Adapting Passive Cooling Techniques from Mughal Architecture to Low Income Tropical Housing

by

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Signed: Dated: 27/05/2015

TECHNICAL ABSTRACT

Mughal Architecture of the sub-continent incorporated many passive cooling strategies to help mitigate the heat and provide thermal comfort to occupants of buildings. This study investigates the efficacy of those techniques when scaled down to a low income, tropical and urban context. Karachi, an example of a tropical mega-city, was chosen as the design location.

Several passive cooling techniques were identified, but the scope was narrowed to four elements: courtyards, ventilation, albedo and shading devices; as these were considered particularly relevant to a low income context.

IES-VE, a building simulation software, was chosen to carry out the investigation. Data from published case studies was used to set up a base case model. In each investigation, the base case model was modified to incorporate the passive cooling elements. Where relevant, the models were then optimised to achieve their full cooling potential. The TM52 Maximum Adaptive Comfort Standard was used as the main performance indicator to judge improvements in comfort from the application of the cooling techniques. For the summer months in Karachi, the TM52 was more or less constant at 32°C, and the base case model predicted temperatures within this limit for 73% of the time.

The investigation of the courtyard was carried out in two stages. In the first stage, the temperature of the courtyard microclimate was manually controlled to determine the level of cooling required to achieve comfort in the surrounding rooms. It was found that for 100% comfort during the summer, the courtyard needed to be 10°C cooler than the ambient temperature; which is considered highly unlikely. However, it was also found that comfort could be achieved for 95% of the time, if the courtyard was just 2°C below ambient.

Appropriate solar orientation was identified as one of the main factors that affect the microclimatic performance of the courtyard. The second stage of the investigation focused on determining the optimum courtyard orientation and aspect ratio. Since IES is not explicitly capable of modelling the courtyard microclimate, thermal simulations were not carried out for this part of the investigation. Two proxy variables: the shading of the courtyard floor and the shading of the courtyard facing walls, were used instead to decide the best orientation. The investigation was carried out on the 21^{st} day of April, May and June, representing a low, medium and high sun angle respectively. It was found that a south facing courtyard performs marginally better that a north facing one. The results for aspect ratio were less conclusive. In some cases a deep and narrow orientation was favourable, whereas in others a wide and shallow courtyard seemed appropriate. On the whole, the deep and narrow orientation was better for more counts, and is recommended for Karachi.

Since Karachi is on the coast and experiences a regular breeze, the ventilation strategy adopted was focused on wind driven cross ventilation. The base case model was modified to include external openings aligned with the openings into the courtyard. It is presumed that maximum ventilation occurs when these openings are normal to the wind direction. Since both wind speed and direction are variable throughout the year, a statistical analysis and corresponding comfort analysis was carried out to determine an appropriate design orientation. The 230° and 260° orientations (East of North) were found to be the best. At these orientations, comfortable conditions were achieved for 85% of the time; but this analysis did not account for the obstruction of wind that is likely in an urban context. The wind pressure coefficients were modified to reflect the lower wind exposure; and it was found that ventilation had very little impact in improving the indoor temperatures, as heat loss from ventilation was offset by additional solar gain from the openings.

The performance of the openings was improved by incorporating shading devices known as *jaali* (porous lattice screens), which served the dual purpose of reducing solar gains and providing privacy. The screens wer modelled by replacing the large opening with multiple smaller ones. The jaali interfered somewhat with the airflow, and the minimum acceptable porosity was found to be about 0.3. However, each individual square within the *jaali* required minimum dimensions of 8cm, to ensure adequate airflow. For the 230° orientation, an appropriately sized *jaali* resulted in comfortable conditions for 84% of the time.

The final element analysed was the albedo of the building. It was found that changing the albedo of the walls had little effect, but incorporating a white painted roof resulted in comfort for 79% of the time, an improvement of 6% on the base case.

This investigation quantified the improvements in comfort that could be achieved from each of the passive cooling elements investigated. It is clear that no single element can achieve complete comfort during the summer; however, they do significantly mitigate the duration of the uncomfortable period. The results are somewhat limited by the approximate nature of the model and the exclusion of thermal mass from the scope (which is an important factor when optimising for ventilation and solar shading). Future work could involve field studies to verify the model and further modelling which includes the effect of material properties. The courtyard microclimate can also be investigated in more detail using specifically designed software such as ENVI-MET.

CONTENTS

1

INTRODUCTION

In 1950, only 30% of the world's population lived in cities; today, this figure has risen to 54% [1]. Rapid urbanisation, particularly in the developing world, has led to the emergence of the *Megacity*, an urban area with over 10 million inhabitants. Currently there are 28 megacities in the world, 12 of which are located in the tropics. Examples include Mumbai and Calcutta in India, Mexico City in Mexico and Karachi in Pakistan. Rising development and income levels will inevitably lead to a surge in energy intensive active cooling systems to counteract the heat and humidity. From an environmental point of view, the effects of this are potentially disastrous. An alternate approach requires shifting from active cooling to passive cooling strategies, many of which are already ingrained in the vernacular of warm regions. A particularly interesting example is the Mughal Architecture of the sub-continent, which employs a number of cooling strategies to combat the extreme climate. There is a need to understand and adapt these strategies to the new context of a tropical megacity.

1.1 Passive Cooling Strategies in Mughal Architecture

The Mughal emperors were invaders from Central Asia who ruled over India from the 16th century, through to the mid 19th century. The architectural style employed was a fusion of indigenous Indian architecture, and the Islamic architecture of Iran and Central Asia. The buildings were characterised by a grand scale, bilateral symmetry, domed and vaulted ceilings and intricate carvings and decorations [2].

Many of the design elements, however, were not merely aesthetic in nature. Babur, the first Mughal emperor, disliked the climate of India and described it in his memoirs as 'oppresively hot and humid' and 'lacking the gardens and clear air of his homeland, Fergana' [3]. Thus Mughal architecture employs many passive cooling strategies to combat the extremes of the weather and give thermal comfort to the occupants of the buildings.

Gupta, in his paper 'Indigenous Architecture and Natural Cooling' identified flexible building envelopes, microclimatic control through vegetation and shading, ventilation, thermal mass and night radiation cooling as some of the key techniques of traditional buildings that can be translated to modern applications [4]. The same principles of microclimatic control, integrated indoor and outdoor living, thermal mass, courtyards, shading, *jaali* and evaporative cooling through water bodies are highlighted by Ali in his paper 'Passive Cooling and Vernacularism in Mughal Buildings in North India: A Source of Inspiration for Sustainable Development' [5]. The underlying principles of these techniques are summarised below.

- The courtyard or *sahan* is an important feature of Mughal architecture, and is in fact common in the vernacular of most warm regions. The passive design of the courtyard is based on the idea of creating a microclimate within the house which is a cooler than the ambient temperature. This in turn can be effective in cooling the surrounding rooms.
- Water channels and fountains were often used in Mughal architecture. They provide a cooling effect by removing heat through evaporation. The fountains in the Shalimar Gardens in Lahore and the *Nahr-i-Behisht* (Stream of Paradise) running through the Red Fort in Delhi are notable examples [5].
- Deep Verandahs were used to provide shade to the external walls of the structures and also acted as a buffer against the environment.
- The Mughals used a complex system of vents and openings, optimised for maximum natural ventilation. Often the air was pre treated and cooled before it entered the building [4].
- *Jaali* or carved stonework screens were placed across openings and holes in the building envelope. They provides both privacy as well as diffused daylight, while reducing the solar gains from direct radiation [5].
- Thick walls with high thermal resistivity were often employed. In areas with a large diurnal range, high thermal mass materials were used to reduce the internal daytime temperatures. High albedo (solar reflectivity) materials were also used to prevent heat gain from solar absorption. This is most famously seen in the Taj Mahal in Agra, which is constructed entirely from white marble.
- Large and luscious gardens surrounded most of the Mughal building in the sub-continent. The plants promote cooling through evapo-transpiration and also act as micro-climate modifiers [4].

1.2 Scope and research aims

Karachi, a tropical megacity of over 15 million people is chosen as the case study location. Not all of the passive cooling techniques discussed in section 1.1 can be incorporated into a low income setting. Deep verendahs and large gardens are ruled out due to the space constraints of a low income house. Although materials with higher thermal resistivity and mass can significantly improve indoor climatic conditions; the materials used are unlikely to change drastically due to both cost and availability factors (discussed in section 2.2). Hence the effects of insulation and thermal mass are not included in the scope of this investigation. Karachi already faces a chronic water shortage, and the use of water channels and fountains is considered unfeasible in most districts. Hence, the scope of this project is limited to four of the above listed strategies, which are considered most applicable to a low income setting. These are as follows

- Courtyards
- A well designed ventilation strategy
- The use of low albedo materials
- Shading devices such as *jaali*

Although these passive cooling strategies have been studied extensively, their particular application to the low income setting of Karachi, Pakistan has not been explored. The main aims of this investigation are as follows:

- To *model* a 'typical' low income house in Karachi, Pakistan.
- To *quantify* the improvements (if any) in thermal conditions that can be achieved by application of the above listed passive cooling strategies.
- To *optimise* (where relevant) the passive cooling strategies under investigation for maximum possible improvements to the indoor thermal conditions.
- To *assess* whether comfort can be achieved for the occupants purely by employing the passive cooling strategies under investigation.

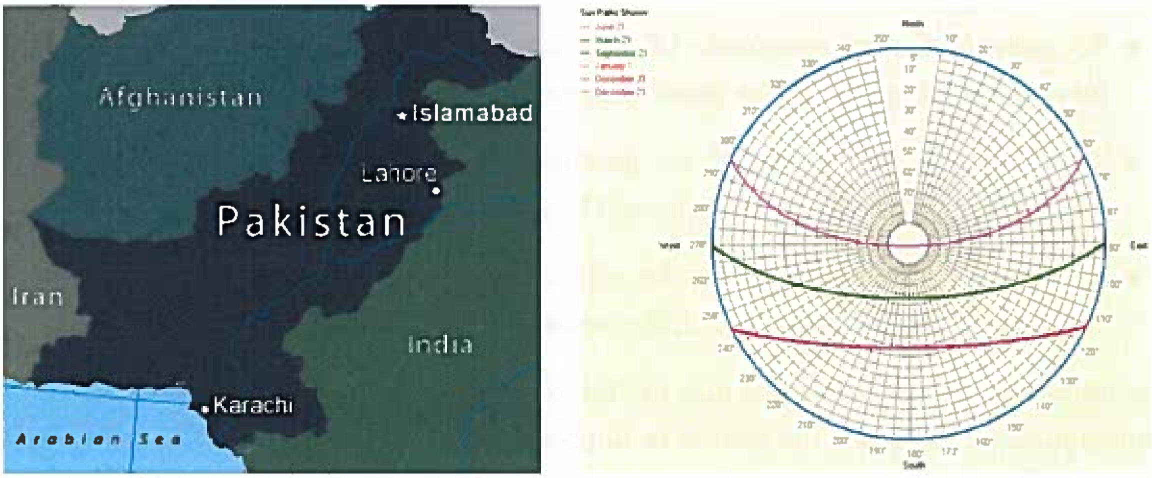
It is important to note that the aim of this research is *not* to radically redesign urban, tropical housing. Instead, the goal is to improve comfort within the existing constraints. On the whole, this research attempts to answer the question:
Do the passive cooling strategies employed in the Mughal architecture of the subcontinent have any significant impact when scaled down to a low income context?

2

THE CONTEXT OF KARACHI

2.1 Weather and climate

Karachi is located at the southern tip of Pakistan, adjacent to the Arabian Sea (at 24.9° N and 67.0° E), as shown in figure 2.1a. Although it is just north of the Tropic of Cancer, the climate is considered tropical. There is however, a reasonable change in the sun angle through the year, as shown in figure 2.1b. The sun altitude peaks at 85° on 21^{st} June, while the lowest point is 45° on 21^{st} December. The 21^{st} of March and September (also plotted) have the same sunpath since the sun angle is symmetric about the 21^{st} of June. These differences must be considered while designing passively cooled housing in Karachi

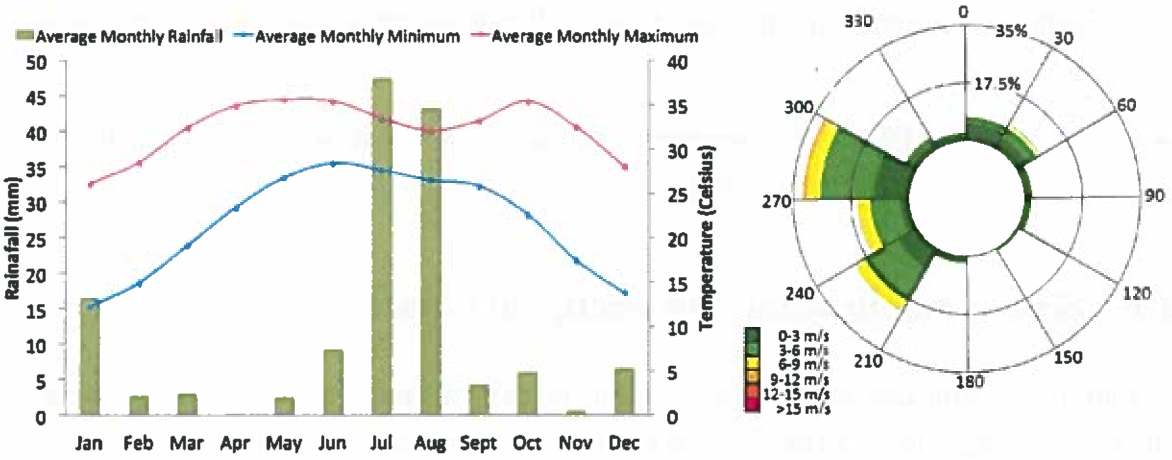


(a) Location of Karachi (b) Sunpath diagram for Karachi

Figure 2.1: Location data

As shown in figure 2.2a, April, May and June are the warmest months of the year with very little rainfall. During July and August, the summer monsoon hits Karachi, resulting in a drop in temperatures.

As Karachi is on the coast, it experiences a constant sea-land breeze during the year. Wind speed varies from about 4 m/s to 7 m/s, with an average of 7 m/s during the summer (from IES weather file). The predominant wind directions are west and south-west, as shown in figure 2.2b. The passive design of building in Karachi can be improved by incorporating these winds.



(a) Average monthly temperatures and rainfall

(b) Wind rose for typical year

Figure 2.2: Weather data for Karachi (from EnergyPlus weather file)

2.2 Existing low income housing

In the wake of rapid urbanisation, Pakistan currently faces a severe shortage of housing for the urban poor. In Karachi, the major port and economic hub, with an estimated population of about 16 million people [6], this problem is particularly exacerbated. Karachi requires 80,000 housing units per year. However, only an average of around 27,000 building permits are issued per year [7]. Although there are no official figures, an estimated 50% of Karachi's population ends up living in slums or squatter settlements, known as *'katchi abadis'* [7].

To investigate the effectiveness of passive cooling strategies, it is important to first understand the context and dynamics of existing low income housing. The next chapter deals with a detailed discussion of the experimental method, model inputs and simulation software. The aim of this section is to present a description of 'typical' low income housing in Karachi, based upon which a model can be developed.

A case study of three low income settlements in Karachi was conducted in 2010 by the International Institute for Environment and Development (IIED) [8]. The results of the case study are presented (along with other sources) to develop an understanding of size, occupancy profile, configuration and construction methods; as well as provide a socio-economic context of 'low income' in Karachi. Three settlments were surveyed. In each case, average household income was about \$100/month.

- Khuda Ki Basti (KKB) - A large, recently developed suburban settlement, planned and managed by the NGO *Saiban*. Average household size was about 6.7.
- Nawalane (NL) - One of Karachi's oldest and most densely populated settlements.

Households consisted of extended families living together, with an average size of 13.56.

- Paposh Nagar (PN) - A government allocated plot scheme dating back to 1954. Average household size was about 6.7.

2.2.1 Size, configuration and occupancy patterns

Each building is typically an independent unit, housing a single family. A larger extended family may live together in a two or three story building. The average number of occupants during the day is usually less than 5, while during the evening and night it is around 10 [9].

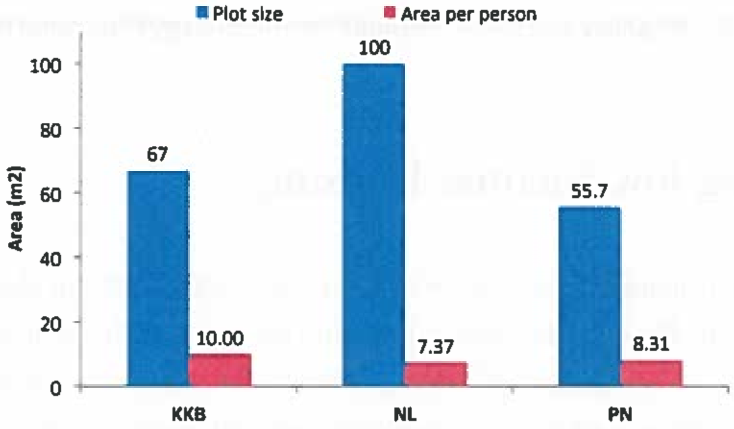


Figure 2.3: Average plot sizes and occupant density for three low income settlements in Karachi

Average sizes of the homes surveyed, along with occupant densities are shown in figure 2.3. Plan lengths of the buildings varied between 10 and 50 meters, and widths between 5 and 30 meters. Single storey construction was commonly found in suburban settlements, whereas 2 to 3 storey buildings were common in urban areas. The typical floor-to-celing height in such buildings is 2.5 meters [9].

Buildings are usually regular squares or rectangles in plan according to the plot size. A main entrance door opens into an interior courtyard or *sahan*, from which one can access rooms or a staircase leading to any upper floors. Additional features like a wash basin, a water pump, and an underground tank may be located within this courtyard [9]. The boundary of the plot is usually the external walls, with no space left around the house.

2.2.2 Materials and construction

Block masonry construction is found in around 3.3% of all construction in Pakistan [10]. Sand, gravel, aggregate, and cement; the necessary ingredients for casting concrete blocks, are readily available in Karachi. The blocks are mass produced and exported to settlements across the area. They have come to define the typical construction of Karachi [9].

Cement is used as a binding agent, which gives the blocks strength and durability (at the cost of adding substantial weight to the structure). They maybe used as infill within an RCC frame; or, as common in low income housing, the block masonry walls are used directly as load bearing elements. Although cement blocks are a low cost and durable option, one of the major downsides is their low insulation capacity. An additional layer of insulation on the walls is quite expensive, and is rarely applied during construction [9].

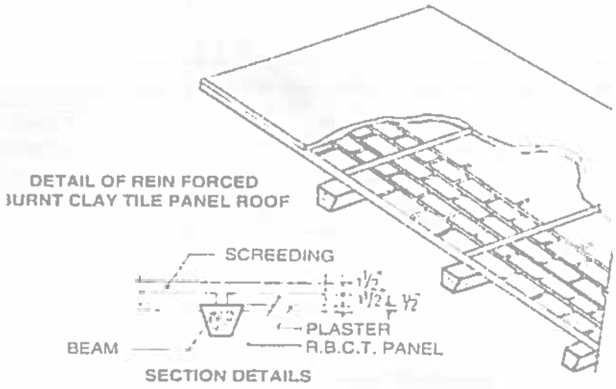


Figure 2.4: Burnt clay tile panel roof schematic [11]

Clay tiles, CGI (corrugated galvanised iron) sheets or concrete slabs are usually used as the roof materials. Single story block masonry houses generally have a lighter roof made of steel girders with tiles or CGI sheets, while RC (reinforced concrete) slabs are used for two or three story buildings [9]. Although construction is rarely standardised, the Pakistan Council for Works and Housing Research (CWHR) has suggested a lightweight roof construction method (figure 2.4), which is adopted for this investigation.

2.2.3 Problems and challenges

In each of the settlements surveyed, the case study report [8] cited small rooms, poor ventilation, over-crowding and over heating the major problems of current low income housing. Poor design due to haphazard and incremental construction was identified as the major cause of these problems. The report concluded with: "Orientations, height of buildings and the relationship of the buildings to each other are important factors in efforts to provide a climatically comfortable environment in the heat and humidity of a Karachi summer." These factors are intrinsically linked to the optimisation of the passive cooling strategies under investigation, and will be considered throughout the investigation.

2.3 Comfort Criteria

This investigation includes an assessment of whether a 'comfortable' temperature can be achieved purely by employing passive cooling strategies. The international ASHRAE Standard 55-2013 (Thermal Environmental Conditions for Human Occupancy) recommends that temperatures in homes be maintained between 19°C and 28°C. In free running buildings, temperatures in excess of this are regularly experienced, without significant discomfort [12].

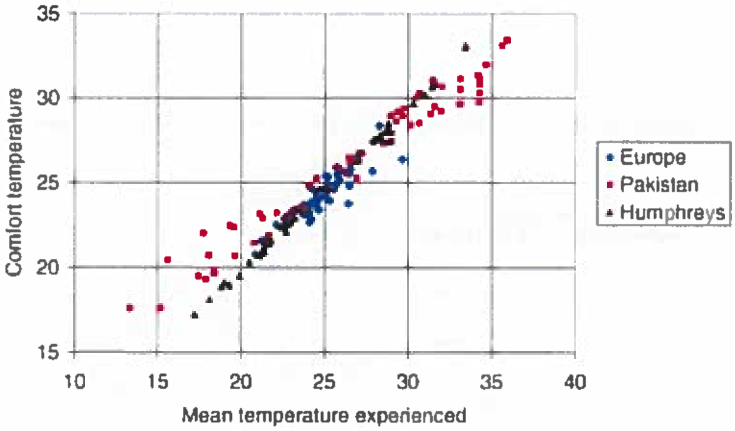


Figure 2.5: Relationship between comfort temperature and mean temperature experienced [13]

Most international standards are based on Fanger's Predicted Mean Vote (PMV) formula which assigns a numeric response to the thermal environment on a seven point ASHRAE scale, with 0 being neutral, 3 being too hot and -3 being too cold. However, the conventional PMV formula gives questionable results when applied to free running buildings, particularly in the tropics [12]. Fanger's model is based on a steady-state heat balance approach, which does not account for the improvements people will make to their environments such as changing clothing and opening windows, hence it tends to predict higher levels of discomfort than are actually observed in subjects during field studies [12]. Studies ([13] and [12]) have also shown that the comfort temperature is closely linked to the mean temperature experienced, as people adapt to conditions they are regularly exposed to. Humphrey's results (figure 2.5) give a linear relationship between the temperature experienced and the comfort temperature.

Other factors like clothing, humidity and the opening of windows also affect the discomfort experienced at a given temperature. Regression analysis based on a detailed field study conducted in Pakistan in 1999 [14] was used to calculate a comfort temperature as a function of mean outdoor temperatures experienced by subjects. This is plotted (purple line) along with the daily mean temperatures (blue line) and the comfort temperature

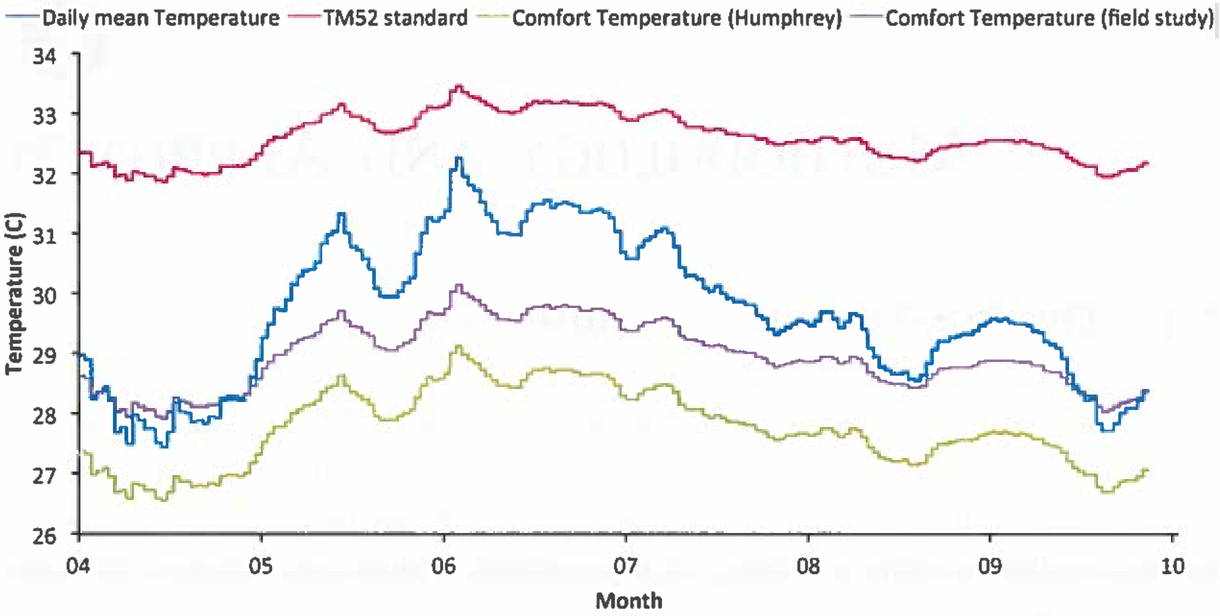


Figure 2.6: Comfort temperatures and max adaptive temperature for free running homes in Pakistan

from Humphrey's model (green line) in figure 2.6. Although the field study results give a comfort temperature about 1°C higher than that predicted by Humphrey, both models predict comfort at temperatures above the 28°C recommended by ASHRAE standards, in the months of June and July.

The CIBSE TM52 Adaptive Comfort Standard (which accounts for differences in clothing, air speed and physical activity) has been adopted as an international standard for free running buildings. The maximum adaptive temperature, based on a clothing insulation of 0.3 clo (typical for the *Shalwar Kameez* worn by most Paksiatnis [14]) was calculated in IES and is also shown (red line) on figure 2.6. This is more or less constant at 32°C for the summer months and is within 2°C of the comfort temperature from the field studies. Hence, the TM52 is applicable to this situation and is used as the upper limit of comfort through this investigation.

3

METHODOLOGY AND APPROACH

3.1 The IES-VE software suite

The *Virtual Environment* Software by *Integrated Environmental Solutions* (IES-VE) is chosen to carry out this investigation. IES-VE is a dynamic building simulation software, consisting of a suite of integrated analysis tools; which can be combined to simulate thermal conditions within a building. It is considered a 'black box' software. The user inputs the specific building conditions through a graphical user interface, based on which the software produces a set of results about the conditions within the building. IES is chosen because of its availability on the Department Teaching System. Below is a brief summary of the IES modules used in this study, and the building physics principles they rely on.

3.1.1 Apache Sim

ApacheSim is a dynamic thermal simulation program based on first principles mathematical modelling of the heat transfer processes occurring within and around a building [15]. The building geometry and material properties are entered by the user in the ModelIT module. Based on the inputs, the software calculates the heat gains (or losses). The conditions within a room or 'thermal zone' are considered uniform, in keeping with the 'stirred tank' model. For a single instant in time, this process is summarised in figure 3.1. This process is repeated over the course of the whole year, with real weather data for a *Typical Meterological Year*, at a user specified time step. The TMY data for Karachi was downloaded from the *EnergyPlus* website.

3.1.2 SunCast

SunCast module is used to perform shading and solar insolation analysis on a building. The sunpath diagram for the site location (based on co-ordinates entered by the user) is used to calculate the shading at each point in the day. This is essential at the planning stage to decide the most appropriate orientation for the building, as well as for psoitining openings. When used in conjunction with ApacheSim, it provides information about the solar heat gains within the building.

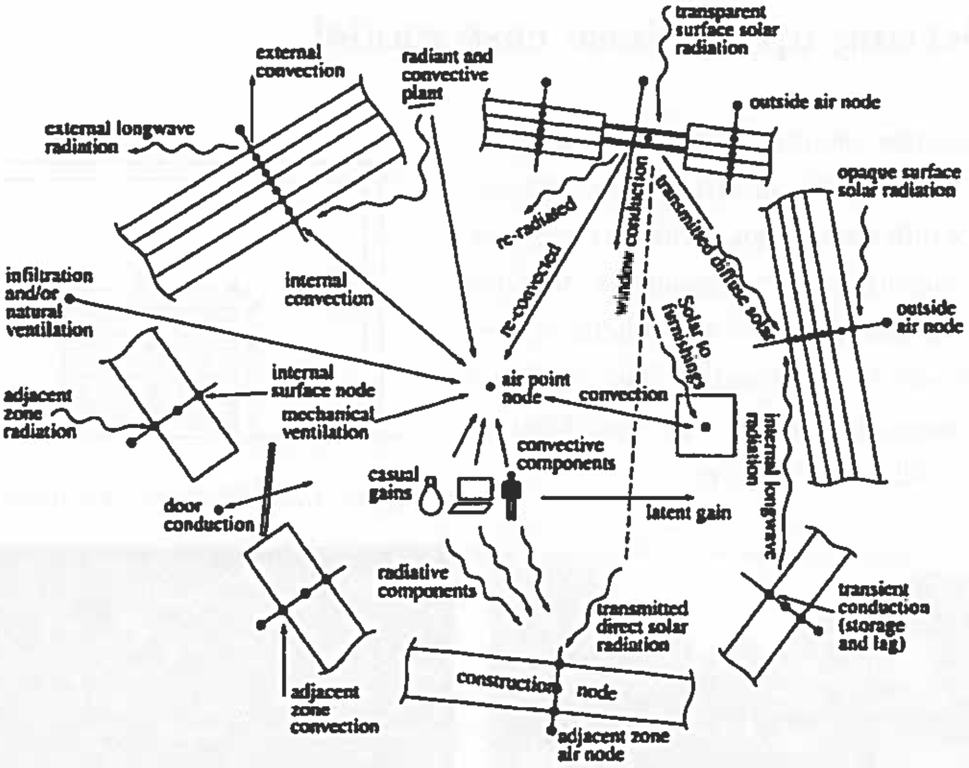


Figure 3.1: Energy flow in buildings [16]

3.1.3 MacroFlo

The MacroFlo module works in conjunction with Apache to simulate the bulk air movement through openings in the building envelope [17]. It has the capability to address both mechanical and natural ventilation. For naturally ventilated buildings, MacroFlo calculates air movements resulting from both buoyancy forces and wind.

3.2 Setting up the base case model

The case studies (chapter 2.2) were used to set up a base case model, in order to investigate the effect of different design decisions on indoor thermal conditions. It is important to note that based on the information available, a very accurate model is not possible. The aim is to achieve a reasonable model, which can then be tested with different variables.

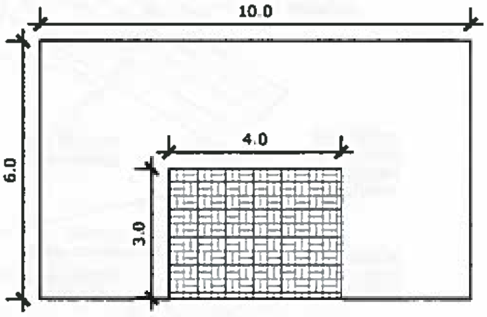
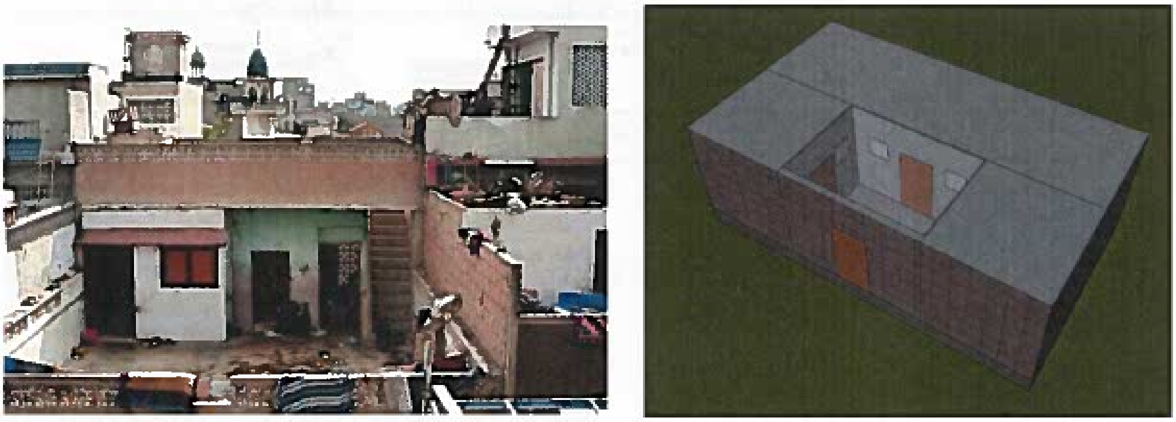


Figure 3.2: The base case model (plan)



(a) House in Nawalane, Karachi) [8]

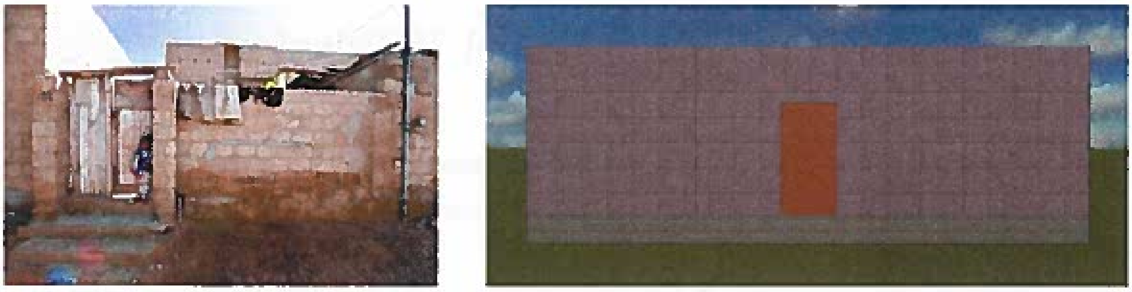
(b) Base case model (axonometric)

Figure 3.3: Actual house and model

A house size of 60 m^2 was chosen as the base size. This corresponds roughly with a typical 3 *Marla* plot (63 m^2). The model geometry was generated in the ModelIT module of IES. The front door opens into a 12 m^2 courtyard, or *sahan*, with three rooms opening onto it. This configuration is shown in figure 3.2. The model is a single storey building, with a plinth height of 0.5 m and a 'floor to ceiling' height of 2.5 m. Figure 3.3a shows a real low income house, while the model geometry generated in IES is shown in figure 3.3b.

IES-VE is not directly capable of simulating the effects of vegetation or fountains within a courtyard microclimate. If the courtyard is just left as 'empty space' i.e. if it is only defined by the rooms around it, it is not considered a separate 'thermal zone' by the software, and is modelled exactly the same as the external atmosphere. This investigation is based on the idea that the courtyard has a separate 'microclimate' distinct from the external. Hence the courtyard is set up as an air-conditioned room (the rest of the house is naturally ventilated), with a glazed roof, left open to the atmosphere. This is not an ideal solution, but it allows us a degree of control in simulating the conditions in the courtyard.

The materials are chosen from the apache systems database to most accurately reflect



(a) Block masonry house in Karachi [8] (b) Base case model (front)

Figure 3.4: Actual house and model

the actual materials used, as discussed in chapter 2.2. The roof construction consists of 12.5 mm of plasterboard, followed by 40 mm of clay tile, 40 mm of insulation and topped by 40 mm of screed (based on figure 2.4). The walls are modelled as two layers of 75 mm thick concrete blocks, covered on the internal side by a layer of plaster. Figure 3.4a shows a block masonry house in Khuda Ki Basti, one of the low income settlements discussed in section 2.2. The front view for the model house is shown alongside, in figure 3.4b. Thermal resistance and thermal mass for the each building element is summarised in Table 3.1.

	Thickness (mm)	**Mass** (kg/m^2)	**U-Value** (W/m^{2}K)	**Thermal Mass** (kJ/m^{2}K)
Walls	162.5	98.75	0.9814	50.00
Roof	132.5	101.2	0.5881	46.28
Glazing	15	-	2.8476	-
Floor	220	275.0	0.3821	85.00

Table 3.1: Summary of thermal properties of building elements

The initial model has no openings in the exterior walls. Each room has a door and two windows opening into the courtyard. In the base case, the windows are considered a 'sharp edged orifice' with an openable area of 95% and a crack length that is 50% of the opening perimeter. The exposure type is set as a 'sheltered wall' (Wind pressure coefficients for this exposure category are included in the appendix).

3.3 Baseline Results and Model Validation

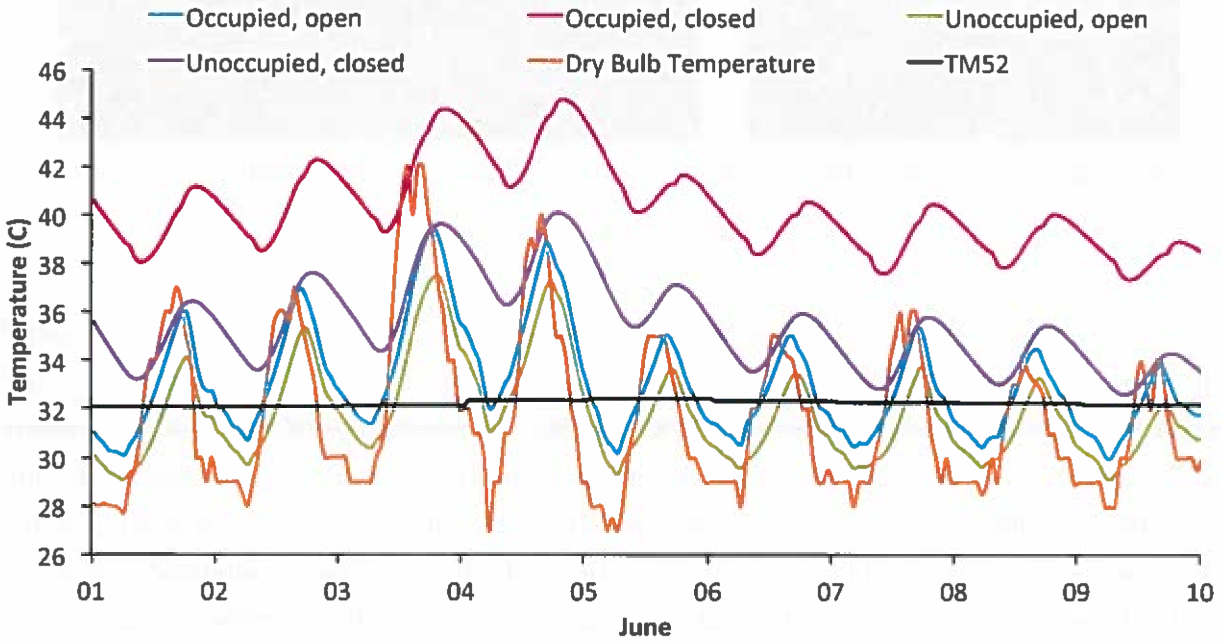


Figure 3.5: Base case model results

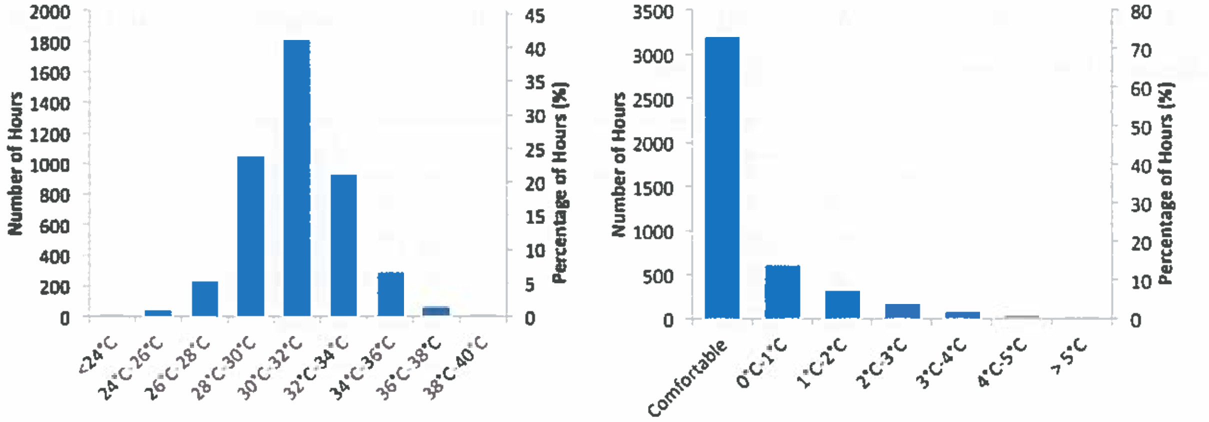
Results for the average air temperature of the house (rooms surrounding the courtyard) are shown in figure 3.5. For the base case, the courtyard is at the same temperature as the ambient air. Results are only shown for the first ten days of June (the hottest period of the year), as a worst case scenario.

Initially, the house was considered with all windows and openings into the courtyard shut at all times. The purple line is the air temperature for an unoccupied house. As expected, due to the poor insulation properties of the construction materials, the internal air temperatures are high, in some cases even higher than the external dry bulb temperature. An unoccupied house is however, unrealistic. The occupancy profile is set such that ten residents are present during the evening and night hours, while during the working day only five people are present (as described in the findings of the case studies). Once people gains are included, the internal temperatures are far higher than what is expected or comfortable (red line). It is apparent that internal gains from occupants are a significant proportion of the overall gains and cannot be neglected. This trend is in keeping with the observations of the case study report [8], which cites overcrowding and overheating as the major problems of existing low income housing in Karachi. There is, however, little quantitative field data available to corroborate the results. One major field study was conducted across different cities in Pakistan in 1995 and 1996, which measured indoor global temperatures. The results obtained for Karachi are shown in table 3.2. The average monthly indoor temperatures obtained from the model (T_{m1}) are also shown on the table for a typical year (August to July). The predicted temperatures are significantly higher than those measured in the study.

	T_{olt}	T_o	T_g	T_{m1}	T_{m2}
Aug-95	28.9			36.08	30.56
Sep-95	28.9			36.16	30.15
Oct-95	27.9			36.26	29.03
Nov-95	23.9			31.34	23.56
Dec-95	19.5			26.56	19.7
Jan-96	18.1	17.4	24.3	24.97	18.21
Feb-96	20.2	20.4	26.5	28.6	21.35
Mar-96	24.5	28.6	29	33.48	26.39
Apr-96	28.3	28.8	32	36.57	29.43
May-96	30.5	30.1	32	39.46	31.88
Jun-96	31.4		31.6	39.26	32.74
Jul-96	30.3		30.7	37.12	31.39

Table 3.2: Survey results for average indoor global temperatures (T_g), along with outdoor temperature at the time of the survey (T_o) and a 30 year average outdoor temperature (T_{olt}) [14]

The internal temperatures predicted by the model can be improved somewhat by allowing for reasonable occupant behaviour like opening windows. The windows and doors are controlled such that they are only shut if the courtyard temperature is higher than the temperature of the surrounding rooms (i.e. usually left open). This maximises the infiltration (bulk air movement) heat loss to the courtyard and minimises any heat gains. The results (blue and green lines on figure 3.5) are closer to what is expected for the internal temperatures. The 'occupied' and windows and doors 'open' scenario (blue line) is the most realistic and the improved average monthly indoor temperatures (T_{m2}) are also shown in table 3.2. This model matches up reasonably well to the measured data for the summer months (April to July), and therefore it is suitable to use as a baseline against which the impact of the passive cooling strategies can be measured. The temperatures for the winter months are lower than measured, but this is because in the model the windows are mostly left open. This is not likely to be the case for the winter months; but as we are only investigating summer conditions, the discrepancy in the model will not impact the final results.



(a) Temperature range (b) Degrees above TM52

Figure 3.6: Frequency distributions

A statistical analysis of the indoor temperatures for the summer months (April to September) is shown in figure 3.6. Figure 3.6a shows the frequency of each temperature range. The temperature is above the recommended ASHRAE upper limit of 28°C for about 94% of the time. Figure 3.6b gives the frequency for degree increments above the TM52 maximum adaptive temperature. This figure shows that despite the high temperatures, it is within the comfort limit (i.e less than the TM52 adaptive temperature) for about 87% of the time.

4

Courtyards

4.1 Background

The courtyard is a building element that is widely used in many hot regions of the world. They are important features, providing daylight and ventilation to a building. According to the case studies discussed in section 2.2, most low income houses in Karachi incorporate a small courtyard or *sahn*.

Courtyards act as microclimate modifiers that improve the thermal conditions of the surrounding rooms [18]. The passive cooling potential of a courtyard depends on a number of factors, which have been identified in the literature as configuration, aspect ratio, orientation, shading, height of the walls and the use of vegetation and water bodies [18]. A courtyard that is optimised with regards to these factors will have a microclimate a few degrees cooler than the ambient conditions, which in turn has a cooling effect on the surrounding rooms [19]. Previous studies ([18], [20]) have highlighted the fact that thermal conditions within a courtyard are highly dependent on the amount of solar radiation. The absorbed solar radiation acts to raise the surface temperatures and consequently the temperature of the adjacent air layers. This has a significant effect on the thermal conditions in the courtyard space, which is, in turn, reflected on the thermal behaviour of the surrounding habitable spaces.

4.2 Variables and assumptions

In this investigation, all the courtyards considered are rectilinear and surrounded by rooms on three sides. As most low income housing in Karachi is terraced housing (with side walls adjacent to neighbouring houses) the overall shape of the building is not a factor that can easily be controlled, and only the footprint of the courtyard within the house is varied.

The investigation is carried out in two stages. Initially, the base case model of section 3.2 is run in *ApacheSim* (dynamic thermal simulation) to determine the effect of the courtyard microclimate on the internal conditions of the surrounding rooms. The overall thermal conditions within the courtyard depend on complex interactions of thermal mass, radiation, surface temperature and evapo-transpiration from any vegetation or water ponds present. IES does not have the explicit capability of modelling the effect of vegetation and water bodies. A workaround exists for modelling evaporative cooling from water bodies [21] but this is complicated to implement and the results have not been verified. Therefore, the actual thermal modelling of the courtyard is beyond the scope of this investigation. The aim of this approach is to determine the degree of cooling in the courtyard required to significantly impact comfort in the surrounding rooms. The performance parameter considered is the number of hours that the internal air temperature is above the TM52 Adaptive Comfort Standard discussed in chapter 2.3.

Solar shading has been identified as an important factor that affects the microclimate of the courtyard. Therefore, the second stage of the investigation involves a shading analysis conducted in *SunCast* to determine the most appropriate orientation and aspect ratio. Thermal conditions of the rooms are not considered. The link between shading and thermal conditions is presumed, and the extent of the impact is not investigated. Two proxy variables are used to assess the impact of adjusting the variables:

- The percentage of the courtyard floor in direct sunlight over the course of a day, as this will impact the surface temperature of the floor and hence the air temperature in the courtyard.
- The percentage of the courtyard facing walls in the sunlight over a whole day, as this will directly impact the solar heat gains of the surrounding rooms; especially as the model assumes that doors and windows facing the courtyard are usually left open.

In Karachi, there is a significant change in sun angle during the year (as discussed in chapter 2.1), which needs to be taken into account in the shading analysis of the courtyard. The investigation is carried out for the 21^{st} of April, May and June; representing a low, medium and high sun angle in the summer. The sun altitude peaks on 21^{st} June, and is symmetric about this point. Therefore the sunpaths for July and August are the same as April and May, and they need not be separately analysed.

4.3 Results and Analysis

4.3.1 Temperature of courtyard microclimate

The courtyard temperature is used as a control variable, and is set by an active cooling system within IES such that it is at a constant offset from the dry bulb temperature. The model is tested for courtyard temperatures at 2°C, 4°C, 6°C, 8°C and 10°C below ambient temperature. For each case, air temperatures within the room are compared against the TM52 'maximum adaptive temperature' standard.

Results for the first 10 days of June (figure 4.1), show a significant improvement in indoor conditions and comfort even when the courtyard is just a couple of degrees below ambient (red line). 3^{rd} June is the hottest day of the year according to the weather file used, therefore for 'comfortable' temperatures to be achieved for *every* hour of the summer (i.e. internal temperatures are always less than the TM52 limit); it is clear that the courtyard needs to be about 10°C below ambient (orange line). However, if allowances are made for temperatures above the comfortable limit for a few hours in the year; a reasonable level of comfort is achieved from a courtyard at 4°C below the ambient temperature (green line).

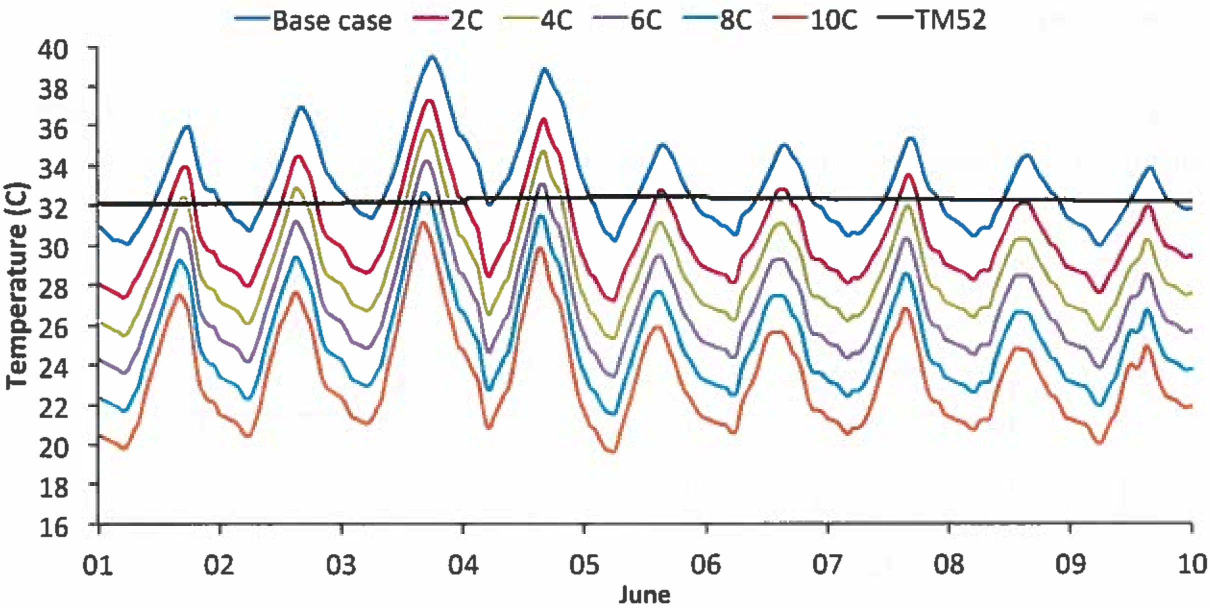


Figure 4.1: Temperature of rooms surrounding courtyard for courtyard temperatures controlled at ambient, and at 2°C, 4°C, 6°C, 8°C and 10°C below ambient

The number of hours (from April to September) that the temperature in the rooms is above the TM52 standard is shown in figure 4.2. A courtyard that is 2°C cooler than the ambient can reduce the number of uncomfortable hours to about 5% of the time, compared to 27% for the base case where the courtyard is at ambient temperature.

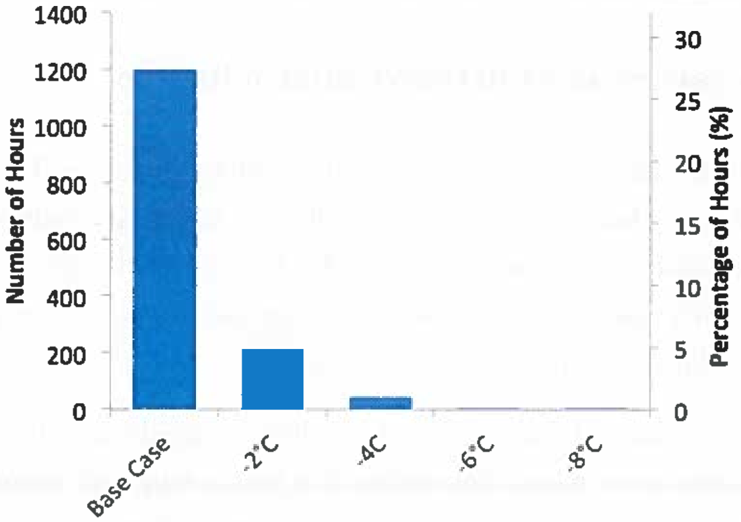
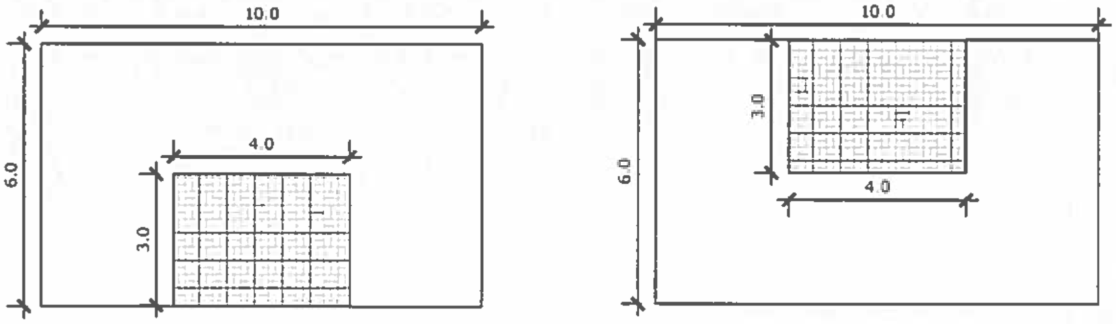


Figure 4.2: Number of hours the temperature is 'uncomfortable' in the house for each courtyard temperature

4.3.2 Shading Analysis

Orientation

To determine the best placement for the courtyard within the house, two models were considered: the base case, and the base case rotated by 180° as shown in figure 4.3.

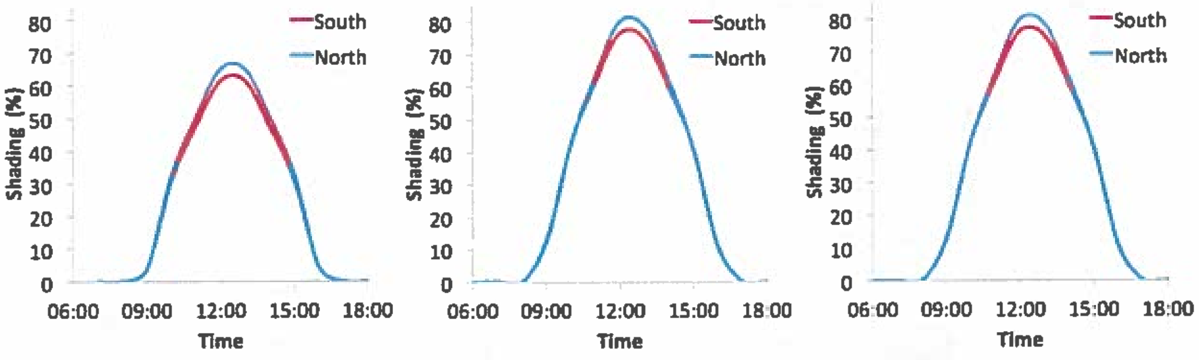


(a) Courtyard on the south side

(b) Courtyard on the north side

Figure 4.3

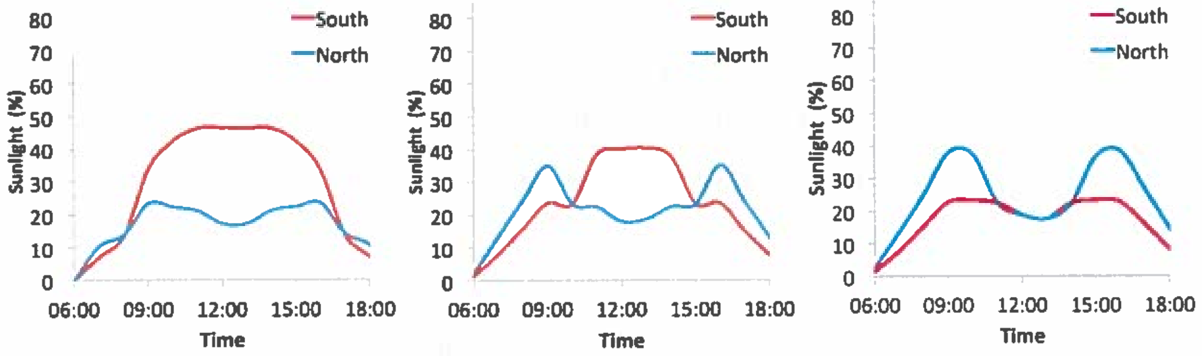
The results for the shading of the courtyard floor are shown in figure 4.4. At lower sun angles (April), both the peak percentage (height of the curve) and the time period that the courtyard is in the sun (width of the curve) is lower, compared to the higher angles (for both orientations). This is as expected, since the lower sun will cast more shadows. In each case, the south facing courtyard (red line) performs marginally better than the north facing one (blue line), and hence it is obvious that if only the shading of the courtyard itself is considered, a south facing courtyard is preferred.



(a) 21 April (b) 21 May (c) 21 June

Figure 4.4: Percentage of courtyard floor in direct sunlight

The shading analysis for the walls is shown in figure 4.5. In this case, the overall shading is the sum of three vertical surfaces instead of a single horizontal one; hence the patterns of the shadows are less easy to predict, and the analysis for the walls is less straightforward. It is clear that the north courtyard performs better in April, while the south courtyard is better for June. In May, however, the south courtyard is better in the morning and evening hours, while the north courtyard is better during midday.



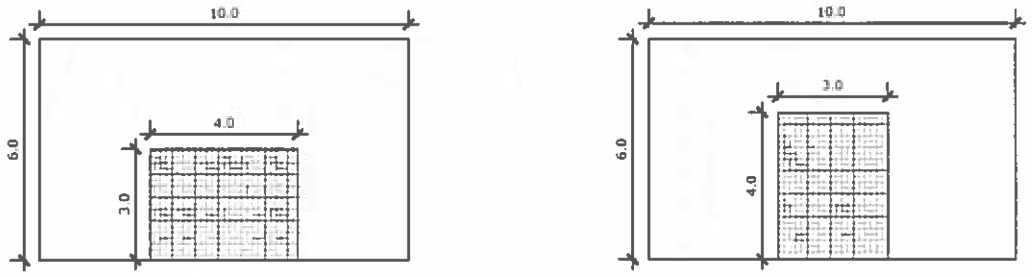
(a) 21 April (b) 21 May (c) 21 June

Figure 4.5: Percentage of courtyard facing walls in direct sunlight

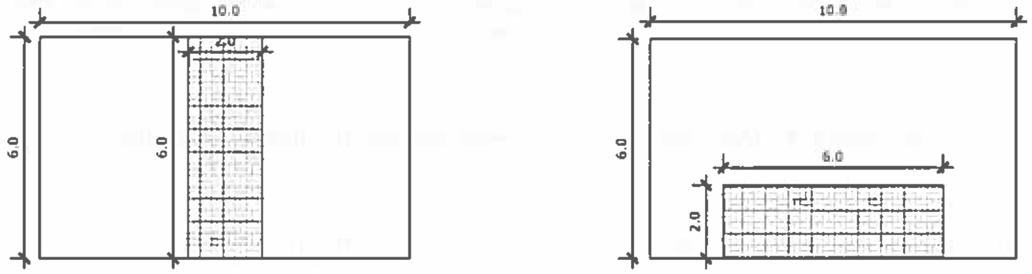
Deciding the 'best' orientation is harder in this case, and requires a subjective judgement.

- The south facing courtyard is preferred for June, when the temperatures are highest. In May, a south facing courtyard favours the morning and evening hours, when occupancy is lower in our model.
- In May, the north facing courtyard receives less midday radiation, which is at a higher intensity than the morning and evening radiation. Hence overall solar heat gain (in kwh) will be lower.

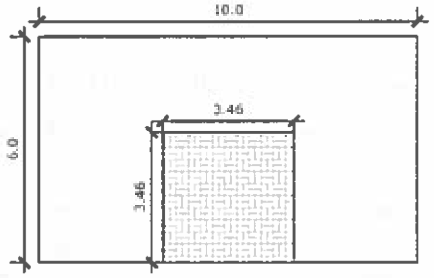
Aspect ratio



(a) Model 1 (base case) with l/d = 1.33 (b) Model 2 with l/d = 0.75



(c) Model 3 with l/d=0.33 (d) Model 4 with l/d=3

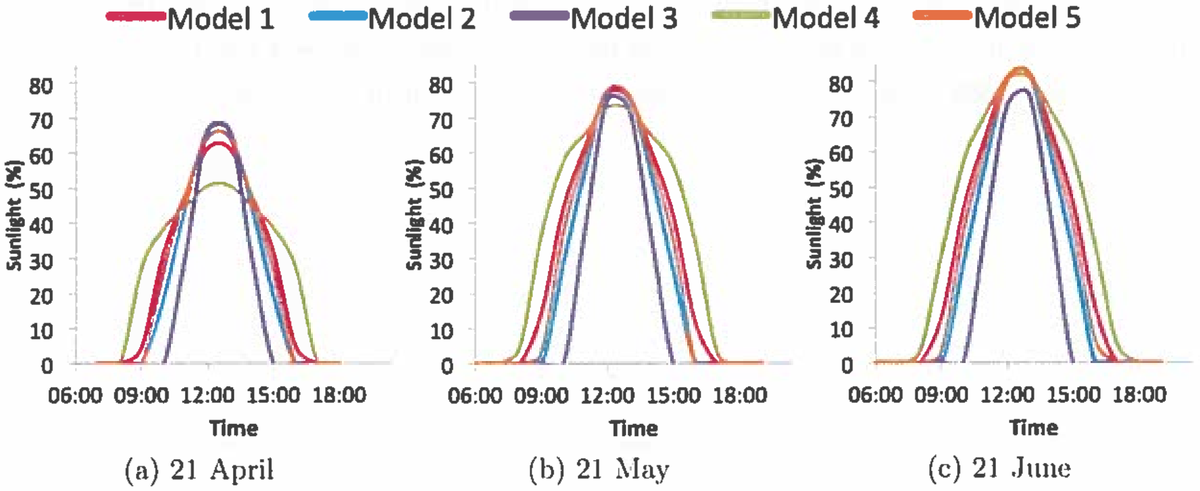


(e) Model 5 (square) with l/d = 1

Figure 4.6: Models with different aspect ratios

After orientation, the effect of courtyard aspect ratio is investigated. In this regard, five different footprints were considered, each with a south facing courtyard; as shown in figure 4.6. In each case, the footprint of the house is 60m^2 with a 12m^2 courtyard. Model 1 is the same as the base case model; model 2 is a slightly narrower and deeper courtyard. Model 3 is an extreme case of a deep narrow courtyard, while model 4 is an extreme shallow, wide courtyard. These models are unlikely as actual configurations, but are included in order to verify the general conclusions. The last configuration considered (model 5) is a square shaped courtyard.

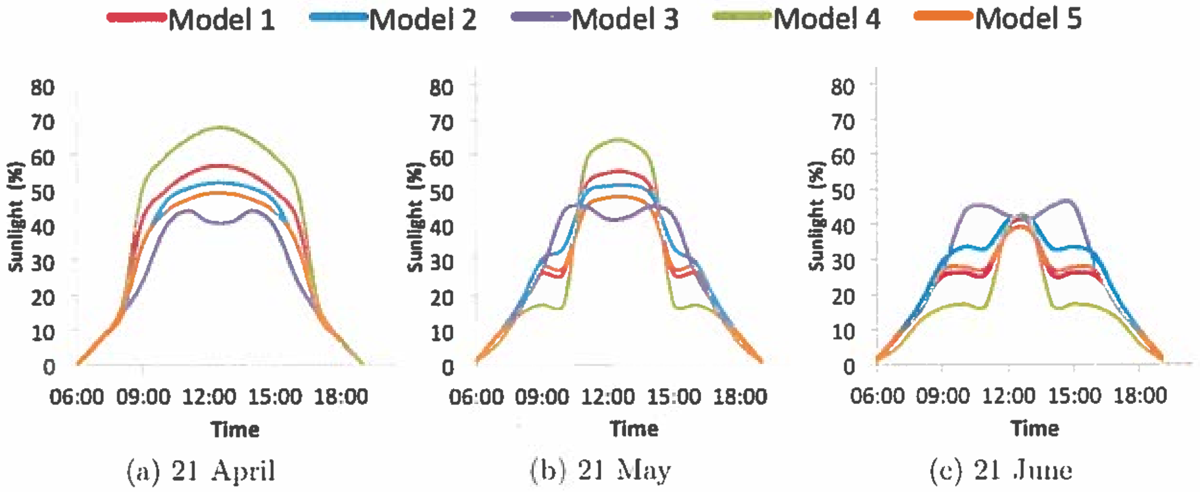
The results for the courtyard floor are shown in figure 4.7. For the high sun angle case (June), it is clear that the deep, narrow courtyard (purple line) performs best. In May, model 4 (green line) has a marginally lower peak percentage, but the curve is significantly wider; hence model 3 (purple line) is still the obvious choice. For the low sun angle case, model 4 (green line) has a much lower peak percentage, but the duration for which the courtyard is in the sun is longer. There is a tradeoff between high intensity, midday sun for a short period, or lower intensity sun over a longer period of the day.



(a) 21 April (b) 21 May (c) 21 June

Figure 4.7: Percentage of courtyard floor in direct sunlight for different aspect ratios

For the wall shading (figure 4.8), narrow courtyards are preferable for April (purple line), while the shallow ones (green line) are better for June. The mid sun angle is again a tradeoff between a dip at midday with a longer duration (purple), or a higher peak but shorter duration (green). In this case, a square courtyard (orange) is a suitable compromise, with a low peak and a short duration.



(a) 21 April (b) 21 May (c) 21 June

Figure 4.8: Percentage of courtyard facing walls in direct sunlight for different aspect ratios

	April	May	June
Floor	Uncertain	Deep and narrow	Deep and narrow
Walls	Deep and narrow	Uncertain	Wide and shallow

Table 4.1: Summary of shading analysis for different aspect ratios

The results are summarised in table 4.1. Although there is no obvious orientation that is suitable for all three months, it is clear that the deep and narrow orientation performance better for more counts. These results are more applicable to sub-tropical regions. For equatorial regions, the sun angle is high for most of the year, and only the results for June are relevant, which makes choosing an appropriate orientation even harder.

5

NATURAL VENTILATION

5.1 Background

In hot, humid climates, natural ventilation is an essential passive cooling strategy. It improves thermal comfort by increasing indoor air movement and removing heat stored in the thermal mass of a building [22]. There are two fundamental principles upon which most natural ventilation strategies are based:

- Stack effect, which is caused by temperature differences between the inside and outside of a building. When the inside of a building is warmer than the outside, warm indoor air will rise and exit through appropriately placed outlets, while cooler, denser air will be drawn in from below [23].
- Wind driven ventilation, which relies on a pressure difference created by wind incident on the building envelope.

Stack effect is dominant in periods of low wind speed, and is low in the summer when temperature differences are minimum. Since our aim is improve thermal comfort in the summer, stack effect is unlikely to have a major impact. Fortunately, since Karachi is on the coast, it experiences a regular sea-land breeze. Hence this investigation will be focused on maximising the wind driven ventilation rate.

Many devices and strategies exist for maximising wind driven ventilation, including wing walls, chimney couls, wind towers, wind catchers and double skinned facades [23]. Of particular relevance to our situation is the use of a courtyard to provide wind driven natural ventilation. A study on the passive cooling potential of a ventilated courtyard was carried out in Columbo, Sri Lanka. Khan et al. (2008), concluded that the airflow patterns in a courtyard house are strongly dependent on openings in the external envelope [24]. The most favourable internal conditions were observed when the courtyard acted as a 'funnel', extracting air from inside the building and discharging it to the environment.

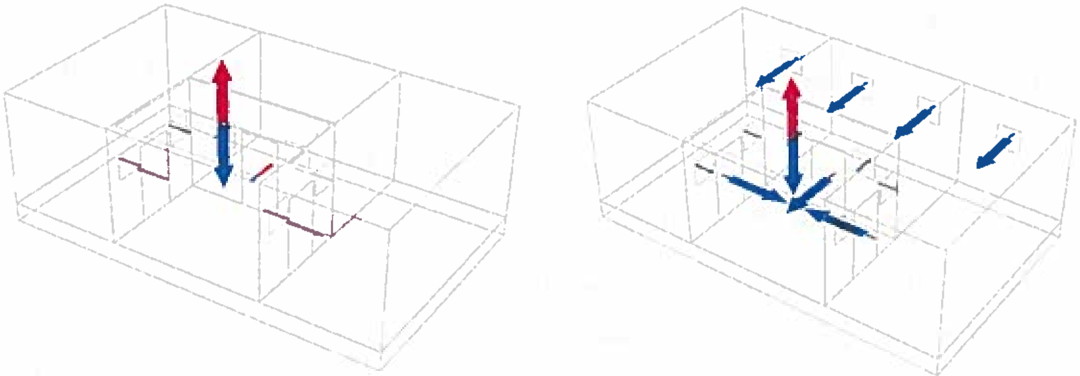
5.2 Variables and assumptions

The focus of this investigation will be to quantify the effects of natural ventilation on thermal comfort, and maximise the ventilation rate for our base case model. The base case model of chapter 3.2 was modified to have four windows in the external envelope on the back wall of the house, aligned with the courtyard facing openings (the side walls are assumed connected to other dwellings).

The orientation is likely to have a significant impact on the ventilation rate in a naturally ventilated building [23], hence the model is optimised for orientation. As before, the performance parameter is the number of hours where the temperature is above the TM52 standard.

5.3 Results and Analysis

The air flow pattern through the base case model and the modified model is shown in figures 5.1a and 5.1b. The model behaves as expected (according to [24]). When there are no openings in the external envelope, the courtyard acts as a 'suction' zone, sucking in air from the open sky to ventilate the building. The ventilation is single sided, with air recirculating through the same opening. When the base case is modified to include external vents, the courtyard becomes a 'funnel' which directs air out of the building. The mode of ventilation is effectively cross ventilation.

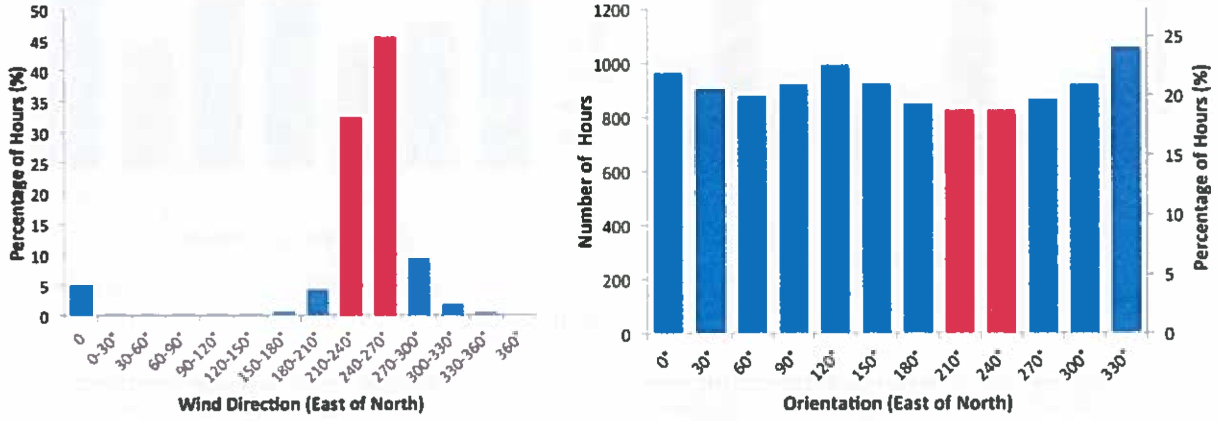


(a) Base case (b) Modified case with external vents

Figure 5.1: Air flow patterns with outflow shown in red and inflow shown in blue

5.3.1 Orientation

Based on the literature [23], maximum wind driven ventilation is achieved when the windward surface of the building is normal to the wind direction, with openings in both the windward and the leeward sides of the buildings. The wind rose for Karachi (figure 2.2b), shows that wind directions over the course of the year are predominantly in two major directions, 210° to 240 ° and 270° to 300°. The major problem with optimising for wind is that the wind fluctuates both in speed and direction over the course of the day and the year. A particular orientation needs to be chosen as the 'design' orientation.



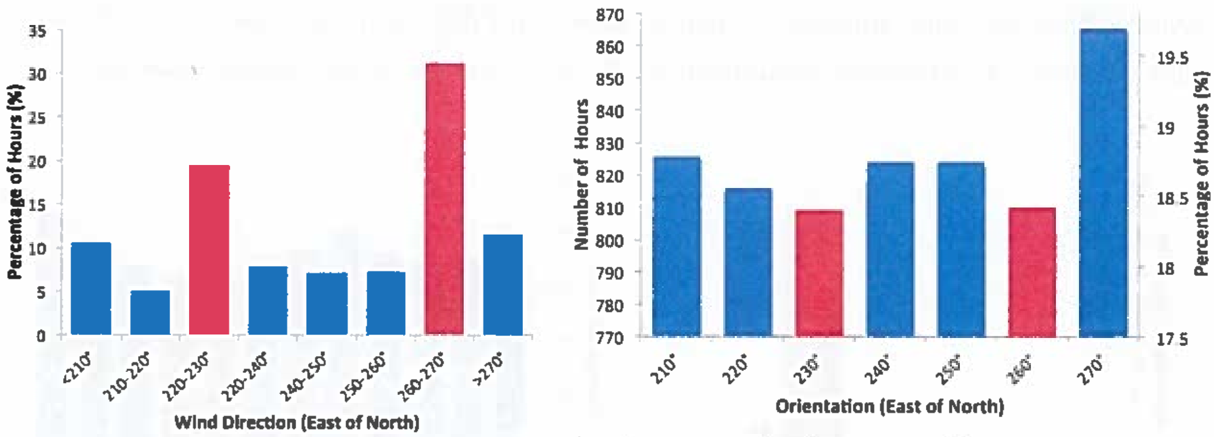
(a) Frequency of each wind direction (b) Number of 'uncomfortable' hours

Figure 5.2: Frequency distributions for summer months (April to September)

In order to choose this design orientation, a statistical analysis of the wind directions is carried out for the summer months (May through to September), based on the wind data in the weather file. The results are shown in figure 5.2a. As in the case for the whole year, the wind is predominantly between 210° and 270° in the summer months. The modified model was rotated through 360° at 30° intervals (with the courtyard facing south as 0°). For each orientation, the number of hours in the 'uncomfortable' range (i.e. above the TM52 adaptive comfort standard) is shown in figure . The lowest number of uncomfortable hours were observed at orientations of 210° and 240° (824 and 823 hours respectively). The maximum number of uncomfortable hours was 1053, at an orientation of 330°. The 180° and 60° orientations were also favourable, despite low wind in those directions for most of the summer. This may be explained by the fact that the wind in these directions corresponds with the most uncomfortable hours, hence even if the duration is low, the impact on comfort is high.

The design range needs to be further narrowed for an 'optimum' design orientation. The same analysis is repeated for a narrower range and smaller intervals. Results are shown in figures 5.3a and 5.3b. The wind is predominantly between 220° and 230°, and 260° and 270°. Maximum comfort was observed at orientations of 230° and 260°. Hence these are the optimum wind orientations for Karachi.

The results show that between the least optimum orientation of 330°, and the optimum orientation of 230° there is an improvement of comfort levels of 245 hours, which is about 6% of the total summer hours.



(a) Frequency of each wind direction

(b) Number of 'uncomfortable' hours for each oreinetation

Figure 5.3: Frequency distributions for summer months (April to September)

5.3.2 Effect of ventilation on indoor air temperatures

To quantify the effect of ventilation on indoor air temperatures, four cases were compared:

- The base case (with no external vents), oriented at 230° (east of north)
- The modified base case (with external vents), oriented at the ventilation 'optimum' orientation of 230°.
- The modified base case oriented at the least optimum orientation for wind driven ventilation (i.e. at 330°).
- The tests conducted so far have been for a building with the long wall completely exposed to the wind. However, in a city scenario, this is unrealistic. In the final case, the wind pressure coefficients are changed to reflect a 'semi-exposed' city environment; which is the more realistic case in Karachi.

Results for internal temperatures for the first ten days of June are shown in figure 5.4, along with the TM52 maximum adaptive temperature. Relative to the base case (blue line), both the modified cases (red and green) are below the adaptive temperature (black line) for longer periods. However, there is also a slight increase in the peak temperatures of each day, which is a result of increased solar and infiltration gains from the openings. Therefore, the external openings effectively act to elongate the temperature curve. Both these scenarios are idealistic in that they assume that the vents are completely exposed to the wind, but they allow us to estimate the 'maximum' possible gain from ventilation. In the more realistic 'semi-exposed' case (purple line), the temperatures do not vary significantly from the base case with no vents. Therefore, although internal conditions (particularly the air quality) can be improved somewhat by ventilation, achieving all of the potential improvement is unlikely in an urban environment like Karachi.

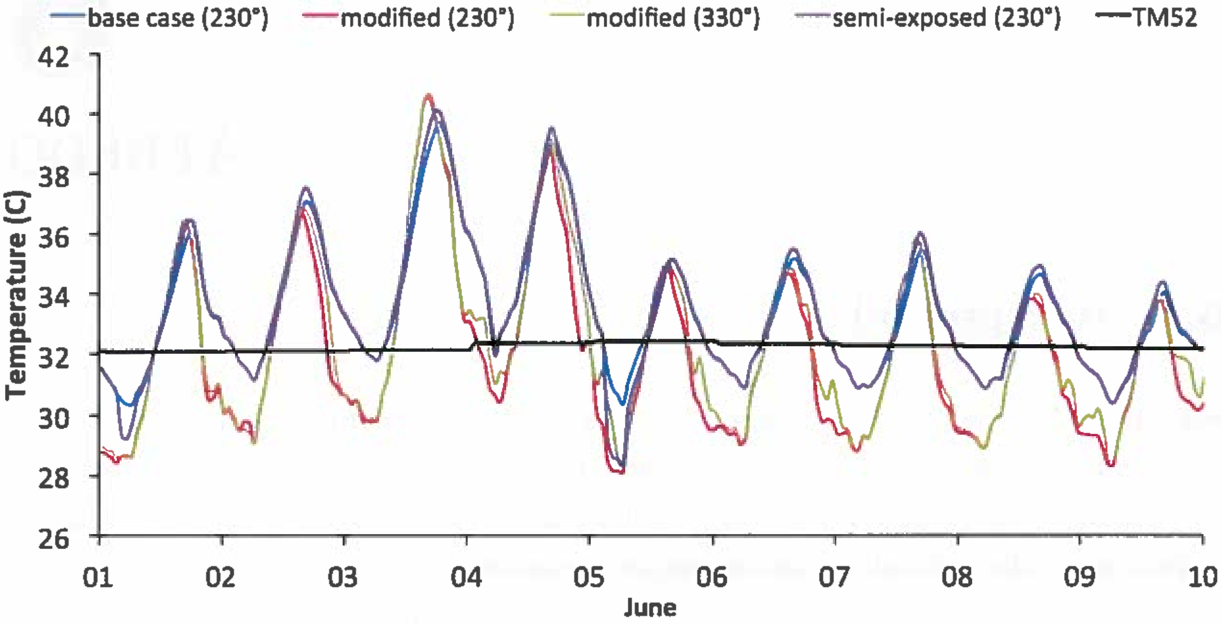


Figure 5.4: Effect of ventilation on indoor air temperatures for the first ten days of June

The general trends visible from the first ten days of June are confirmed by conducting a frequency analysis for April to September. Figure 5.5 shows the number of comfortable hours for each case. A potential gain of 543 hours (12%) is available relative to the base case for an optimally oriented building with external vents. However, this gain is unlikely to be achieved in Karachi, due to the obstruction of the wind in urban areas. In the realistic case, there is a reduction in comfort hours by about 20. The results suggest that unless the houses are located in relatively open areas on the outskirts of the city; increasing ventilation has little effect on comfort levels.

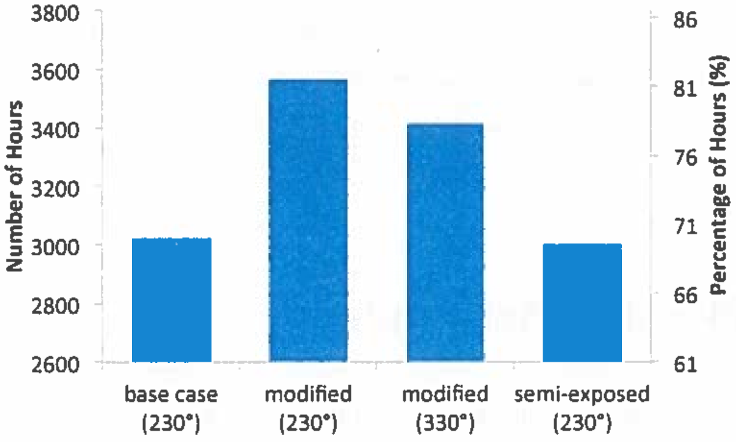


Figure 5.5: Comfort analysis for April to September

It is, however, important to note that air temperature is not the only metric for judging comfort. There is a 'perception' of comfort that is associated with clean, moving air. Hence where possible, external vents should be included to allow for cross ventilation of the buildings.

6

ALBEDO

6.1 Background

Solar radiation incident on a building envelope can have a significant impact on internal conditions. Radiation can either be reflected back to the atmosphere, or absorbed into the building. The heat flow into the envelope can be reduced by either increasing the reflectivity of the material, or increasing the insulation.

The albedo of a surface is defined as the ratio of incident radiation that is reflected back to the environment [25]. The use of high albedo materials (i.e. using light coloured surfaces) is a well known passive cooling strategy. It is a relatively cheap and simple way (compared to increased insulation) of reducing internal temperatures, hence it is particularly applicable in a low income context. It is also most applicable in tropical climates, where the winter temperatures are high enough for there to be no adverse impact on heating demand.

Several investigations have been conducted on the benefits of high albedo, both at a city wide scale and at the microscale (i.e a single dwelling). At the building scale, a field investigation conducted in Sacramento, California by Akbari et. all found a reduction in summer cooling load of 80% by incorporating a white roof [26]. Similarly, Givoni and Hoffman conducted tests on small building with different exterior colours in Israel and found that internal temperatures were about 3°C cooler than the same building with a grey exterior [27]. Building simulations are also commonly used to investigate the effect of albedo, as in Taha et. all [28], as they allow greater versatility in testing a variety of different scenarios.

6.2 Variables and Assumptions

The effect of albedo is dependent on the surface area of the envelope, the intensity and angle of the incident solar radiation and the thermal mass of the house [28]. Although we expect increasing the albedo to improve thermal conditions within our model, the aim of this investigation is to quantify this effect in the specific context of Karachi.

The main control variable in this case is the external solar absorbance of the building envelope, which is equivalent to (1 - *albedo*); and in IES this can be manually inputed by the user. In theory, the albedo can take any number between 0 and 1, however, practical construction materials usually have albedos in the 0.2-0.8 range [29]. In this investigation, an albedo of 0.3 is used in the base-case model, while an albedo of 0.8 is used to model a white painted roof.

Since Karachi is reasonably north of the equator, the walls of the house may also contribute significant solar radiation, particularly in April and May. Hence four cases are analysed:

- The base case model, with all surfaces at an albedo of 0.3, corresponding to a medium-dark material
- The base case with a white roof
- The base case with white external walls
- The base case with white roof and walls.

6.3 Results and Analysis

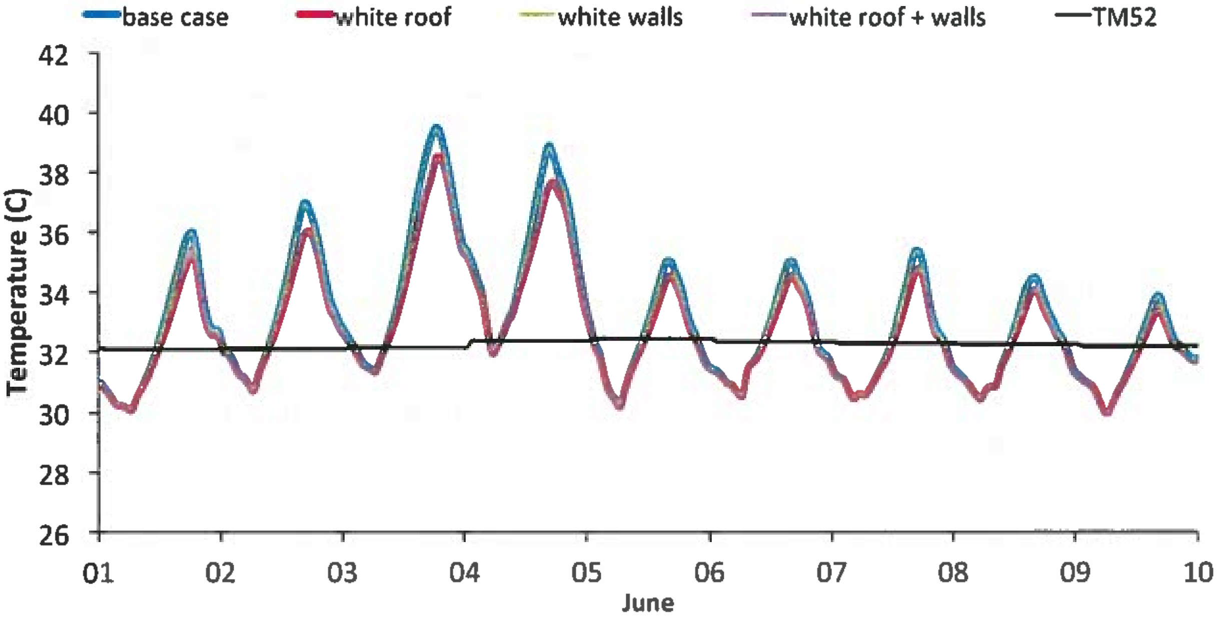


Figure 6.1: indoor temperatures for the first ten days of June for each case

The effect of albedo on internal temperatures for each case is shown in figure 6.1. The results show that using a white roof (red line) gives up to a 1°C reduction in peak temperatures during the first ten days of June. Albedo acts in such a way that it reduces the peak temperatures, without having much of an effect on temperatures below 35°C i.e. it effectively 'compresses' the graph. This is as expected, since albedo reduces radiation from the sun, which is highest at midday. Incorporating a white roof is seene to have a major impact, while using white walls without a white roof (green) is not noticeably different from the base case (blue line). The hours for which the internal conditions are below the TM52 standard over the entire summer is shown in figure 6.2. The findings are as expected for the first ten days of June. According to our model, using a white roof can improve comfort within the building by about 6% (263 hours). The improvement from only incorporating white walls is negligible (about 0.2% change).

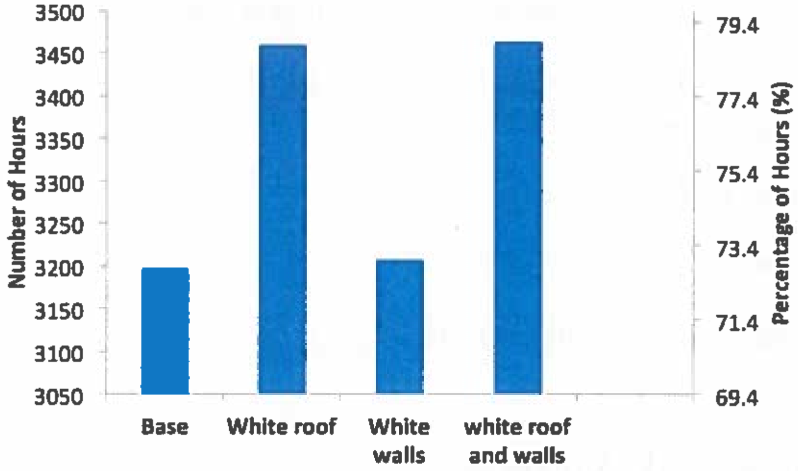


Figure 6.2: Number of 'comfortable' hours for each case

The white paint on a surface is expected to deteriorate over time. and the albedo does not remain fixed at the initial value. Hence, the effect on comfort was analysed for a range of albedos, with '0' being the worst case scenario and '1' as an ideal best case. The percentage of comfortable hours for each albedo is shown in figure 6.3. These results show a fairly linear correlation, suggesting that the houses should be designed for the highest possible albedo.

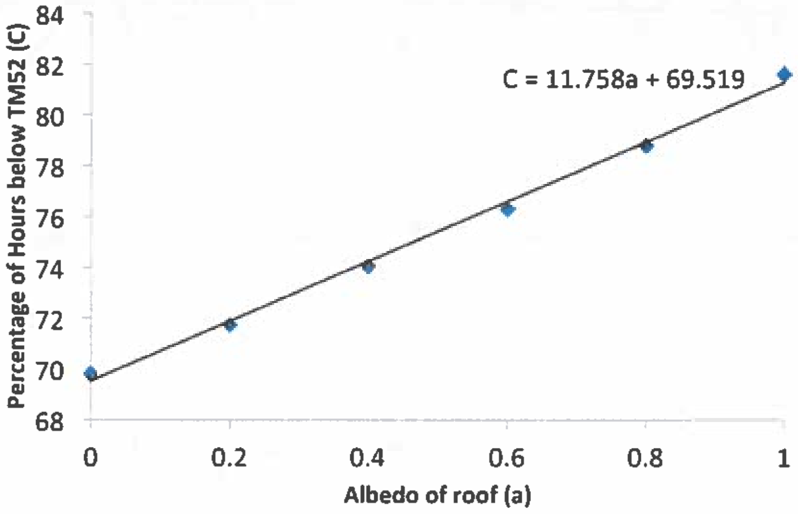


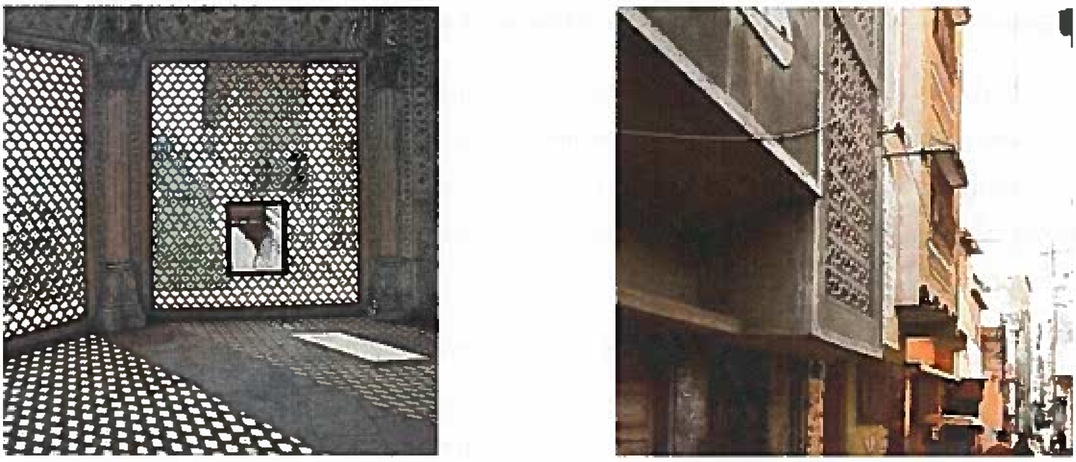
Figure 6.3: Effect of albedo on indoor thermal comfort

7

LATTICE SCREENS

7.1 Background

The *Jaali* is an ornamental perforated screen, commonly found in Mughal and Middle Eastern architecture [5]. It filters sunlight and reduces solar gains, while also providing privacy for the residents of a building. It is already extensively used in low income housing in many regions of Pakistan, including Karachi. Figure 7.1a shows a typical *Jaali* across an opening in the Lahore Fort, providing filtered daylight to the interiors. Figure 7.1b shows the *jaali* concept applied to a low income house in Nawalane (one of the low income settlements discussed in chapter 2.2).



(a) *Jaali* in the Lahore Fort [5]

(b) *Jaali* in a low income house [8]

Figure 7.1: Applications of *Jaali*

Qualitative studies on the passive cooling aspects of indigenous sub-continental architecture ([5] and [4]) mention the use of *Jaali* for reducing solar gains. Although it is intuitive to see that shading the opening will reduce sunlight, there is no quantitative literature available on the impact of these features on internal conditions. However, quantitative assessments of vertical window shades and blinds have previously been carried out. One study, conducted in 2009, attempted to balance the improved thermal conditions with the reduction in daylighting using computer simulations for a number of horizontal and vertical shading devices, and concluded that there was an optimum position and spacing for sun breakers that can simultaneously provide good daylight and minimise solar heat gain [30].

7.2 Variables and Assumptions

The initial base case model considered in this investigation only had inward, courtyard facing openings. For a correctly orientated courtyard, direct solar insolation into the rooms is small; and it is assumed to have negligible effect on the internal conditions. Hence, for investigating the performance of lattice screens, the modified base case with external vents is used. Figure 7.1b also shows the jaali on an external opening, justifying the assumption.

Often the lattice screens have intricate and ornamental carving patterns. However, for simplicity in modelling, a square patterned screen is considered. The basic control variable is the porosity of the screen, which depends on the size of each individual 'hole' in the screen, and the overall number of holes. Porosity is defined as:

$$\text{Porosity} = \frac{\text{Area of cut out section}}{\text{Area of original opening}}$$

The original opening area in this case is fixed at 0.4225 m^2.

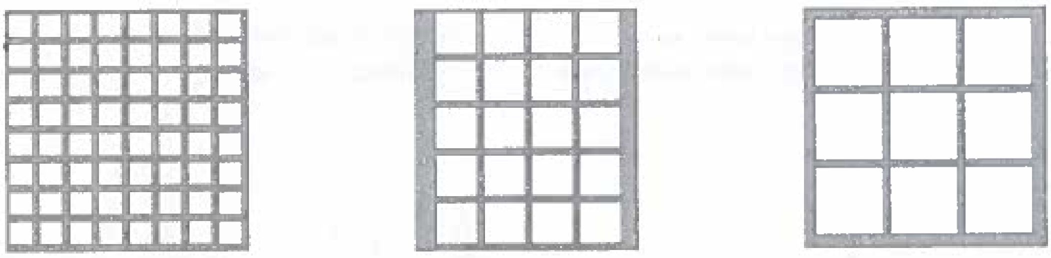
The modified base case has four square external vents (65cm X 65cm) along the back wall of the house. Tests are conducted by replacing these openings with a number of much smaller openings to mimic the effect of the *jaali.* Although IES has an in built function for adding shading to windows, this does not allow us control over the screen porosity, hence is not used.

As the courtyard facing walls in this case do not have any *jaali*, there is unlikely to be any adverse impact on internal lighting conditions (This may be verified using the Radiance model of IES). However, including the lattice screen will affect the air flow pattern through the openings. This investigation focuses on optimising the porosity for minimum solar gain and maximum ventilation . The tests are conducted at the 230° (East of North) orientation which was the optimum for ventilation (see chapter 5). As before, the number of 'comfortable' hours for the summer months is the variable used to judge the best jaali porosity.

7.3 Results and Analysis

Initially, three types of screens with varying hole sizes were considered. as shown in figure 7.2.

The fine jaali is expected to have the best impact on solar gains, but will also have an adverse effect on airflow. To visualise these effects, and the overall impact on air



(a) 6cm (fine) (b) 12cm (medium) (c) 18cm (wide)

Figure 7.2: Screens with different opening dimensions

temperature; the results for the first ten days of June are shown below. As expected, incorporating the jaali reduces solar gains into the building (figure 7.3). The fine mesh (green line), cuts solar gains by half, while a wider jaali also has a significant impact. Not much difference was observed between the medium jaali (12 cm) and the wide jaali (18cm).

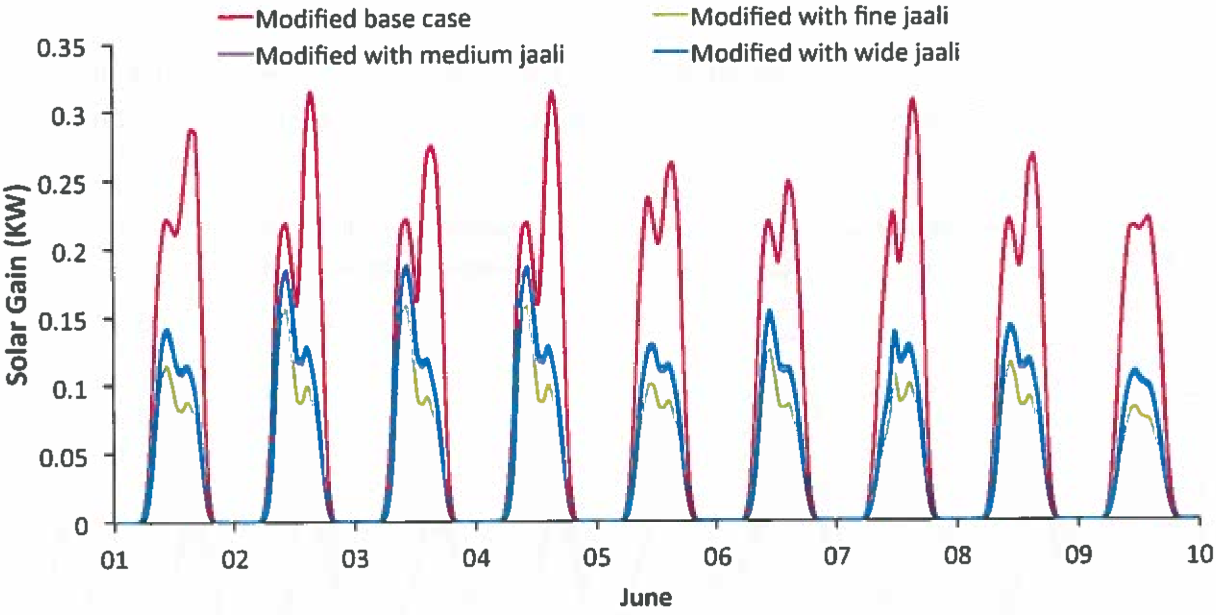


Figure 7.3: Effect of Jaali on solar gain

The trend for the ventilation results was also as expected (figure 7.4). The fine jaali (green) completely restricted airflow into the building and hence is not desirable, while the wide jaali (red) allowed the maximum ventilation rate. However, these results may underestimate the actual ventilation rates. Since the jaali is modelled as multiple small windows in the external wall, its depth is the depth of the wall; which will result in greater frictional losses in mass flow than for a thinner jaali. Hence actual airflows through the jaali are likely to be higher than those predicted by the model.

The combined effects of ventilation and solar gain impact the internal temperatures. Adding vents resulted in a more elongated curve (i.e. higher peaks but lower troughs)

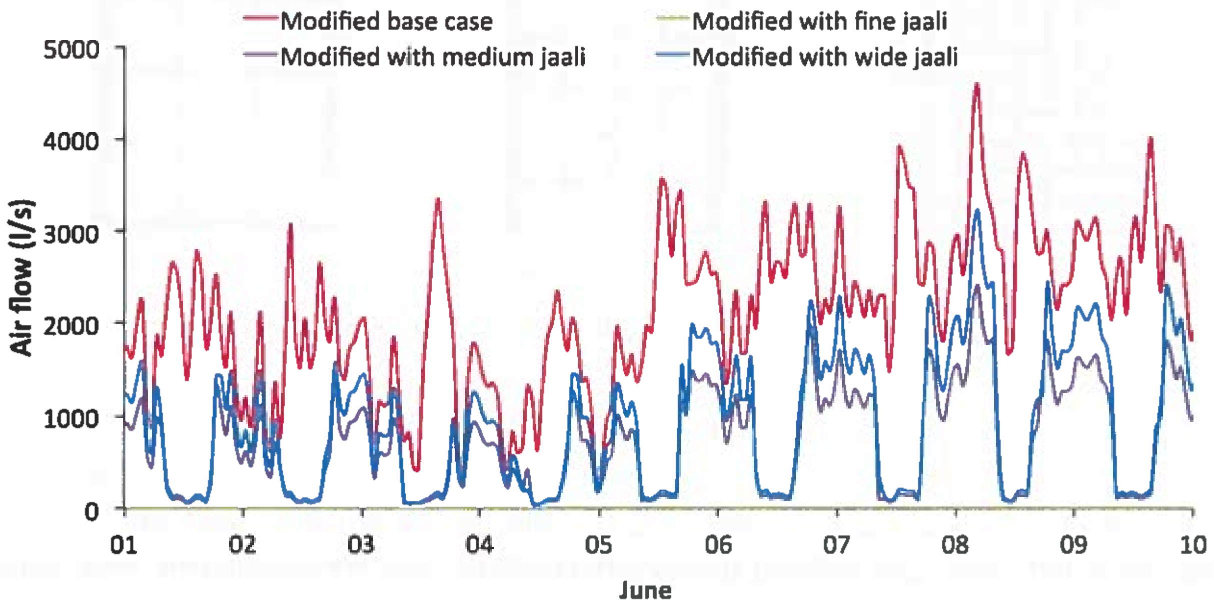


Figure 7.4: Effect of Jaali on ventilation rate

relative to the base case. Jaali counteracts the higher peaks from extra solar gain. It is clear that an optimum hole size exists which allows air flow while reducing the solar gains.

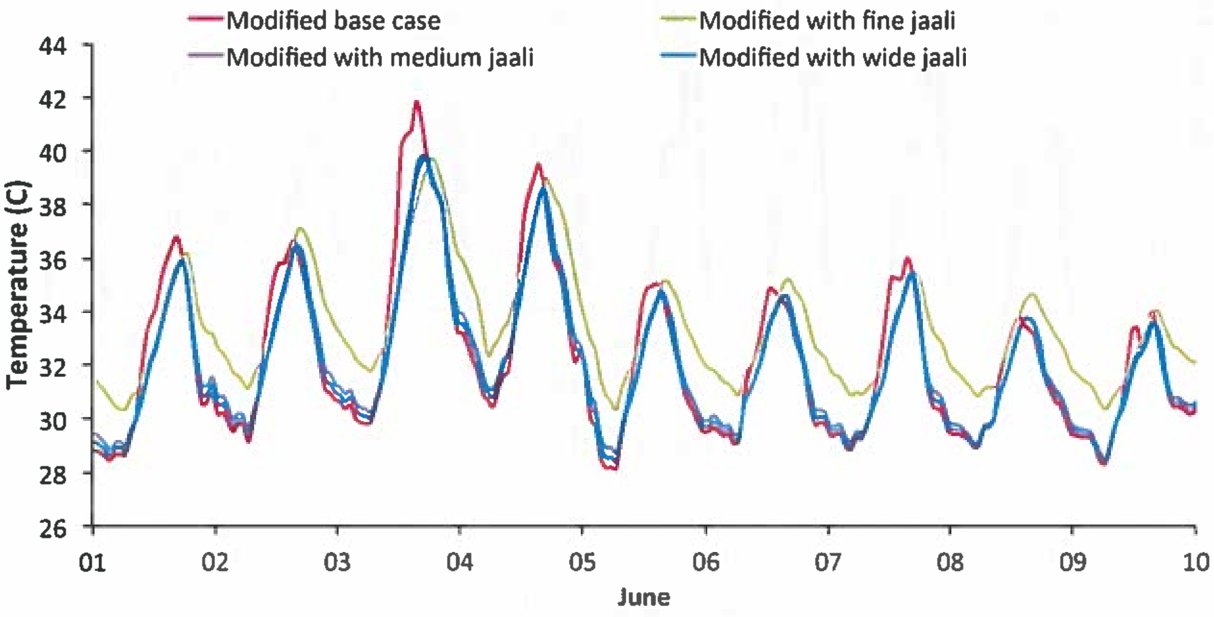


Figure 7.5: Effect of Jaali on internal temperatures

In the cultural context of Karachi, a house without jaali is unlikely as it ensures privacy for the occupants. However, it is also clear from the above figures, that too fine a jaali may have a negative affect on internal conditions by restricting ventilation. A comfort analysis is conducted to find the smallest hole size that can provide an adequate level of ventilation. Figure 7.6, shows that there is clearly an optimum at a hole size of 8cm. Above 8cm, the curve flatlines; indicating a balance between solar gain and ventilation

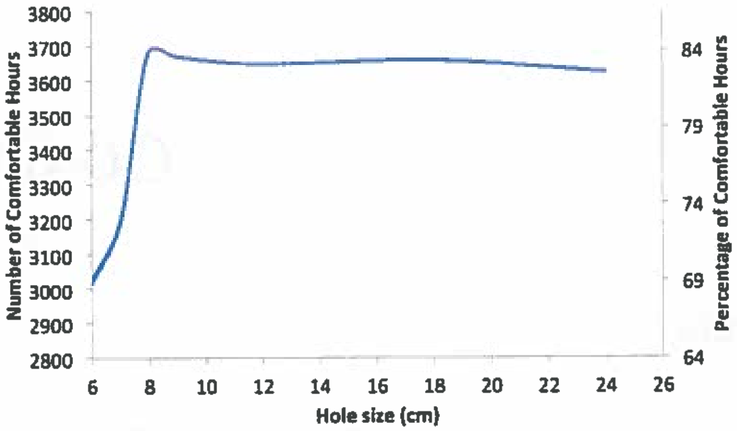
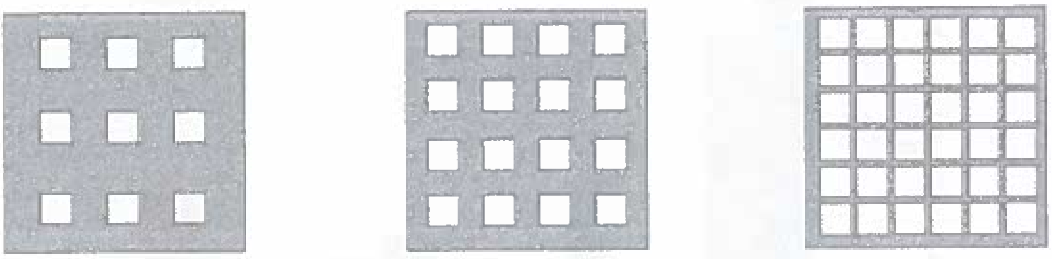


Figure 7.6: Number of comfortable hours plotted against comfortable hours

Further tests were conducted to determine the optimum number of holes for a fixed hole size (in this case at 8cm). The comfort analysis was repeated with the jaali configurations in figure 7.7. The results are plotted in figure 7.8. It is clear that there is little benefit from increasing the number of holes beyond 20. Hence, the optimum jaali has a hole size of 8cm and 20 holes, giving an overall porosity of 0.3. Although the porosity can be further increased without any adverse impacts, cultural norms dictate a preference for low porosities.



(a) 9 holes (b) 16 holes (c) 36 holes

Figure 7.7: Configurations of jaali with fixed hole size of 8cm

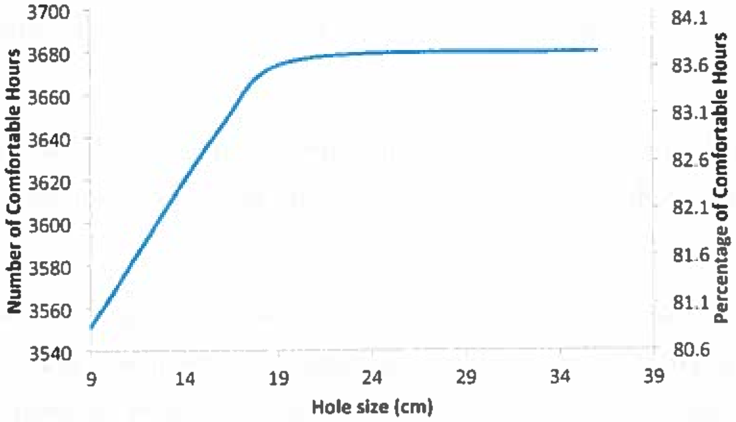


Figure 7.8: Number of comfortable hours plotted against number of holes in the jaali

8

CONCLUSIONS

8.1 Findings

This investigation focused on assessing the passive cooling potential of four commonly used elements within a building. Typical comfort standards such as Fanger's PMV model that are usually applied to actively cooled buildings were deemed unsuitable for application to free running homes in the tropics. Hence the comfort criterion adopted was the TM52 maximum adaptive temperature standard. For Karachi, this standard was a more or less constant 32°C for the summer months. In each case, the number of 'comfortable' hours was considered. A summary of the percentage improvement in the number of comfort, for both the ideal case and the practically achievable case is shown in figure 8.1.

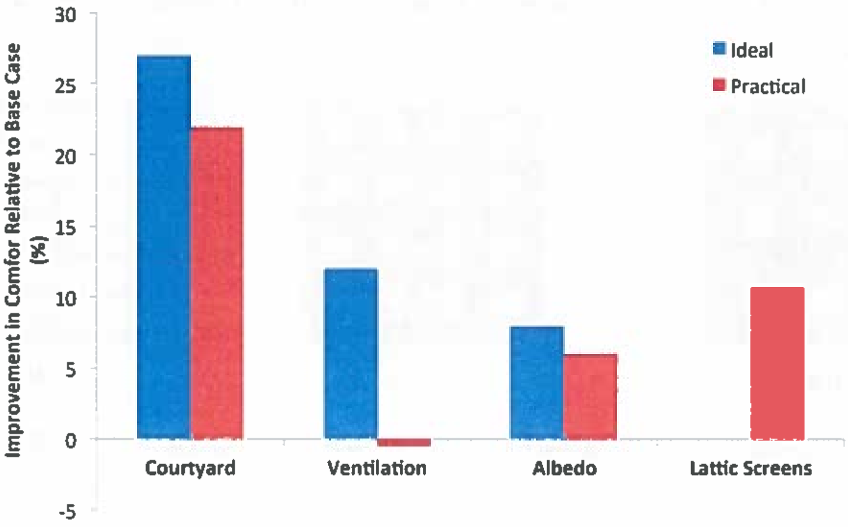


Figure 8.1: Summary of findings for each element investigated

Our base case model predicted comfortable temperatures for 73% of the summer months (April to September). Hence the indoor conditions were uncomfortable for a total of 1186 hours.

To achieve comfort for the remaining 27%, it was found that the courtyard microclimate needed to be 10°C below ambient temperature: which is a highly unlikely scenario. However, it was also found that a courtyard just 2°C below ambient would reduce the uncomfortable time period to 5%. Large green spaces such as parks have been shown to have a cooler temperature than surrounding urban areas, but it is unclear whether a similar effect can be achieved by a courtyard of only 12m^2. The effects of vegetation and water bodies were not modelled, but correct solar design was identified as having a significant effect on the courtyard microclimatic performance. A south facing courtyard orientation was found to be more favourable than a north facing courtyard. The results for the courtyard aspect ratio, however, were less conclusive. A deep and narrow courtyard was found to be favourable in some conditions, while in others the wide and shallow courtyard performed better. An absolute 'optimum' cannot be chosen and the orientation needs to be subjectively decided depending on usage patterns by the occupants of the house.

The configuration of a courtyard house is well suited to wind driven, cross ventilation. The model was modified to include external vents at the back of the house. In a hypothetical, exposed to the wind scenario, comfort levels were improved 12% relative to the base case by orientating the house at either 230° or 260°(East of North). However, in urban Karachi, the wind is likely to be obstructed by other buildings. Including this in the investigation yielded an over all drop in comfort levels by 0.5%, due to increased solar penetration into the envelope. This effect can be counteracted by covering openings with *Jaali* (carved lattice screens). However, care needs to be taken to ensure that the porosity of the screen is large enough for adequate air flow. For an appropriately sized jaali, an improvement in comfort of about 11% can be achieved.

A simple measure that is particularly applicable to tropical and low income settings is the improvement of roof albedo (i.e. reflectance). By painting the roof white, an improvement in comfort of 6% is predicted by the model.

This investigation shows that each individual element has quite a signifiant effect on indoor thermal conditions, but only when it is properly optimised. Poor design configurations can in some cases have adverse effects, as in the case of too fine a lattice screen over a ventilation opening. Figure 8.1 gives us useful optimistic and realistic estimates of the improvements that each element can create. It is clear that no individual element can achieve the full 27% improvement in comfort required for the indoor conditions to always be below the TM52. However, it is possible that if applied together, 100% comfort can be achieved.

8.2 Limitations and Possible Future Work

In this investigation, computer simulations was chosen as the method for understanding the effects of the passive cooling techniques considered. The simulation inputs were based on previously conducted field studies of low income housing in Karachi, and the model was validated against thermal field studies. This gave a reasonable model against which the passive cooling strategies could compared; however the model is unlikely to be completely accurate. The research could be extended and validated by conducting first hand field studies in Karachi, which would lead to a more in depth understanding of the behaviour of the residents and their interactions with the environment.

Material properties such as insulation and thermal mass were excluded from the scope of this investigation, and each investigation was conducted for a fixed set of materials. However, the optimisation of the courtyard and ventilation strategy is dependent on the materials, particularly the distribution of the thermal mass. Further modelling is needed to optimise these elements with regard to thermal mass.

The modelling of the actual microclimate within the courtyard was also excluded from the scope of this investigation. Instead a workaround was used to measure the effect of the microclimate on the house. Long term field measurements are one way of determining whether a microclimate 2°C below ambient is possible. Another way in which the process can be sped up is further modelling in softwares such as ENVI-MET, which is specifically capable of modelling the surface-air-plant interactions at fine scales.

While investigating ventilation, only the effect of orientation was considered. Other variables such as the size of the openings, the number of openings and their positioning also affect wind driven ventilation. Further investigations could focus on optimising for these variables.

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Appendix A: Wind Pressure Coefficients

Exposure	**Location**				**Angle of Attack (Degrees)**					
Type	**Used**	0	22.5	45	67.5	90	112.5	135	157.5	180
Exposed	Ventilation openings	0.700	0.606	0.350	-0.041	-0.500	-0.465	-0.400	-0.276	-0.200
Semi Exposed	Ventilation openings	0.400	0.300	0.100	-0.100	-0.300	-0.347	-0.350	-0.265	-0.200
Sheltered	Courtyard openings	0.200	0.156	0.050	-0.091	-0.250	-0.285	-0.300	-0.274	-0.250

Appendix B: Risk Assessment Retrospective

Due to the computational nature of this project, the risks identified were limited to the health implications of working at computers for long time periods. These were mitigated by adjusting the chair and screen height for maximum ergonomic comfort. Regular breaks were also taken to counteract eye strain.