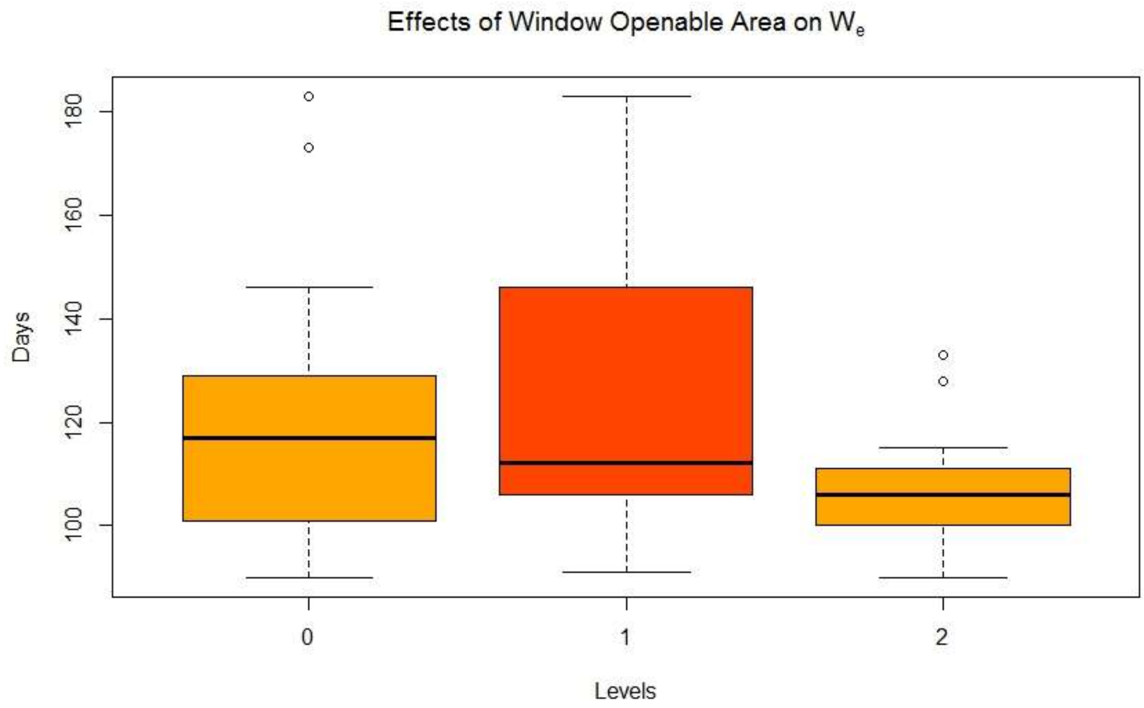


Figure 36 Individual sensitivity of window openable area

5.4.3 Conclusions

The conclusions in this section are drawn from the concepts raised in the discussion.

- The use of the Morris method for screening in combination with a linear function for statistical analysis can adequately predict the sensitivity of design parameters in a low income housing unit in Thailand.

- There are no cases of paired parameter interactions that change the interpretation of a parameter's effects in isolation. This means that the main effects of the parameter changes have a greater influence on the performance of the system and are an adequate representation of parameter sensitivity.
    - This was shown in the assessment of the effects of both roof material and wall material. The mean number of days of overheating was 101.59 with both parameters set to level 1 whereas this number was 98.56 when only the effects of roof material were considered.

- The system is shown to be most sensitive to a change in the roof material and the incorporation of a balcony into the design. The parameters which are least sensitive to changes in the system include the shading of windows and wall material.

- The mean number of days of overheating was reduced to 98.56 with the incorporation of 50mm insulation and increased to 150.45 when the balcony was removed. These effects can be attributed to a reduction of heat gain through the roof when insulation is incorporated but an increase in heat gain due to a lack of ventilation without a balcony opening.

6 CONCLUDING REMARKS

This chapter provides a combined overview of the various results that have been established in this study. It also lays the groundwork for future work with regards to the ELITH project and the design and planning of energy efficient housing units in Thailand.

6.1 Discussion

This dissertation encompassed the study of a specific low income housing project in urban areas of Bangkok, Thailand. The scope of the study extended from extracting information about the various housing unit designs, identifying a case study design and then assessing this design in terms of its adequacy in meeting thermal comfort conditions under adaptive comfort standards.

It was outlined by the literature review that the dominant housing designs under the Baan Ua-Arthorn housing programme are low-rise high-density condominiums. The results show that the construction methods and material composition of these units are typical of low to lower middle income designs. The primary observation was the use of materials with a high thermal mass and low thermal resistance in the building envelope. In the subsequent building energy simulations that were executed these characteristics were shown to have a significant influence on the thermal performance of the system.

The conduction of Dynamic Thermal Simulations of the case study housing unit allowed weaknesses in the design in terms of providing thermal comfort to inhabitants to be identified. The results were assessed according to the CIBSE TM 52 guideline for assessing overheating in naturally ventilated buildings. It was observed that the building failed to comply with the limits of overheating established by this guideline. The primary concerns include the severity of overheating far exceeds what is deemed appropriate for achieving a comfortable internal environment and the living zones breached the absolute daily maximum daily temperature limit. This means that the current housing designs are not adequate for establishing a comfortable living environment for the inhabitant in this climate.

The main sources of the low thermal performance quality in these apartments were identified as resulting from:

i. Thermal storage effects due to the high thermal mass of the apartment walls and floor.
ii. The lack of sufficient natural ventilation through the living zones resulting from the high levels of humidity and low natural wind speeds in the area but exacerbated by a poor indoor layout and a lack of sufficient openings in the building envelope.
iii. The high conduction gains through the roof resulting from its inadequate material properties.

The investigation now turns its attention to the sensitivity analysis of passive design parameters for improving the thermal performance. The five parameters that were chosen were wall material, shading of windows, balcony, window openable area and roof material in order to assess how the relative importance that those improvements in thermal storage properties, solar gains, ventilation and roof conduction would have in for this specific housing unit. The Morris method was used to screen the parameters and output a set of a set of simulation permutations, which were then executed in the external energy model. The results of the data were statistically analysed and showed how each parameter caused a deviation in the baseline condition. This deviation influenced how sensitive this parameter was deemed to be.

An interesting outcome of this investigation was the identification of the sensitivity of the system to a particular parameter. The incorporation of measures to reduce heat gain in the roof has a major influence on the performance of the system, reducing the severity of overheating by 21.43% to a mean of 98.56 days. The provision of adequate ventilation was observed as the second major influencing factor on the system. The exclusion of the balcony was shown to increase the number of days of overheating by 19.94% to a mean of 150.45 days. It was also observed that the elementary effects of the parameter changes have a greater influence compared to incorporating the uncertainties from each of inputs i.e. individual sensitivities are more profound than total sensitivities.

6.2 Recommendations

The results of this study are not aimed at designing an ideal low income housing unit for the National Housing Authority, however this assessment can be used to make recommendations based on the adequacy of the design strategies in naturally ventilated buildings in consideration of the Thai context. In consideration of the assessment of the thermal performance of the case stud house and the analysis of the sensitivity of passive design parameters, it can be recommended that for adequate building performance the following considerations need to be made:

- Improved forethought with regards to the selection of materials in the building envelope, the roof and internal structural elements
- The identification of the roof as a key area of concern which can be improved with the use of insulation materials
- The design of an internal layout that is conducive to allowing the maximum amount of air flow to reach all living zones
- Increase the size, number and location of openings to improve ventilation in the living zones.
- The incorporation of different window designs in order to reduce the airflow restrictions experienced with louvre windows.
- Orientating the building to maximise the effects of wind speed and in particular the “wind scoop” effect of the balcony

Essentially design strategies to limit the amount of internal heat gain and reduce the effects of humidity should be prioritised in future housing projects.

6.3 Future Work

An essential part of the work that still needs to be done with regards to this study includes the validation of the simulation results. This includes installing data loggers in one of these housing units in order to collect information on the fluctuations in operating temperature over the year. While this study showed the most important individual parameters that need to be considered future, work needs to incorporate the quantitative comparison between using mechanical means of cooling such as fans and air conditioners with passive design features. This is necessary to understand the practicalities of incorporating passive design, particularly in consideration of the bioclimate. A thermal energy storage system, like a rock store, could also be investigated as it may be well suited to this application.

In combination with this, the accuracy of the lifestyles of the inhabitants needs to be verified. A detailed study needs to be executed with regards to those social factors that influence how individuals interact with their surroundings. This includes more information about occupancy patterns and as well as investigating the incorporation of passive design strategies into the social constructs regarding the perception of modernity and mechanical cooling.

Housing projects of this nature are not only highly capital intensive, placing a large financial burden on government entities, the cost advantages obtained through scaling up of these projects have not been realised. Future studies should focus on the economic side of incorporating passive design elements in low income housing projects in Thailand. The question surrounding whether passive design can be low cost needs to be investigated and in particular and does it make sense from an economic point of view to implement these strategies rather than using active means of cooling. The ultimate goal would be to incorporate all the findings from this research with the findings to deliver a comprehensive conceptual design to the NHA which could be used to formulate policy and building standards with regards to low income housing design for the tropical Thai climate.

7 REFERENCES

Antarikananda, P., Douvlou, E., McCartney, K., 2006. Lessons from traditional architecture: Design for a climatic responsive contemporary house in Thailand, in: Proceedings of the 23rd Conference on Passive and Low Energy Architecture-PLEA2006-, Geneva, Switzerland. pp. 11–43.

Archer, D., 2010. Social capital and participatory slum upgrading in Bangkok, Thailand. University of Cambridge.

ASHRAE 55-2004 Thermal Environmental Conditions for Human Occupancy (ANSI Approved), 2004.

Bangkok Climate & Temperature [WWW Document], 2015. . ClimaTemps. URL http://www.bangkok.climatemps.com/ (accessed 6.15.15).

Booth, A.T., 2015. IES Virtual Environment — Energy modelling and building physics resource base [WWW Document]. URL http://www-embp.eng.cam.ac.uk/software/iesve (accessed 5.28.15).

Chiarakorn, S., Rakkwamsuk, P., Aransiri, K., Aneksaen, N., Parnthong, R., 2014. Evaluation of greenhouse gas emission from residential buildings in Thailand, in: Evaluation of Greenhouse Gas Emission from Residential Buildings in Thailand. Presented at the 5th International Conference on Sustainable Energy and Environment (SEE 2014): Science, Technology and Innovation for ASEAN Green Growth 19-21 November 2014, Bangkok, Thailand, Bangkok, pp. 358–361.

Clarke, J.A., 2001. Energy Simulation in Building Design. Routledge.

de Dear, R., Schiller Brager, G., 2001. The adaptive model of thermal comfort and energy conservation in the built environment. International Journal of Biometeorology 45, 100–108. doi:10.1007/s004840100093

Eyre, M., 2015. Transition in Housing Design in Rural Tanzania's Temperate Tropical Regions: An Analysis of Thermal Comfort Performance and Possible Design Improvements. University of Cambridge.

Fanger, P.O., 1970. Thermal comfort. Analysis and applications in environmental engineering. 244 pp.

French, M.A., Majale, M., Tipple, G., 2011. Affordable Land and Housing in Asia, Adequate Housing Series. UN-HABITAT, Nairobi, Kenya.

Garde, F., Boyer, H., Gatina, J.C., 1999. Elaboration of global quality standards for natural and low energycooling in French tropical island buildings. Building and Environment 34, 71–83.

Golubchikov, O., Badyina, A., 2012. Sustainable housing for sustainable cities: a policy framework for developing countries. UN-HABITAT, Nairobi, Kenya.

Hannula, E.-L., 2012. Going green: a handbook of sustainable housing practices in developing countries. UN-HABITAT, Nairobi, Kenya.

Hwang, R.-L., Cheng, M.-J., Lin, T.-P., Ho, M.-C., 2009. Thermal perceptions, general adaptation methods and occupant's idea about the trade-off between thermal comfort and energy saving in hot–humid regions. Building and Environment 44, 1128–1134. doi:10.1016/j.buildenv.2008.08.001

International Building Performance Simulation Association, 2012. BEMBook [WWW Document]. Thermal Zoning Determination. URL http://bembook.ibpsa.us/index.php?title=Thermal_Zoning_Determination (accessed 7.29.15).

Janssen, D., Janssen, C., 2010. What is a Proof of Concept (POC)? [WWW Document]. Techopedia.com. URL http://www.techopedia.com/definition/4066/proof-of-concept-poc (accessed 7.29.15).

Jayasinghe, M.T.., Attalage, R.A., Jayawardena, A.I., 2002. Thermal comfort in proposed three-storey passive houses for warm humid climates. Energy for Sustainable Development 6, 63–73.

Jayasinghe, M.T.., Priyanvada, A.K.., 2002. Thermally comfortable passive houses for tropical uplands. Energy for Sustainable Development 6, 45–54.

Kritayanavaj, B., 2012. Affordable housing in Thailand (No. 10), Housing Finance and Affordability.

Ministry of Information and Communication Technology, 2010. Energy Consumption of Households [WWW Document]. National Statistical Office. URL http://web.nso.go.th/en/survey/env/data_env/580121_Pocket%20Book_13.pdf (accessed 7.1.15).

Ministry of Information and Communication Technology, 2004. The gender statistics survey [WWW Document]. National Statistical Office. URL http://web.nso.go.th/en/survey/gender/gender.htm (accessed 7.29.15).

Morris, M.D., 1995. Factorial Sampling Plans for Preliminary Computational Experiments. Technometrics 33, 167–174.

Nguyen, A.T., Singh, M.K., Reiter, S., 2012a. An adaptive thermal comfort model for hot humid South-East Asia. Building and Environment 56, 291–300. doi:10.1016/j.buildenv.2012.03.021

Nguyen, A.T., Singh, M.K., Reiter, S., 2012b. An adaptive thermal comfort model for hot humid South-East Asia. Building and Environment 56, 291–300. doi:10.1016/j.buildenv.2012.03.021

Nicol, F., 2013. The limits of thermal comfort: avoiding overheating in European buildings. The Chartered Institution of Building Services Engineers.

Nicol, F., 2004. Adaptive thermal comfort standards in the hot–humid tropics. Energy and Buildings 36, 628–637. doi:10.1016/j.enbuild.2004.01.016

Park, G.-J., 2007. Analytic Methods for Design Practice. Springer London.

Peel, M.C., Finlayson, B.L., Mcmahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrology and earth system sciences discussions 4, 439–473.

Petr, K., Filip, J., Karel, K., Jan, H., 2007. Technique of uncertainty and sensitivity analysis for sustainable building energy systems performance calculations, in: Proceedings of 10th IBPSA Building Simulation Conference, Tsinghua University, Beijing. Citeseer, pp. 629–636.

Prianto, E., Depecker, P., 2002. Characteristic of airflow as the effect of balcony, opening design and internal division on indoor velocity: A case study of traditional dwelling in urban living quarter in tropical humid region. Energy and Buildings 34, 401–409.

Rangsiraka, P., 2006. Thermal Comfort in Bangkok residential buildings, Thailand, in: PLEA2006. Presented at the The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Santamouris, M., 2003. Solar Thermal Technologies for Buildings: The State of the Art. Earthscan.

Santamouris, M., Pavlou, K., Synnefa, A., Niachou, K., Kolokotsa, D., 2007. Recent progress on passive cooling techniques Advanced technological developments to improve survivability levels in low-income households. Energy and Buildings 39, 859–866. doi:10.1016/j.enbuild.2007.02.008

SimLab2.2, 2015. Simlab2.2 Reference Manual.

Suenderman, T., 2005. Energy Efficiency in Affordable Low-to-Medium-Income Urban Housing of the National Housing authority of Thailand (Consultancy Report). GIZ.

Tantasavasdi, C., Srebric, J., Chen, Q., 2001. Natural ventilation design for houses in Thailand. Energy and Buildings 33, 815–824.

Tarantola, S., Giglioli, N., Jesinghaus, J., Saltelli, A., 2002. Can global sensetivity analysis steer the implementation of models for environmental assessments and decision making? Stochastic Environmental Research and Risk Assessment 16, 63–76.

Telford, J.K., Uy, M., 2009. Optimization by Design of Experiment techniques, in: Aerospace Conference, 2009 IEEE. IEEE, pp. 1–10.

The Chartered Institution of Building Services Engineers, 2006. CIBSE Guide A Environmental design. The Chartered Institution of Building Services Engineers, London.

The Concrete Centre, 2015. MPA-The Concrete Centre [WWW Document]. URL http://www.concretecentre.com/about_us.aspx (accessed 8.3.15).

University of Cambridge, 2015. Energy and Low Income Tropical Housing — Low Income Tropical Housing [WWW Document]. Low Income Tropical Housing. URL http://www.elith.eng.cam.ac.uk/ (accessed 6.14.15).

Usavagovitwong, N., Pruksuriya, A., Supaporn, W., Rak-U, C., Archer, D., McGranahan, G., 2013. Housing density and housing preference in Bangkok's low-income settlements (Working Paper No. Working Paper 12), Urbanisation and Emerging Population Issues. International Institute for Environmnet and Development.

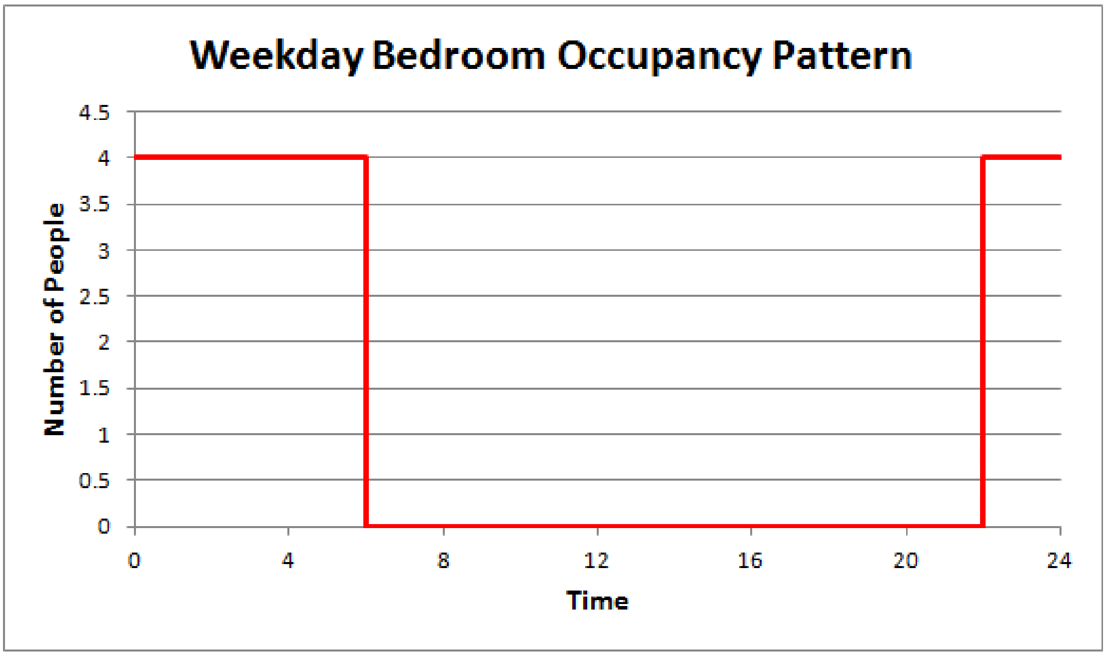
8 APPENDICES

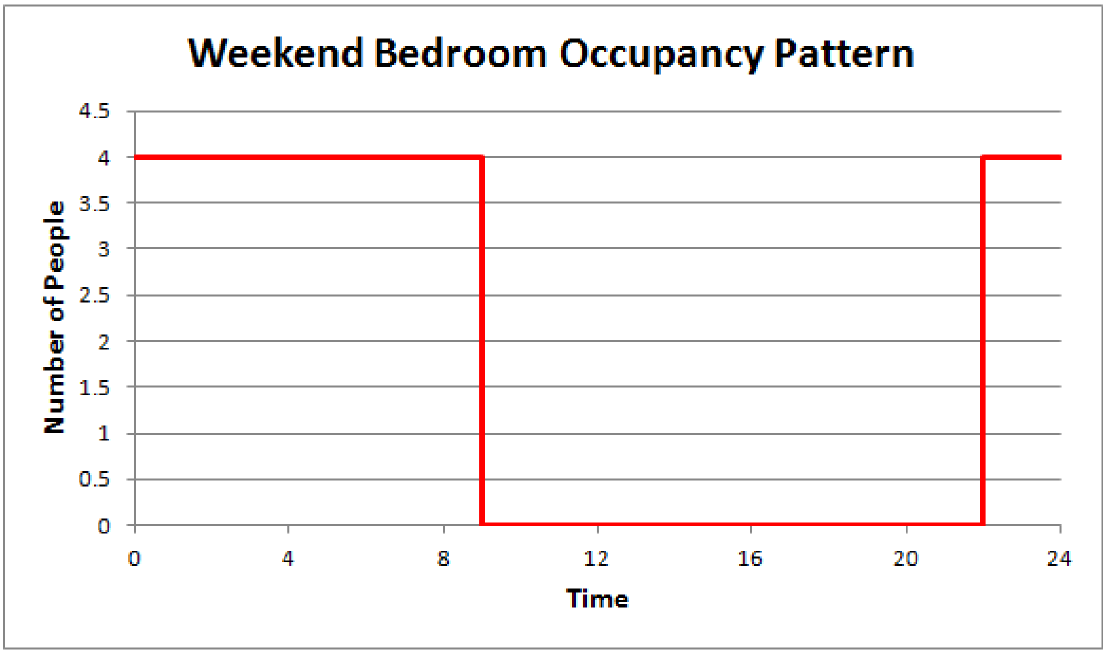
APPENDIX 1: BILL OF QUANTITIES

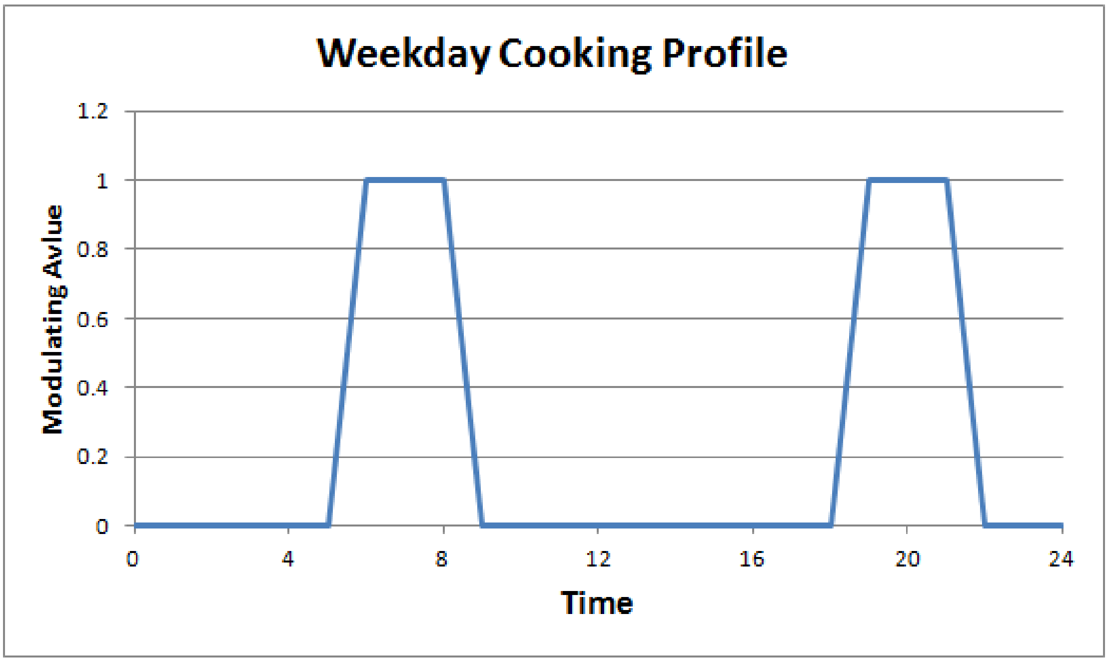
		BOQ. from NHA		Unit conversion	
	Materials	**Quantity**	**Unit**	**Quantity**	**Unit**
Structural work	Sand	18	m^3	28 800.00	kg
	Concrete	427	m^3	982 100.00	kg
	Steel	47 011.00	kg	47011.00	kg
Roof construction	Slate Roof Tiles	1 060.00	sheet	5 872.80	kg
Ceiling	Cement	355	m^2	7 100.00	kg
Plastering work	Cement	7 330.00	m^2	146 600.00	kg
Clay brick wall (haft-sheet)	Brick	2 308.00	m^2	415 440.00	kg
	Cement	2 308.00	m^2	36 928.00	kg
	Sand	115.4	m^3	184 640.00	kg
	Lime	2 308.00	m^2	23 749.32	kg
Clay brick wall (full-sheet)	Brick	75	m^2	26 910.00	kg
	Cement	75	m^2	2 550.00	kg
	Sand	9	m^3	14 400.00	kg
	Lime	75	m^2	1 544.25	kg
Concrete block wall	Cement	12	m^2	81.00	kg
	Concrete	12	m^2	1 014.00	kg
	Sand	0.36	m^3	576.00	kg
	Lime	12	m^2	46.44	kg
Windows	Glass	3 780.00	flake	1799.28	kg

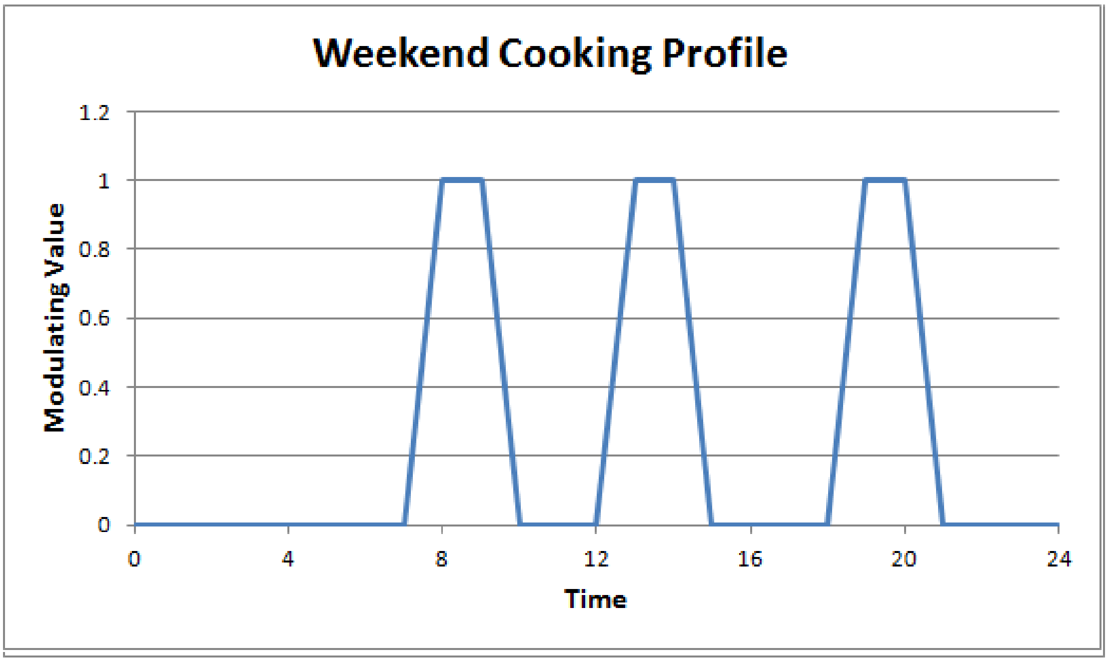
Condominium 5 floor area 2,121.15 m^2 (**ELITH Project Thailand group**)

APPENDIX 2: PROJECT PROFILES FOR CASE STUDY HOUSE






Weekday Cooking Profile
Modulating Avlue
1.2
1
0.8
0.6
0.4
0.2
0
0
4
8
12
16
20
24
Time


Weekend Cooking Profile
Modulating Value
1.2
1
0.8
0.6
0.4
0.2
0
0
4
8
12
16
20
24
Time

APPENDIX 3: CIBSE TM 52 DESIGN EQUATIONS

The adaptive equation for comfort relates the equation relating indoor comfort temperature to outdoor temperature

$$T_{comf} = 0.33\ T_{rm} + 18.8 \qquad (1)$$

T_{max} is the **maximum acceptable temperature** of **3 °C** above the comfortable temperature (**Tcomf**) for buildings in free-running mode.

$$T_{max} = 0.33\ T_{rm} + 21.8 \qquad (2)$$

APPENDIX 4: TEST MATRIX OF PERMUTATIONS

No.	Wall Material	Shading of Windows	Balcony	Window Openable Area	Roof Material
1	0	1	1	1	0
2	0	1	0	1	0
3	1	1	0	1	0
4	1	1	0	2	0
5	1	0	0	2	0
6	1	0	0	2	1
7	1	1	1	1	0
8	0	1	1	1	0
9	0	1	1	0	0
10	0	1	0	0	0
11	0	1	0	0	1
12	0	0	0	0	1
13	0	0	1	0	1
14	0	0	1	0	0
15	0	0	0	0	0
16	0	0	0	1	0
17	1	0	0	1	0
18	1	1	0	1	0
19	1	1	1	1	1
20	1	0	1	1	1
21	1	0	1	2	1
22	1	0	0	2	1
23	0	0	0	2	1
24	0	0	0	2	0
25	1	0	1	1	0
26	0	0	1	1	0
27	0	1	1	1	0
28	0	1	1	1	1
29	0	1	1	2	1
30	0	1	0	2	1
31	0	0	0	1	1
32	1	0	0	1	1
33	1	0	0	0	1
34	1	0	1	0	1
35	1	0	1	0	0
36	1	1	1	0	0
37	0	1	1	1	1
38	0	0	1	1	1
39	0	0	1	0	1
40	1	0	1	0	1
41	1	0	0	0	1
42	1	0	0	0	0

43	0	1	1	1	1
44	1	1	1	1	1
45	1	0	1	1	1
46	1	0	1	2	1
47	1	0	0	2	1
48	1	0	0	2	0
49	0	0	1	1	0
50	0	1	1	1	0
51	0	1	0	1	0
52	0	1	0	0	0
53	0	1	0	0	1
54	1	1	0	0	1
55	1	1	1	2	0
56	0	1	1	2	0
57	0	0	1	2	0
58	0	0	1	2	1
59	0	0	1	1	1
60	0	0	0	1	1

APPENDIX 5: CONFIGURATION MATRIX OF SIMLAB SIMULATIONS UNDER THE MORRIS METHOD

0				
60				
5				
0				
0	1	1	1	0
0	1	0	1	0
1	1	0	1	0
1	1	0	2	0
1	0	0	2	0
1	0	0	2	1
1	1	1	1	0
0	1	1	1	0
0	1	1	0	0
0	1	0	0	0
0	1	0	0	1
0	0	0	0	1
0	0	1	0	1
0	0	1	0	0
0	0	0	0	0
0	0	0	1	0
1	0	0	1	0
1	1	0	1	0
1	1	1	1	1
1	0	1	1	1
1	0	1	2	1
1	0	0	2	1
0	0	0	2	1
0	0	0	2	0
1	0	1	1	0
0	0	1	1	0
0	1	1	1	0
0	1	1	1	1
0	1	1	2	1
0	1	0	2	1
0	0	0	1	1
1	0	0	1	1
1	0	0	0	1
1	0	1	0	1
1	0	1	0	0
1	1	1	0	0
0	1	1	1	1
0	0	1	1	1

0	0	1	0	1
1	0	1	0	1
1	0	0	0	1
1	0	0	0	0
0	1	1	1	1
1	1	1	1	1
1	0	1	1	1
1	0	1	2	1
1	0	0	2	1
1	0	0	2	0
0	0	1	1	0
0	1	1	1	0
0	1	0	1	0
0	1	0	0	0
0	1	0	0	1
1	1	0	0	1
1	1	1	2	0
0	1	1	2	0
0	0	1	2	0
0	0	1	2	1
0	0	1	1	1
0	0	0	1	1
1				
5				
1	-0.18227	-0.09371	0.084944	0.070641
-0.18227	1	0.076654	-0.05035	-0.23076
-0.09371	0.076654	1	0.003355	0.031505
0.084944	-0.05035	0.003355	1	0.001859
0.070641	-0.23076	0.031505	0.001859	1
0.457627	0.501751	0.153659	-1.98815	
0.440678	0.499772	0.222648	-1.96032	
0.542373	0.50318	-0.18633	-1.98831	
0.983051	0.758561	-0.01059	-1.26348	
0.525424	0.504017	-0.11823	-2.00649	
Default Truncations:				
0.001	0.999			
5 Distributions:				
Discrete				
WallMaterial				
0 means 200mm clay brick and rendering, 1 means 200mm lightweight concrete and rendering				
1	2			
0	1	0.5		
1	2	0.5		

Discrete				
ShadingofWindows				
0 means shading, 1 means no shading				
1	2			
0	1	0.5		
1	2	0.5		
Discrete				
Balcony				
0 means balcony, 1 means no balcony				
1	2			
0	1	0.5		
1	2	0.5		
Discrete				
WindowOpenableArea				
0 means 25%, 1 means 50%, 2 means 75%				
1	3			
0	1	0.333		
1	2	0.333		
2	3	0.334		
Discrete				
RoofMaterial				
0 means slate tiles, 1 means slate tiles with 50mm insulation				
1	2			
0	1	0.5		
1	2	0.5		
Correlation information				
0 -1 0				
0 -1 0				
0 -1 0				
0 -1 0				
0 -1 0				
Correlation Matrix:				
1	0	0	0	0
0	1	0	0	0
0	0	1	0	0
0	0	0	1	0
0	0	0	0	1
Stein Information:				
0				
0				
0				

2				
4				
Morris				
4				
10				
60				
5				
1				

Appendix 6: Basic Script for Response Surface Analysis

#Make sure the working directory is set correctly

#Choose the .csv file where the permutations are located.

trials = read.csv(**'PERMUTATIONS.csv'**,header = TRUE)

 # Select the results file which includes the results from the various simulations run according to the relative permutations

results = read.csv(**'RESULTS.csv'**,header = TRUE)

#define discrete variables in the form of factors the '$' is informing R to access variables within a data set i.e. within each column of data for the various factors.

WM = as.factor(trials$WallMaterial)

SW = as.factor(trials$ShadingofWindows)

BA = as.factor(trials$Balcony)

WA = as.factor(trials$WindowOpenableArea)

RM = as.factor(trials$RoofMaterial)

#The '$' is informing R to access variables within the results column of data

c2 = results$**CRITERIA**

#need to output linear model for identifying effects of parameters

LR60.model = lm(c2 ~ WM + SW + BA + WA + RM)

#to get the interaction between factors use the term: LR60.model = lm(c2 ~ (WM + SW + BA + WA + RM)^2)

summary(LR60.model)

#Output graphical representation of the permutations

APPENDIX 7: RESULTS FROM SA

Living Room

Criteria 1

Main Effects Only

```
Call:
lm(formula = c1 ~ WM + SW + BA + WA + RM)

Residuals:
    Min      1Q  Median      3Q     Max 
-3.0653 -1.1002 -0.4063  0.6728  6.0077 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) 17.40924    0.57083  30.498  < 2e-16 ***
WM1          0.04962    0.43005   0.115  0.90858    
SW1          0.38621    0.44473   0.868  0.38908    
BA1          5.27343    0.42947  12.279  < 2e-16 ***
WA1         -1.74035    0.50761  -3.429  0.00118 ** 
WA2         -2.73383    0.55739  -4.905 9.28e-06 ***
RM1         -3.63140    0.43029  -8.439 2.24e-11 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 1.614 on 53 degrees of freedom
Multiple R-squared:  0.827,	Adjusted R-squared:  0.8074 
F-statistic: 42.23 on 6 and 53 DF,  p-value: < 2.2e-16
```

Main Effects + Two Parameter Interactions

```
Call:
lm(formula = c1 ~ (WM + SW + BA + WA + RM)^2)

Residuals:
    Min      1Q  Median      3Q     Max 
-1.3915 -0.3309 -0.0162  0.3678  3.2332 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  15.4143     0.5527  27.889  < 2e-16 ***
WM1          -0.4046     0.5841  -0.693 0.492581    
SW1           1.1525     0.5798   1.988 0.053899 .  
BA1           6.4846     0.6163  10.522 5.94e-13 ***
WA1           0.7916     0.6544   1.210 0.233709    
WA2          -0.1114     0.7274  -0.153 0.879109    
RM1          -0.6987     0.5554  -1.258 0.215887    
WM1:SW1       0.7930     0.4939   1.606 0.116435    
WM1:BA1       1.3784     0.4690   2.939 0.005510 ** 
WM1:WA1       0.2458     0.5560   0.442 0.660861    
WM1:WA2      -0.4040     0.6250  -0.646 0.521781    
WM1:RM1      -1.5588     0.4849  -3.215 0.002622 ** 
SW1:BA1       2.4545     0.5395   4.550 5.13e-05 ***
SW1:WA1      -2.0814     0.6299  -3.304 0.002049 ** 
SW1:WA2      -1.4126     0.6741  -2.095 0.042672 *  
SW1:RM1      -1.9957     0.4981  -4.007 0.000268 ***
BA1:WA1      -2.0760     0.5873  -3.535 0.001069 ** 
```

```
BA1:WA2      -4.9006     0.6196  -7.910 1.25e-09 ***
BA1:RM1      -0.7661     0.5268  -1.454 0.153885
WA1:RM1      -2.1724     0.6025  -3.605 0.000873 ***
WA2:RM1       0.2348     0.6158   0.381 0.705093
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.8405 on 39 degrees of freedom
Multiple R-squared:  0.9655,   Adjusted R-squared:  0.9478
F-statistic: 54.53 on 20 and 39 DF,  p-value: < 2.2e-16
```

Criteria 2

Main Effects Only

```
Call:
lm(formula = c2 ~ WM + SW + BA + WA + RM)

Residuals:
    Min      1Q  Median      3Q     Max
-24.639  -6.289  -2.049   4.714  40.317

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  125.435      3.827  32.775  < 2e-16 ***
WM1           -1.471      2.883  -0.510 0.611975
SW1            2.806      2.982   0.941 0.350988
BA1           25.011      2.879   8.686 9.11e-12 ***
WA1           -9.097      3.403  -2.673 0.009970 **
WA2          -14.807      3.737  -3.962 0.000223 ***
RM1          -26.878      2.885  -9.317 9.41e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 10.82 on 53 degrees of freedom
Multiple R-squared:  0.7811,   Adjusted R-squared:  0.7563
F-statistic: 31.52 on 6 and 53 DF,  p-value: 8.026e-16
```

Main Effects + Two Parameter Interactions

```
Call:
lm(formula = c2 ~ (WM + SW + BA + WA + RM)^2)

Residuals:
     Min       1Q   Median       3Q      Max
-10.2915  -2.8038  -0.0418   2.6528  20.8974

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  113.037      3.749  30.150  < 2e-16 ***
WM1           -3.941      3.962  -0.995  0.32608
SW1            7.178      3.933   1.825  0.07567 .
BA1           31.650      4.181   7.571 3.58e-09 ***
WA1            7.061      4.439   1.591  0.11975
WA2            0.149      4.934   0.030  0.97607
RM1           -7.409      3.768  -1.966  0.05639 .
WM1:SW1        5.185      3.350   1.547  0.12982
WM1:BA1        9.764      3.182   3.069  0.00390 **
WM1:WA1        1.075      3.772   0.285  0.77705
```

```
WM1:WA2       -1.717      4.239  -0.405  0.68768
WM1:RM1      -11.450      3.289  -3.481  0.00125 **
SW1:BA1       17.250      3.660   4.713 3.08e-05 ***
SW1:WA1      -14.929      4.273  -3.494  0.00120 **
SW1:WA2      -10.058      4.573  -2.199  0.03384 *
SW1:RM1      -11.960      3.379  -3.540  0.00105 **
BA1:WA1      -11.228      3.984  -2.818  0.00754 **
BA1:WA2      -30.205      4.203  -7.187 1.19e-08 ***
BA1:RM1       -6.574      3.574  -1.840  0.07346 .
WA1:RM1      -14.371      4.087  -3.516  0.00113 **
WA2:RM1        3.440      4.177   0.824  0.41521
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 5.702 on 39 degrees of freedom
Multiple R-squared:  0.9553,   Adjusted R-squared:  0.9323
F-statistic: 41.65 on 20 and 39 DF,  p-value: < 2.2e-16
```

<u>Criteria 3</u>

Main Effects Only

```
Call:
lm(formula = c3 ~ WM + SW + BA + WA + RM)

Residuals:
    Min      1Q  Median      3Q     Max
-6.3761 -0.5835  0.4593  0.8028  3.2159

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  13.5724     0.5108  26.569  < 2e-16 ***
WM1          -1.9851     0.3849  -5.158  3.8e-06 ***
SW1           0.1180     0.3980   0.297    0.768
BA1          -5.9064     0.3843 -15.368  < 2e-16 ***
WA1           0.4970     0.4543   1.094    0.279
WA2           0.7100     0.4988   1.423    0.160
RM1          -5.0998     0.3851 -13.244  < 2e-16 ***
---
Signif. codes:
0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.444 on 53 degrees of freedom
Multiple R-squared:  0.8995,   Adjusted R-squared:  0.8881
F-statistic: 79.02 on 6 and 53 DF,  p-value: < 2.2e-16
```

Main Effects + Two Parameter Interactions

```
Call:
lm(formula = c3 ~ (WM + SW + BA + WA + RM)^2)

Residuals:
    Min      1Q  Median      3Q     Max
-4.1041 -0.4998 -0.0182  0.6412  2.8797

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 14.61461    0.77362  18.891  < 2e-16 ***
WM1         -3.72158    0.81760  -4.552 5.09e-05 ***
```

```
SW1          -0.02100    0.81155  -0.026  0.97949
BA1          -6.44400    0.86265  -7.470 4.89e-09 ***
WA1           0.86408    0.91596   0.943  0.35130
WA2          -1.36369    1.01812  -1.339  0.18819
RM1          -6.49727    0.77742  -8.358 3.18e-10 ***
WM1:SW1      -1.08966    0.69135  -1.576  0.12307
WM1:BA1       0.61722    0.65652   0.940  0.35294
WM1:WA1       0.64914    0.77823   0.834  0.40929
WM1:WA2       1.63698    0.87479   1.871  0.06882 .
WM1:RM1       2.32591    0.67869   3.427  0.00145 **
SW1:BA1       1.48155    0.75515   1.962  0.05693 .
SW1:WA1      -1.15511    0.88173  -1.310  0.19784
SW1:WA2       1.89482    0.94362   2.008  0.05160 .
SW1:RM1      -0.01974    0.69716  -0.028  0.97756
BA1:WA1      -0.32196    0.82202  -0.392  0.69743
BA1:WA2      -0.70284    0.86724  -0.810  0.42261
BA1:RM1      -0.11039    0.73740  -0.150  0.88177
WA1:RM1       0.01040    0.84335   0.012  0.99023
WA2:RM1       1.62393    0.86197   1.884  0.06704 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.176 on 39 degrees of freedom
Multiple R-squared:  0.9509,   Adjusted R-squared:  0.9257
F-statistic: 37.78 on 20 and 39 DF,  p-value: < 2.2e-16
```

Bedroom

Criteria 1

Main Effects Only

```
Call:
lm(formula = c1 ~ WM + SW + BA + WA + RM)

Residuals:
     Min       1Q   Median       3Q      Max
-2.50510 -0.26654  0.00571  0.19613  1.82671

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  10.7999     0.2020  53.472  < 2e-16 ***
WM1           0.2117     0.1522   1.392  0.16987
SW1           0.2788     0.1574   1.772  0.08220 .
BA1           1.4288     0.1520   9.403 6.93e-13 ***
WA1          -0.6190     0.1796  -3.446  0.00112 **
WA2          -1.3903     0.1972  -7.049 3.76e-09 ***
RM1          -3.2886     0.1522 -21.601  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.5711 on 53 degrees of freedom
Multiple R-squared:  0.9247,   Adjusted R-squared:  0.9162
F-statistic: 108.5 on 6 and 53 DF,  p-value: < 2.2e-16
```

Main Effects + Two Parameter Interactions

```
Call:
lm(formula = c1 ~ (WM + SW + BA + WA + RM)^2)

Residuals:
     Min       1Q   Median       3Q      Max 
-0.90707 -0.17392  0.03995  0.14014  0.78487 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) 10.66418    0.22456  47.489  < 2e-16 ***
WM1          0.02834    0.23733   0.119 0.905557    
SW1          0.30883    0.23557   1.311 0.197531    
BA1          0.93050    0.25041   3.716 0.000634 ***
WA1         -0.00193    0.26588  -0.007 0.994245    
WA2         -1.34558    0.29553  -4.553 5.07e-05 ***
RM1         -2.58183    0.22566 -11.441 4.95e-14 ***
WM1:SW1      0.31632    0.20068   1.576 0.123056    
WM1:BA1      0.65727    0.19057   3.449 0.001365 ** 
WM1:WA1      0.11967    0.22590   0.530 0.599303    
WM1:WA2      0.07940    0.25393   0.313 0.756185    
WM1:RM1     -0.83684    0.19701  -4.248 0.000130 ***
SW1:BA1      1.06150    0.21920   4.843 2.06e-05 ***
SW1:WA1     -0.69655    0.25594  -2.721 0.009662 ** 
SW1:WA2     -0.07039    0.27391  -0.257 0.798555    
SW1:RM1     -0.83981    0.20237  -4.150 0.000174 ***
BA1:WA1     -0.24605    0.23861  -1.031 0.308816    
BA1:WA2     -1.00869    0.25174  -4.007 0.000268 ***
BA1:RM1      0.48434    0.21405   2.263 0.029296 *  
WA1:RM1     -0.87415    0.24480  -3.571 0.000964 ***
WA2:RM1      0.54666    0.25021   2.185 0.034977 *  
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1 

Residual standard error: 0.3415 on 39 degrees of freedom
Multiple R-squared:  0.9802,   Adjusted R-squared:   0.97 
F-statistic: 96.47 on 20 and 39 DF,  p-value: < 2.2e-16
```

<u>Criteria 2</u>

Main Effects Only

```
Call:
lm(formula = c2 ~ WM + SW + BA + WA + RM)

Residuals:
     Min       1Q   Median       3Q      Max 
-20.4900  -2.0739  -0.2883   2.4641  14.8806 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)   82.533      1.663  49.623  < 2e-16 ***
WM1            3.435      1.253   2.741  0.00833 ** 
SW1            2.381      1.296   1.837  0.07176 .  
BA1           12.210      1.251   9.757 1.97e-13 ***
WA1           -4.439      1.479  -3.001  0.00410 ** 
WA2          -10.252      1.624  -6.313 5.73e-08 ***
RM1          -26.641      1.254 -21.250  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Residual standard error: 4.703 on 53 degrees of freedom
Multiple R-squared:  0.9224,   Adjusted R-squared:  0.9136
F-statistic: 104.9 on 6 and 53 DF,  p-value: < 2.2e-16
```

Main Effects + Two Parameter Interactions

```
Call:
lm(formula = c2 ~ (WM + SW + BA + WA + RM)^2)

Residuals:
    Min      1Q  Median      3Q     Max 
-8.3977 -1.4016 -0.3125  1.4963  7.5164 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept)  81.5513     1.9663  41.475  < 2e-16 ***
WM1           1.7484     2.0781   0.841 0.405265    
SW1           3.4240     2.0627   1.660 0.104939    
BA1           6.4077     2.1926   2.922 0.005752 ** 
WA1           1.8296     2.3280   0.786 0.436678    
WA2          -7.6618     2.5877  -2.961 0.005199 ** 
RM1         -21.8019     1.9759 -11.034 1.47e-13 ***
WM1:SW1       1.6472     1.7572   0.937 0.354315    
WM1:BA1       8.4634     1.6687   5.072 9.98e-06 ***
WM1:WA1      -0.4312     1.9780  -0.218 0.828586    
WM1:WA2      -0.2326     2.2234  -0.105 0.917235    
WM1:RM1      -7.2636     1.7250  -4.211 0.000145 ***
SW1:BA1       7.7218     1.9193   4.023 0.000255 ***
SW1:WA1      -6.4440     2.2410  -2.875 0.006505 ** 
SW1:WA2      -1.4293     2.3984  -0.596 0.554648    
SW1:RM1      -5.5571     1.7720  -3.136 0.003250 ** 
BA1:WA1      -2.4347     2.0893  -1.165 0.250969    
BA1:WA2      -7.8994     2.2042  -3.584 0.000929 ***
BA1:RM1       5.5692     1.8742   2.971 0.005055 ** 
WA1:RM1      -6.7473     2.1435  -3.148 0.003149 ** 
WA2:RM1       2.1241     2.1908   0.970 0.338242    
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

Residual standard error: 2.99 on 39 degrees of freedom
Multiple R-squared:  0.9769,   Adjusted R-squared:  0.9651 
F-statistic: 82.47 on 20 and 39 DF,  p-value: < 2.2e-16
```