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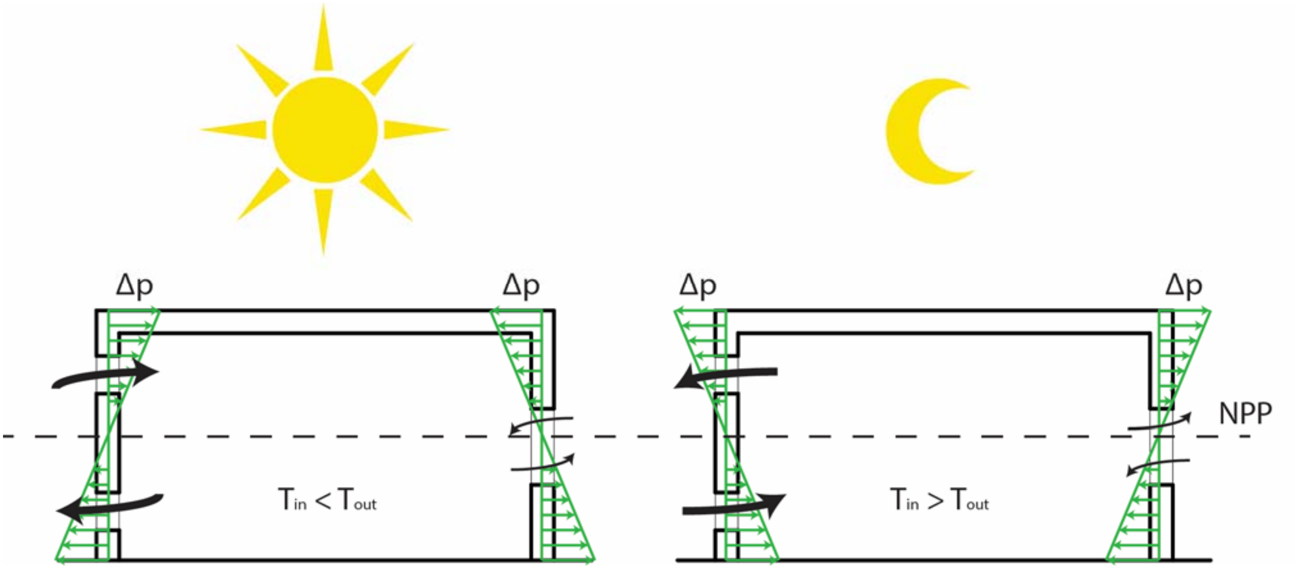

Enhancing the building performance of low-cost schools in Pakistan

A study of natural ventilation, thermal comfort and moisture safety

Master's thesis in Structural Engineering and Building Technology

ERIKA ALATALO

Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2016, BOMX02-16-18

MASTER'S THESIS BOMX02-16-18

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Cover:

Illustration of neutral pressure plane and resulting air flows during day and night in a passively cooled building in a hot-dry climate

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Abstract

This thesis studies how the building performance of low-cost charity schools in Pakistan could be improved. More specifically, the thesis studies the thermal comfort, natural ventilation and moisture safety of existing schools and aims to find ways to improve these with the help of passive techniques. Developing passive techniques is important because they mitigate climate change. In developing countries like Pakistan, passive techniques are also more easily accessible, because of the unreliable electricity supply and the cost of mechanical devices.

The first step of the investigation was a field study to Pakistan where existing schools of The Citizens Foundation, a local educational non-profit organization, were visited in different parts of the country. During this field study traditional passive cooling techniques in Pakistan and Iran were also studied as a source of inspiration. The existing schools have then been studied with the help of a computational model developed in MATLAB and Simulink that calculates the free-running temperature and air change rate simultaneously. Alternative designs have then been tested with the same model to see which changes would be most beneficial. The focus has been on different natural ventilation strategies, but other factors such as building materials have also been studied.

Thermal inertia, night ventilation, complementing regular windows with alternative openings, and reducing absorption of solar radiation with lighter surface colors have been identified as the most efficient passive design strategies. Pakistan has a variety of climates, and although the main problem in terms of thermal comfort is the heat of summer, winters in the north can be uncomfortably cold and this has also been identified as a problem during the thesis. These findings can be used as a basis when designing new schools.

During the field study, mould growth and other moisture problems were also identified with the existing schools. The cause of these problems have been studied with the commercial software WUFI, but no definitive results have been obtained, and the problem would require further investigation.

Keywords: natural ventilation, passive thermal comfort, passive design, passive cooling, free-running temperature, moisture safety, school buildings, Pakistan, Iran, windcatchers

Contents

Preface

This master's thesis has been done in collaboration with The Citizens Foundation (TCF), a Pakistani educational non-profit organization. I would like to thank TCF and the numerous TCF employees (engineers, teachers etc.) that I met during my visit for organizing my school visits and for providing me with information about the schools that allowed me to do this work. I would especially like to thank Atif Ashraf, TCF's senior architect.

Angela Sasic Kalagasidis has been the supervisor of this work and I would like to thank her for her guidance during the process.

A crucial part of this work was a field study made at the start of the thesis process. I would like to thank Sven Steens forsknings- och stipendiefond and Byggnadstekniska Föreningen I Göteborg (BTF) for the scholarships that made it possible for me to travel to Pakistan and Iran. I would also like to thank Dr. Khurrum Shaukat for helping organize my trip to Pakistan. Lastly, I would like to thank Hyderabad Development Authority for the information given about windcatchers in Hyderabad.

This work is the first part of a longer project that consists of two master's theses. The second part is done by the same author at the Department of Architecture during the spring of 2016.

Göteborg February 2016
Erika Alatalo

1 Introduction

1.1 Background

Climate change and the need to reduce carbon emissions is forcing buildings to become more energy efficient and sustainable all over the world. While in many developed countries the pressure is increasingly on renovating old buildings, in developing countries new buildings are being built at a very fast pace. Often these new buildings are designed like in Western countries, despite large differences in climate. This results either in large energy requirements for ventilation and cooling, or in uncomfortable and unhealthy indoor environments when mechanical ventilation and cooling cannot be afforded. Because of these challenges, it is important to develop and use passive techniques that promote building in a way that fits the local climate.

This master's thesis studies ways to improve the thermal comfort and ventilation of school buildings in Pakistan using passive techniques. The thesis is done in collaboration with The Citizens Foundation (commonly abbreviated TCF), a Pakistani non-profit organization that builds and runs primary and secondary schools in Pakistan. Most of Pakistan lies in the subtropical climate zone and the main challenge in terms of thermal comfort is to provide cooling and air flow. Because the thesis focuses on schools where many people use a small classroom at the same time, it is also important that adequate fresh air is provided for health reasons even when air flow is not wanted for thermal comfort reasons.

In Pakistan there is an extra reason to promote passive techniques, because the country has an insufficient electricity generation capacity and suffers from daily power cuts. When buildings are designed to rely on mechanical cooling, the thermal comfort of the users suffers greatly during these power cuts. Moreover, if less electricity was used for mechanical cooling, the electricity that is available could be used for other purposes that are more important for growing the economy, such as computers.

This thesis studies traditional passive cooling and natural ventilation techniques as a source of inspiration. People have been living in Pakistan and other similar climates for thousands of years, and over time people have learned how to use natural energy sources such and winds and the sun to create a comfortable indoor environment. These traditional techniques are not perfect however, and it is important to assess them critically before using them in modern buildings. With the help of modern knowledge of building physics and calculation tools, the traditional techniques can be improved and new techniques can be developed to complement them. Many people also view traditional techniques as inferior and backward when compared to modern techniques, and by assessing and improving the performance of traditional techniques, their status can be raised.

The Citizens Foundation is currently building less schools than what they used to do, and one of the reasons for this is the high maintenance cost of the existing schools. However, there is definitely a need to build more schools in Pakistan, and because of this it is important to bring down the maintenance costs. Some existing schools have moisture problems that are causing extra maintenance costs, and for this reason this thesis will go beyond the thermal comfort aspect to look also at moisture safety.

The results of this thesis will form the basis for a second master's thesis that is to be done at the Department of Architecture in the spring of 2016. This thesis will be done by the same author, and it will investigate how the overall sustainability of the schools could be further improved, looking at both technical and social aspects. The architectural thesis will then combine the analysis from both theses into one revised school design.

1.2 Objective

The aim of this thesis is to improve the performance of low-cost schools in Pakistan in terms of passive thermal comfort, natural ventilation and moisture safety. The aim is first to investigate the performance of the existing schools and then to suggest solutions to the existing problems. More specifically the aim is to improve the schools of The Citizens Foundation but the results can be used as a reference for other schools in Pakistan as well. The goal is also to promote passive design as a suitable and sustainable alternative to mechanical devices.

1.3 Method

This thesis started with a two-month field study to Pakistan, Iran and Bangladesh in January-February 2015. Parts of the field study are more relevant for the architectural thesis, and for this thesis mainly the parts in Pakistan and Iran are relevant. The field study had two main goals. The first goal was to visit existing schools of The Citizens Foundation in order to identify their characteristics, strengths and weaknesses. The second was to study traditional passive cooling and natural ventilation techniques in Pakistan and Iran, in particular windcatchers. During the field study some temperature measurements were made and people were interviewed. The field studies are complemented by literature studies.

The field study and literature studies form the basis for analyzing the existing schools and potential improvements. A building energy and air flow simulation tool has been developed in MATLAB/Simulink and used to determine how the typical existing schools perform throughout the year in terms of thermal comfort and natural ventilation. The performance has then been optimized by varying the school designs and the operation and comparing the performance of these alternatives with the existing schools.

During the study trip it was also identified that schools in and around Lahore in northern Pakistan have severe moisture problems that are causing large maintenance costs. The cause of this problem is studied by calculating moisture transport in typical construction details using the commercial software WUFI.

1.4 Limitations

This thesis focuses on improving passive thermal comfort, natural ventilation and moisture safety. The aim is not to develop a complete design but instead to identify the most appropriate design strategies that can then be used as a basis when designing schools. The effects of both the design of the school and the operation are studied. Schools in four cities of Pakistan with different climates are studied.

2 Theory

In order to design passive thermal comfort and natural ventilation, it is important to first understand the physics that determines the indoor climate. The local climate also needs to be understood in order to identify what is needed to provide thermal comfort (eg. heating, cooling, air flow and humidity) and what energy sources (eg. wind, sun and temperature differences) are available to create air flow and heat transfer. Understanding the climate and the local building techniques is also important for preventing moisture problems.

2.1 Climate and comfort

The Köppen climate classification system divides the world into five main climatic zones with 29 subtypes (Peel et al. 2007). In the same way the definition of thermal comfort varies around the world depending on climatic and cultural factors. In order to build optimally performing buildings in such a varying world, it is crucial to first understand the local context and climate. Based on the climate and the comfort requirements, passive strategies can be developed to achieve the comfort.

2.1.1 Climate of Pakistan

Pakistan is a large country located between the Karakoram mountain range to the north and the Indian Ocean to the south, and the country has a variety of climates. Most of Pakistan lies in the subtropical climate zone and the main challenge in terms of thermal comfort is the heat. Four cities are studied in this thesis, Karachi, Lahore, Islamabad and Mansehra, and these cities are shown on the map in Figure 2.1 along with the climatic zones of Pakistan according to the Köppen classification. Schools in and around these cities were visited during the field study.

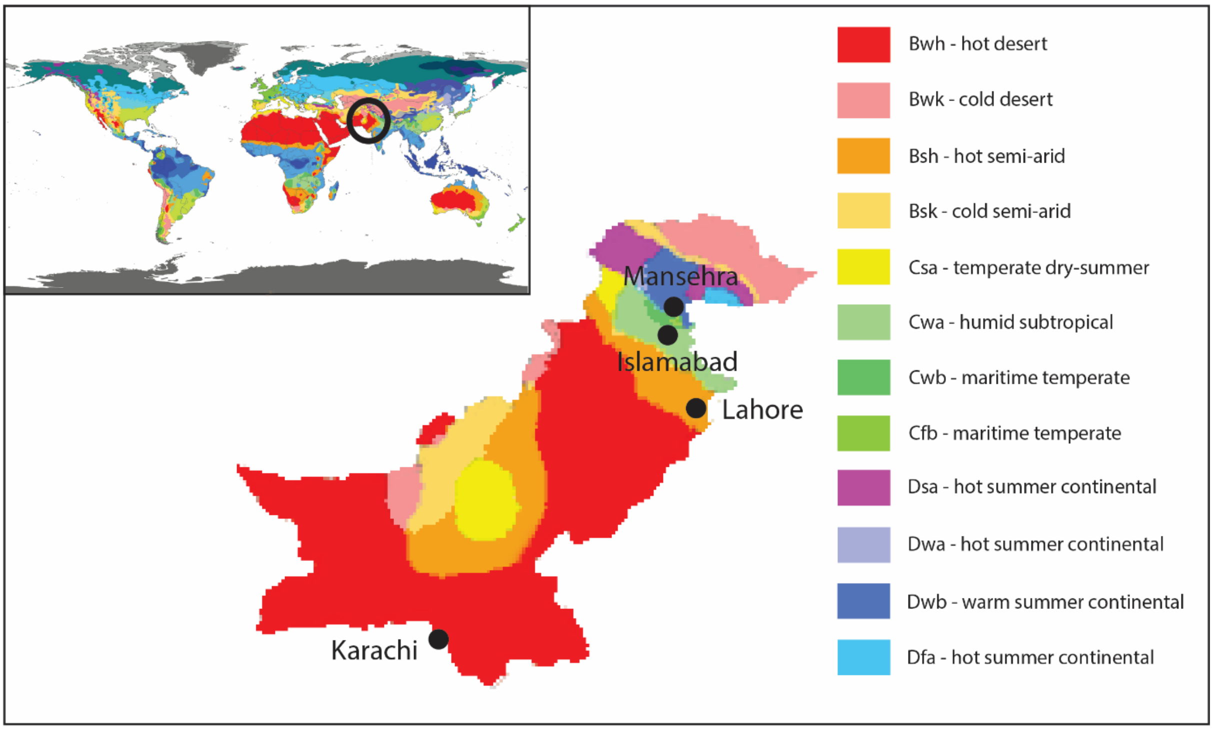


Figure 2.1: Map of Pakistan showing its climatic zones according to Köppen classification and the location of the four cities studied. Figure modified from figure by Peel et al. (2007).

Hourly climate data for the four cities has been obtained from the database of Meteonorm. Climate data for Mansehra was unavailable and data for nearby Balakot is used instead. Figure 2.2 below shows the average monthly temperatures for the four cities. Karachi in the south is hot throughout the year with slightly milder temperatures during the winter months. In the north temperatures vary more throughout the year and the summers are uncomfortably hot while the winters are uncomfortably cold, especially in the mountains where Mansehra is located. The hottest temperatures occur in June just before the rainy season starts.

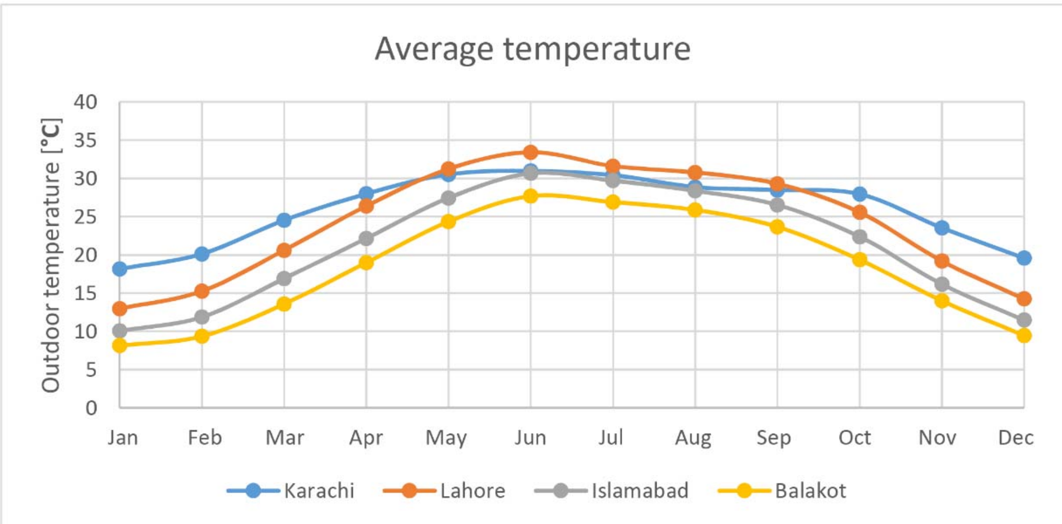


Figure 2.2: Average monthly air temperatures in the four cities studied.

Most of Pakistan has an arid or semi-arid climate with a short rainy season, except for the very north which receives more rainfall throughout the year. In the mountains in the very north there is also snowfall. Most of the precipitation falls during the rainy season which is from June to September. Figure 2.3 below shows the total annual precipitation in the four cities studied, and it can be seen that the amount of rainfall increases further north.

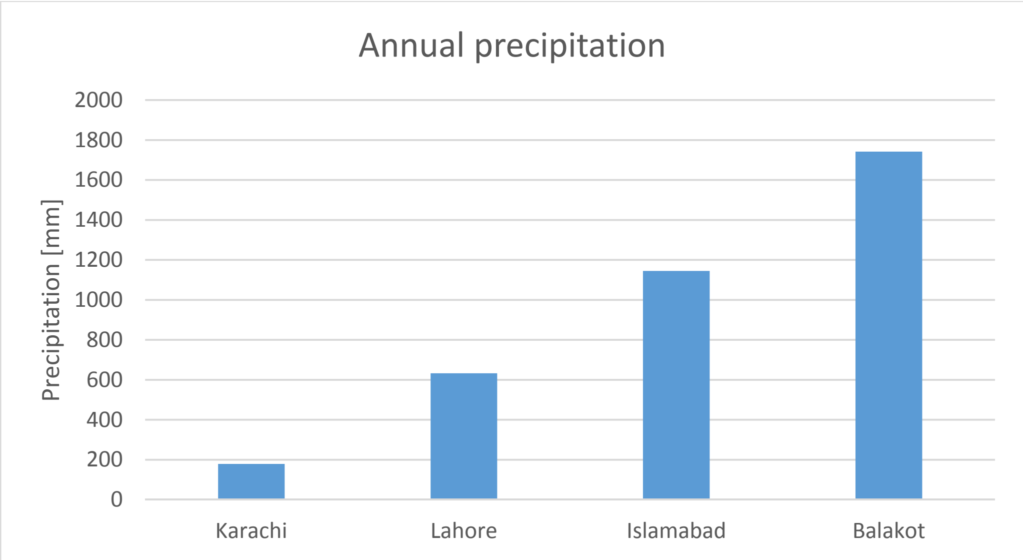


Figure 2.3: Total annual precipitation in the four cities studied.

Figure 2.5 shows that in the north the relative humidity is high during the rainy season and during the colder winter months, but the humidity drops during the hotter, drier months. In Karachi the relative humidity is more constant and it is fairly high because of winds from the sea, but the humidity drops somewhat during the cooler months.

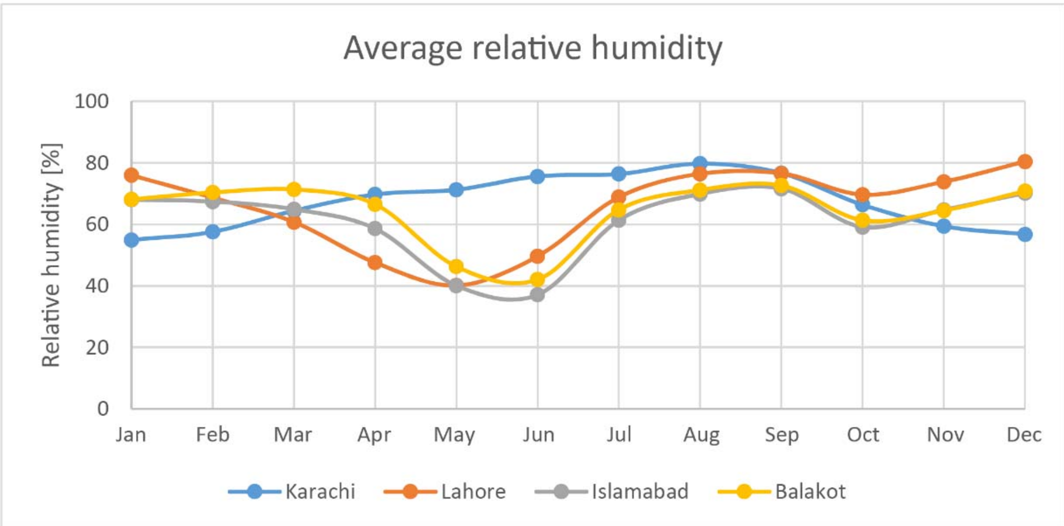


Figure 2.4: Average monthly relative humidity in the four cities studied.

Figure 2.5 below shows that Karachi has a steady and strong wind, but in the north wind speeds are lower and vary more. Karachi is located by the Indian Ocean and most of the wind comes from the sea.

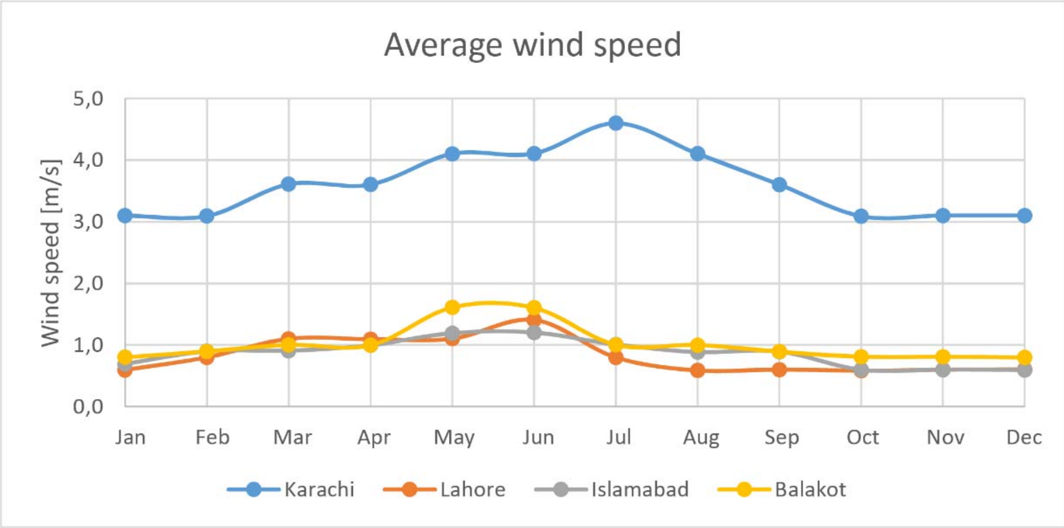


Figure 2.5: Average monthly wind speed in the four cities studied.

2.1.2 Thermal comfort

The human body is constantly generating heat that needs to be dissipated into the external environment in order to keep a stable body temperature. When the external temperature is high, the rate of heat loss from the body decreases and this causes discomfort. However, people can endure a variety of temperatures and climatic conditions and some variation is also good. People also adapt to changes in indoor climate, and in free-running buildings that rely on passive techniques more variation is allowed than in mechanically controlled buildings (Gething & Puckett 2013).

2.1.2.1 Thermal comfort and air flow requirements

Thermal comfort is affected by the air temperature, surrounding surface temperatures, the relative humidity of the air and the amount of air flow. Air temperature, surface temperatures and air flow together give the operative temperature. In hot climates thermal comfort is improved by creating areas where the operative temperature is kept as low as possible so that the body can keep dissipating its heat. This means that the air temperature should be kept as low as possible, but also that air flow should be provided and that solar radiation should be blocked.

Air flow improves thermal comfort in hot climates because it increases the rate of heat loss through convection, and because of this higher temperatures can be tolerated if there is air flow. People lose heat through evaporation of sweat and air flow makes the sweat evaporate faster. Air flow is even more important if it is also humid. When the relative humidity of the air is high, the air next to the skin soon becomes saturated with water vapour meaning no more sweat can evaporate. Air flow ensures that air around the skin keeps changing and thus prevents it from saturating. Air flow above 0.2 m/s provides a cooling effect corresponding to approximately 1°C per 0.275 m/s increase in air flow, and air flows of up to 2 m/s can be tolerated in hot climates (Gething & Puckett 2013). However, in very dry climates, air flow provides less of a cooling effect since evaporation of sweat is not difficult even without air flow.

Ole Fanger, an expert in the field of thermal comfort, has developed a model that describes the level of thermal comfort with the help of PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied). For a certain operative temperature, PMV gives an indication of whether people feel the indoor conditions are too hot or cold, and PPD predicts how many people will de dissatisfied with the thermal comfort. In a hot climate in an area where there are little air conditioned buildings, such as Pakistan, the upper temperature limit would be 29°C for a PPD of 10% and 30.5°C for a PPD of 20%. This is based on a seated person with light clothing, air flow of 0.3 m/s and a relative humidity of 70%. (Fanger & Toftum 2002)

Since this thesis deals with school buildings, it is important that fresh air is provided even when air flow is not desired for thermal comfort reasons. If the supply of fresh air is in inadequate, the level of carbon dioxide in the classroom rises quickly and this can cause tiredness. A seated child produces on average 9 to 12 liters of CO_2 in an hour while a seated adult produces approximately 12-15 l/hour (Abel & Elmroth, 2006). The level of other chemicals and particles also increases when there is inadequate ventilation and some of these can cause health problems during long term exposure.

2.1.2.2 Passive thermal comfort

Buildings today are increasingly designed to rely on mechanical cooling and ventilation to provide thermal comfort. Mechanical devices require electricity which generates carbon emissions and contributes to climate change. Mechanical devices also require money, making them a luxury that most people in developing countries can’t afford. Unreliable energy supplies in some countries, including Pakistan, make it even harder to rely on mechanical devices. Because of these challenges it is important to promote building technologies that provide thermal comfort and ventilation in passive ways.

The existing schools of The Citizens Foundation rely on cross-ventilation through windows. The classrooms have mechanical ceiling fans but these might not work because of power cuts, and air conditioning devices are too expensive. This means that thermal comfort needs to be achieved using passive methods and the goal of this thesis is to improve the passive thermal comfort as much as possible, not necessarily to reach a certain level below which mechanical devices would be required. However, if it seems like comfort levels can’t be reached through passive means, fans connected to solar panels could be considered as the fans are needed when the sun is out and this means costs can be saved by not having a battery for the solar panel.

2.2 Passive cooling and heat transfer

The built environment changes the surrounding microclimate in many ways. Buildings block and redirect winds, and different materials and shapes absorb, reflect and transfer the heat from the sun and the air in different ways, resulting in warmer or cooler temperatures within cities and inside buildings. This change in microclimate can have either a positive or a negative effect on thermal comfort. The aim of passive cooling is to purposely build in a way that lowers the indoor air and surface temperatures and creates air flow within buildings, thus improving thermal comfort in hot climates. The main principle is to keep heat from entering the building as this is easier to do than removing heat.

In order to understand and to design passive cooling systems, it is first important to understand the basic physics behind them. Passive cooling systems are based on the three basic mechanisms of heat transfer, conduction, convection and radiation:

> *Conduction* is the process of transferring heat energy within and between objects through the vibration of molecules. The rate of conduction depends on the conducting material's thermal conductivity, and on the temperature difference across the material.
>
> *Convection* refers to the transfer of heat due to the flow of a fluid such as air or water. The fluid moves because of pressure differences and carries with it heat from one place to another. The fluid is heated by warmer surfaces and then the fluid in turn heats up colder surfaces. Natural convection can be created either through temperature differences or by wind.
>
> *Radiation* is heat transfer through electromagnetic radiation and all objects constantly radiate heat. When two objects are facing each other, there will be a net radiative transfer of heat from the warmer to the cooler object. The larger the temperature difference between the two objects is, the more heat will be exchanged through radiation. How much heat a particular object emits and absorbs depends on the material's emissivity value.

The design and operation of the building determines how much heat is gained and lost through these three basic mechanisms of heat transfer.

2.2.1 Thermal inertia

A structure with a high thermal heat capacity, also called thermal mass or thermal inertia, can absorb a large amount of heat energy before its temperature rises. Buildings with a high thermal inertia have a thick building envelope made of dense materials such as stone, earth or concrete. The thermal inertia can be quantified with the volumetric heat capacity. The volumetric heat capacity of a building, C [J/kg], is the sum of the volumetric heat capacities of all layers inside a potential insulating layer, and it is given by:

$$C = \sum_{i=1}^{n} \rho_i V_i c_{pi}$$

where

ρ_i is the density of material i [kg/m^3]

V_i is the volume of material i [m^3]

c_{pi} is specific heat capacity of material i [J/kgK]

In hot-dry climates there are usually large diurnal temperature variations with low night temperatures. In this kind of climate buildings with a high thermal inertia can keep the indoor temperature relative stable and close to the average daily outdoor temperature. During the day the heat from the sun and the air heats up the walls and the roof, and since the structure can absorb a lot of heat before raising its temperature, the structure stays cool and heat is not transferred to the indoor air. During the night this absorbed heat is then released as the structure heats the cooler night air.

In order for thermal inertia to be beneficial, the building needs to be efficiently ventilated during the night. If the building is not ventilated properly, the heat inside the structure can start to build up and the indoor temperature can become uncomfortable. The diurnal temperature difference should be at least 5-7°C for thermal inertia and night ventilation to be effective (Gething & Puckett 2013). Figure 2.6 below shows that the diurnal temperature variations in the studied cities in Pakistan are above this limit.

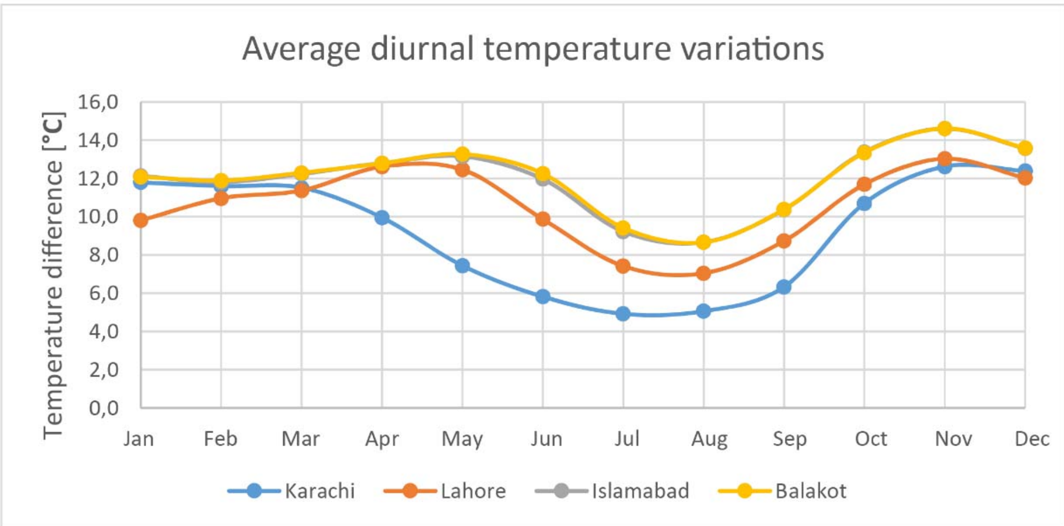


Figure 2.6: Average monthly diurnal temperatures variations in the four cities studied.

2.2.2 Insulation and transmission losses

Insulating materials have a low thermal conductivity and they slow down conduction of heat. Insulating materials generally have low density. When the building envelope has a layer of insulating material, very little heat is transmitted through the building envelope. The insulation value of a layer of a material can be expressed with its resistance value, R_i [m^{2}K/W], calculated as:

$$R_i = \frac{d_i}{\lambda_i}$$

where

d_i is the thickness of material i [m]

λ_i is the thermal conductivity of material i [W/mK]

When a construction such as a wall consists of several layers of different materials, the individual resistance can be added to get the total resistance of the construction:

$$R_{tot} = \sum_i^n R_i$$

In hot climates, the purpose of insulation is to keep heat from the outside from entering the interior. The amount of heat, Q [W], that that passes a construction from outside to inside is given by:

$$Q = A \cdot \frac{T_{out} - T_{in}}{R_{tot}}$$

where

A is the indoor surface area of the construction [m^2]

T_{in} is the indoor air temperature [ºC]

T_{out} is the outdoor air temperature [ºC]

R_{tot} is the total thermal resistance of the construction [m^{2}K/W]

When the indoor temperature is lower than the outdoor temperature, a low value of Q prevents heat from entering the building.

Insulating buildings against the heat is not common in hot-arid climates because thermal mass is seen as a more effective way of achieving thermal comfort, as long as sufficient night ventilation is provided. The downside of insulation is that it prevents heat from leaving the building during the night. In some hot-arid areas traditional roofs are made of insulating materials, because the roof receives the most solar heat radiation and insulating the roof makes the largest difference.

2.2.3 Convective heat transfer

Exterior surfaces are often hotter than the outdoor air because these surfaces absorb solar heat radiation. Exterior air movement can cool down buildings by removing this extra heat from the surfaces. The amount of heat transferred depends on the convective heat transfer coefficient, α_c [W/m^{2}K], which depends on wind speed and is given by:

windward side: $\alpha_c = 5 + 4.5u - 0.14u^2$

leeward side: $\alpha_c = 5 + 1.5u$

where u [m^2/s] is the wind speed. (Hagentoft 2001)

The heat lost to the outdoor air, Q [W], is then given by

$$Q = A \cdot \alpha_c \cdot (T_s - T_{out})$$

where

A is the area of the surface [m^2]

α_c is the convective heat transfer coefficient [W/m^{2}K]

T_s is the temperature of the surface [ºC]

T_{out} is the outdoor air temperature [ºC]

2.2.4 Long-wave heat radiation

When an object receives radiation from another object, a part of this radiation is absorbed, a part reflected and a part transmitted. For most building materials, except for glass, the transmitted part is zero. The object is also emitting radiation itself.

The amount of radiation that an object absorbs and the amount it emits are given by its absorptivity and emissivity values respectively. For the same wave length of radiation, the emissivity and absorptivity values are the same, and the radiation that is not absorbed is reflected. The energy, E [W/m^2], an object emits through radiation is given by:

$$E = \epsilon \sigma T^4$$

where

ϵ is the emissivity of the object [-]

σ is the Stefan-Boltzmann constant, 5.67 × 10^8 W/m^{2}K^4

T is the temperature of the object [K]

When two surfaces are facing one another, both of them will emit heat radiation to the other, but the one with the lower temperature will receive a net gain of heat radiation, and the one with a higher temperature will have a net loss.

How much radiation is exchanged between the two surfaces depends on the view factor which depends on the angle between the surfaces and on the size of the surfaces. The view factor varies between 0 and 1 and is the highest for parallel surfaces. The view factor and the properties of the surfaces determine the radiant heat transfer coefficient, α_r, which for two surfaces whose temperatures are of the same order of magnitude is given by:

$$\alpha_r = \frac{4\sigma\left(\frac{T_1+T_2}{2}\right)^3}{\frac{1-\varepsilon_1}{\varepsilon_1}+\frac{1}{F_{12}}+\frac{1-\varepsilon_2}{\varepsilon_2}.\frac{A_1}{A_2}}$$

where

T_1, T_2 are the temperatures of surfaces 1 and 2 [K]

A_1, A_2 are the areas of surfaces 1 and 2 [m^2]

$\varepsilon_1, \varepsilon_2$ are the emissivities of surfaces 1 and 2 [-]

F_{12} is the view factor between surface 1 and 2 [-]

σ is the Stefan-Boltzmann constant, 5.67 × 10^8 W/m^{2}K^4

The heat flow, Q_{12} [W], from surface 1 to surface 2 is then given by:

$$Q_{12} = \alpha_r \cdot A_1(T_1 - T_2)$$

The sky is usually clear in hot-dry climates, and while this means solar radiation (discussed in Section 2.2.5) needs to be avoided during the day, at night the clear sky is beneficial as a heat sink. The clear night sky has a very low temperature when compared with the temperature of the earth or buildings. The sky temperature is given as:

$T_{sky} = 1.2 \cdot T_{out} - 14$ for horizontal surfaces, clear sky

$T_{sky} = 1.1 \cdot T_{out} - 5$ for vertical surfaces, clear sky

$T_{sky} = T_{out}$ for cloudy sky

where

T_{out} is the outdoor air temperature [K]

T_{sky} is the sky temperature [K]

(Hagentoft 2001).

This temperature difference between the earth and the sky means that a lot of heat radiates from the earth to the night sky. Similarly, roofs of buildings radiate heat to the nights sky which cools down the roofs and consequently the whole building. The amount of heat, Q [W], lost by a horizontal roof surface due to long-wave radiation is given by:

$$Q = 4\varepsilon A\sigma \cdot \left(\frac{T_{out}+T_{sky}}{2}\right)^3 \cdot \left(T_{out} - T_{sky}\right)$$

where

ϵ is the emissivity of the roof surface [-]

A is the area of the roof [m^2]

σ is the Stefan-Boltzmann constant, 5.67 × 10^8 W/m^{2}K^4

T_{out} is the outdoor air temperature [K]

T_{sky} is the sky temperature [K]

Wall surfaces are also cooled down due to long-wave radiation exchange with the sky, but the effect is less significant than for roofs because the view factor is lower.

2.2.5 Solar radiation

Buildings receive the majority of heat radiation from the sun. As stated before, the sky is usually clear in hot-dry climates, which means that a large amount of solar heat radiation is received during the day. This radiation is uncomfortable for people, because it heats them directly through radiation and indirectly through heating the air and the built environment. The amount of solar energy, Q [W], that a building surface absorbs is given by

$$Q = A \cdot I_{sol} \cdot \cos(\theta) \cdot \alpha_{sol}$$

where

A is the area of the surface [m^2]

I_{sol} is the intensity of solar radiation [W/m^2]

θ is the angle between the incident solar radiation and the normal of the surface [-]

α_{sol} is the absorptivity for solar radiation of the surface material [-]

For radiation at regular temperatures, most nonmetallic surfaces have high absorptivity values (approximately 0.8-0.9 for most building materials) and only a small amount of the radiation is reflected. However, for solar heat radiation lighter colored surfaces have a much lower absorptivity value. A surface with white paint can have an absorptivity for solar radiation, α_{sol}, as low as 0.15 while for a black surface it is close to 1. Thus a white external surface reflects more solar heat radiation and keeps buildings cooler than a darker surface. This effect is especially noticeable on the roof and other horizontal surfaces which receive the most solar radiation.

When solar radiation hits a window, only some of the solar radiation will be transmitted through the glass into the building. The solar energy, Q [W], received through a window is given by:

$$Q = A \cdot \left(I_{sol} \cdot \tau(\theta) + I_{dif} \cdot \tau_{dif}\right)$$

where

A is the area of the window [m^2]

I_{sol} is the intensity of direct solar radiation [W/m^2]

$\tau(\theta)$ is the transmittance value of the window for direct radiation, depending on the incident angle of solar radiation, θ [-]

I_{dif} is the intensity of diffuse solar radiation [W/m^2]

τ_{dif} is the transmittance value of the window for diffuse solar radiation [-]

A relatively simple way to reduce solar radiation is to provide shading. Shading windows and other openings is especially important because otherwise solar radiation can enter buildings directly through these openings. Generally southern windows are easier to shade than eastern and western windows because of the angle of the incoming sun, while northern windows mainly receive diffuse light which means they need less shading.

Shading walls and the roof is also beneficial because it keeps the structure cooler. Shaded outdoor spaces should also be provided because these areas can be more comfortable than indoor areas due to higher air flows. Shading areas around buildings also means that the air that enters the building through natural ventilation is kept cooler. Shaded areas still receive some reflected solar radiation from other surfaces as well as diffuse radiation from the sky.

2.2.6 Other passive cooling techniques

Fountains are a common element in traditional architecture in hot-dry climates because they have a cooling effect. When water evaporates, energy is required to release the water molecules from the liquid water. This energy comes from the water itself and thus the temperature of the water drops as the water evaporates. This cooled water then in turn cools the air around it creating air movement and convection. Evaporative cooling is most effective if water is in direct contact with the building, for example in the form of a roof pond. However, these kind of systems need to be carefully designed and maintained so that leakages and water damages can be avoided.

Plants also provide evaporative cooling through the natural process of evapotranspiration. Plants that are in direct contact with the building, for example green roofs, are better than plants which are only in contact with the building through the air that the plants cool. Plants also provide shading and reduce reflections of solar radiation.

Heat is also transferred through ventilation and this is explained in Section 2.3.4.

2.3 Natural ventilation

Natural ventilation essentially means air movement created by naturally occurring pressure differences. This pressure difference can be created either by wind or by temperature differences. Air flows created by temperature differences are weaker and they are rarely fast enough to provide comfort through increased air flow, but they can still be effective for providing fresh and cool air.

2.3.1 Wind

When wind hits a building, it creates a positive pressure on the windward side and a negative pressure on the leeward side of the building. This forces air into the building from the windward side and out from the leeward side, creating cross-ventilation through the building. Figure 2.7 shows how the pressure profile created by wind varies on different sides of the building.

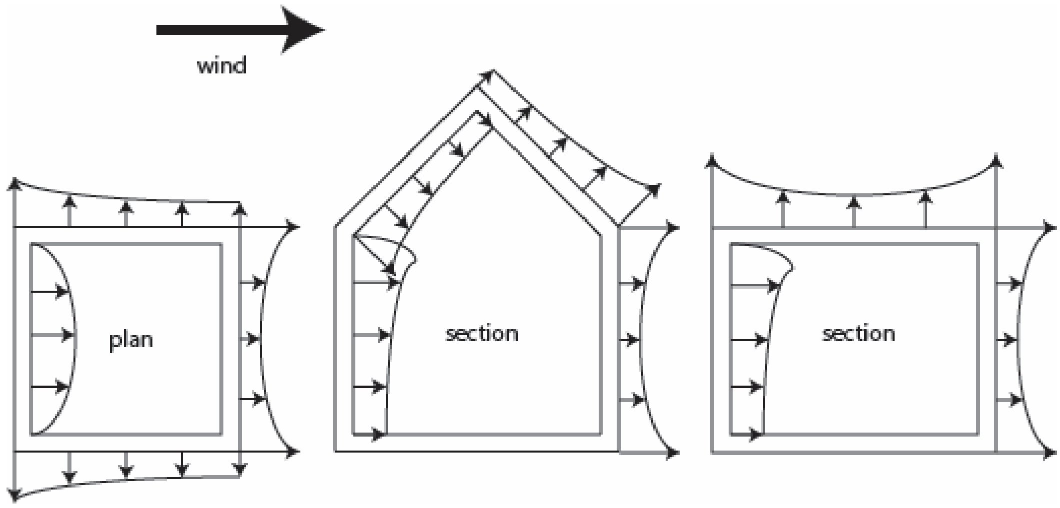


Figure 2.7: Illustration of pressure differences created by wind on different sides of the building in plan and section.

If a particular location has a dominant wind direction, orientating the building in such a way that the long side is facing the wind means there will be more cross-ventilation through the building. Openings should be provided on both the windward and leeward sides for effective cross-ventilation.

The pressure, P_w [Pa], created by wind at the surface of the building is given by

$$P_w = 0.5 \cdot \rho_a \cdot C_p \cdot v_z^2$$

where

ρ_a is the density of air [kg/m^3]

C_p is the wind pressure coefficient [-]

v_z is the velocity of the wind at height z [m/s]

The value of the wind pressure coefficient C_p depends on the direction of the wind. On the leeward side the value of C_p is negative and on the windward side it is positive.

The wind velocity depends on the height of the opening. If v_m [m/s] is the wind speed at a weather station at a height 10 meters above ground, then the wind speed at height z, v_z [m/s], is given by

$$v_z = v_m \cdot k \cdot z^a$$

where *k* and *a* are constants that depend on the terrain.

The wind induced pressure difference, ΔP_w [Pa], across the building envelope is then given by

$$\Delta P_w = 0.5 \cdot \rho_a \cdot (C_p - C_{pi}) \cdot v_z^2$$

where C_{pi} is the internal pressure coefficient. The value of the internal pressure coefficient depends on the relative size of openings facing each wind direction. If the openings are evenly distributed, the internal pressure coefficient is approximately -0.3. The value is negative because most surfaces have a negative wind pressure, as can be seen from Figure 2.7.

2.3.2 Stack effect

Air flow can also be created by temperature differences, more specifically due to the stack effect. When air heats up, the air expands and becomes lighter, causing warm air to rise and similarly cool air to fall. This means a vertical pressure gradient exists, with warm air creating an area of lower pressure and the cooler air creating an area of higher pressure. The pressure gradient is illustrated in Figure 2.8.

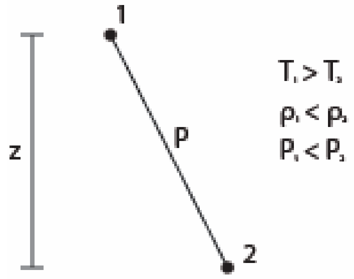


Figure 2.8: Vertical pressure gradient created by temperature differences.

At lower temperatures, the pressure changes more rapidly with temperature, which means that the gradient of the density is higher at lower temperatures. This means that when there is a difference in temperature between outdoor and indoor air, the pressure gradients outdoors and indoors will be different. This principle can be used to ventilate buildings in the absence of wind when there is a temperature difference between outdoor and indoor air. At the height of the neutral pressure plane (NPP), the indoor and outdoor pressure will be the same. The resulting pressure differences are illustrated in Figure 2.9 below.

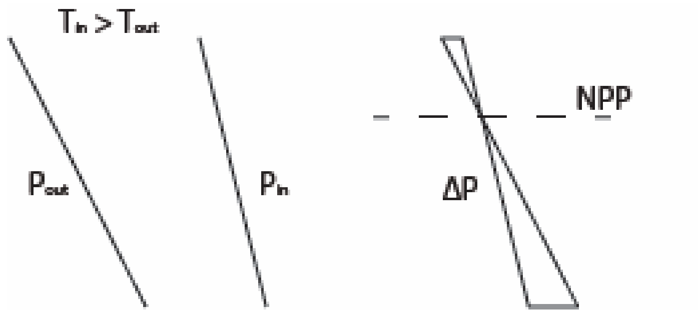


Figure 2.9: Illustration of indoor and outdoor pressure gradients and the resulting pressure difference with the neutral pressure plane.

The further an opening is located from the neutral pressure plane, the higher the pressure difference across the opening will be and thus the more air exchange there will be between the indoor and outdoor air. Providing both low and high openings means that buildings can be ventilated taking advantage of the pressure difference between the outdoor and indoor air. The size and location of openings determines the location of the neutral pressure plane, where no air exchange happens between indoor and outdoor air. If the indoor temperature is lower than the outdoor temperature, the heavier indoor air will exit the building through openings below the neutral pressure plane and outdoor air will enter through the openings above the neutral pressure plane. If the temperature indoors is higher than outdoors, the reverse is true. Figure 2.10 illustrates the air flow through different openings during the day and the night in hot-dry climates, where the outdoor temperature typically varies more than the indoor temperature.

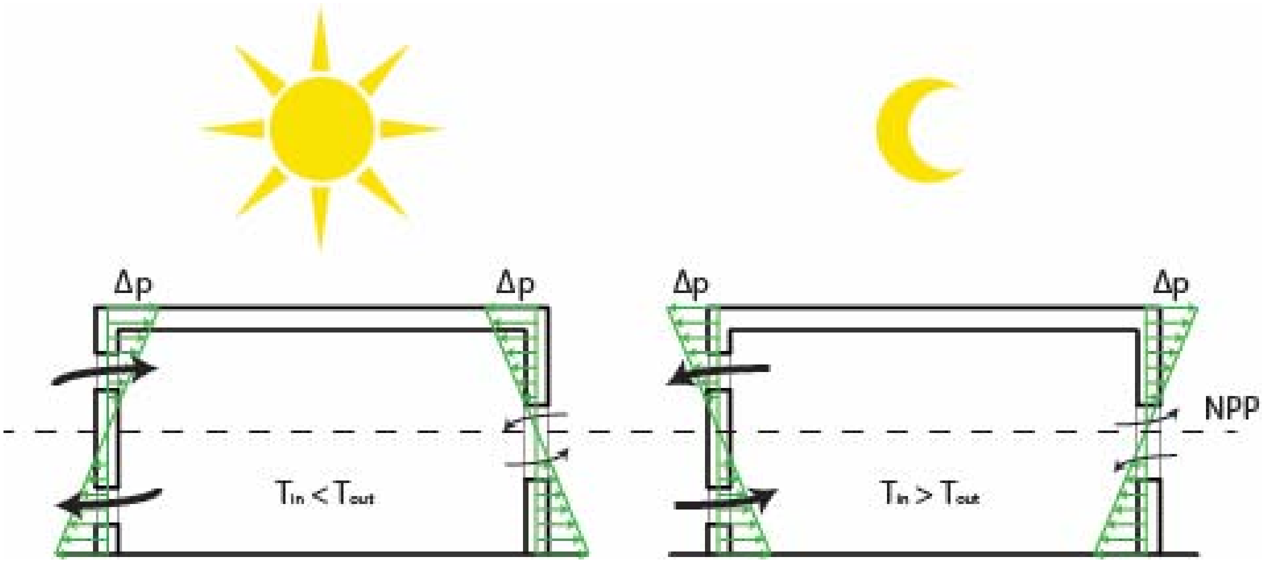


Figure 2.10: Neutral pressure plane and the direction of air flow.

In hot climates the goal is to keep the indoor temperature lower than the outdoor temperature during the day. This means air will exit below the neutral pressure plane and enter above it. The openings shouldn't be too low because the coolest air should be kept inside the building. However, if the openings are too close to each other in height, they will also be close to the neutral pressure plane and there will be less air exchange between the outdoor and indoor air. Having a high ceiling is beneficial because of this and also because this way the hottest indoor air will be above the height of where people are. If the indoor air gets hotter than the outdoor air, for example if the opening is heated by the sun, it can reverse the direction of air flow. During the night the air flow is also reversed when outdoor temperatures drop.

From the general gas law, an expression for the pressure difference, ΔP_s [Pa], at a height z below the neutral pressure is found to be

$$\Delta P_s = \rho_0 \cdot g \cdot T_0 \cdot z \cdot \left(\frac{1}{T_{out}} - \frac{1}{T_{in}}\right)$$

where

ρ_0 is the density of air at 0 ºC, 1.293 kg/m^3

g is the acceleration due to gravity, 9.81 m/s^2

T_0 absolute temperature in Kelvin at 0 ºC, 273 K

T_{out} is the outdoor air temperature [K]

T_{in} is the indoor air temperature [K]

The location of the neutral pressure plane can be calculated with the help of mass balance, since the net flow of air into a building should equal the net flow of air out of the building.

2.3.3 Air change rate

The air change rate, n [1/h], is a measure of how often the air inside a building is replaced with fresh air. The air change rate depends on the size of the openings and the pressure difference across the openings. Combining wind and stack effect gives the total pressure difference over an opening, as illustrated in Figure 2.11. Once the total air flow in and out of the building is known, the air change rate can be calculated.

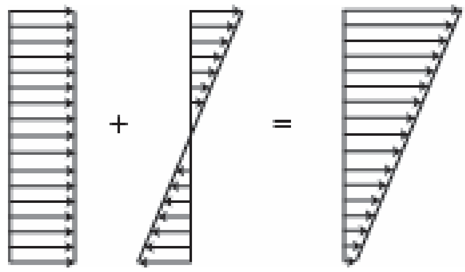


Figure 2.11: Wind and stack effect together give the total pressure difference across an opening.

Naturally created air flows constantly fluctuate and there are many types of air flows which makes them difficult to quantify (Etheridge 2012). The air flow rate, R_a [m^3/s], through a defined opening such as a window can be estimated by:

$$R_a = C_d \cdot A \sqrt{\frac{2\Delta P}{\rho_a}}$$

where

C_d is the discharge coefficient of the opening [-]

A is the area of the opening [m^2]

ΔP is the pressure difference across the opening, $\Delta P_w + \Delta P_s$ [Pa]

ρ_a is the density of air [kg/m^3]

The value of the discharge coefficient C_d depends on the size and shape of the opening as well as the flow rate and it can be difficult to estimate without complex computer models. A value of 0.62 can be used for windows (Swami & Chandra 1987).

When the air flow rate is known for all openings, the total flow in and out can be calculated. Once the total flow is known, the air change rate can then be calculated by:

$$n = \frac{3600 \cdot R_a}{V}$$

where V [m^3] is the volume of the room or building.

2.3.4 Heat transfer through ventilation

Heat is also transferred between outdoor and indoor air through ventilation. The amount of heat, Q [W], lost to the outdoor air through air flow is given by:

$$Q = \frac{nV}{3600}\rho_a c_{pa}(T_{in} - T_{out})$$

where

n is the air exchange rate [1/h]

V is the volume of the indoor air [m^3]

ρ_a is the density of air [kg/m^3]

c_{pa} is the specific heat capacity of air, 1000 J/kgK

T_{in} is the indoor air temperature [ºC]

T_{out} is the outdoor air temperature [ºC]

2.4 Moisture safety

When moisture enters the building construction, it is transported though the construction. If the construction doesn’t let the moisture dry out and a high amount of moisture remains in the construction for a long period of time, it can lead to mould growth or deterioration of building materials. Different materials can hold and transport moisture in different ways and proper design of connections between materials is crucial for moisture safety design. This section introduces the five most common sources of moisture in buildings.

2.4.1 Precipitation

When it rains, the exterior surfaces of buildings absorb water from the rain. How much water is absorbed depends on the material with porous materials absorbing more rain. Depending on the materials and the conditions, the moisture can be transported further into the construction. If the construction doesn’t dry properly after the rain, for example because of the design of the construction or because the humidity of the air is high, the moisture can cause problems.

2.4.2 Indoor moisture

Air always contains a certain amount of water vapour. Air also has a maximum water vapour content beyond which it can’t hold more water vapour. The value of this saturation vapour content varies depending on the temperature of the air, and warmer air can hold more vapour. Once the vapour content and the saturation vapour content is known, the relative humidity, Φ [%], of the air can be calculated as:

$$\Phi = \frac{v}{v_s}$$

where

v is the vapour content of air [kg/m^3]

v_s is the saturation vapour content of air [kg/m^3]

If the relative humidity is 100% there will be condensation of water vapour into liquid water.
For a particular vapour content, there is a corresponding dew point temperature which is the temperature where this particular vapour content is the saturation vapour content. If a surface has a temperature that is lower than the dew point temperature of the air, there will be condensation on the surface, even if the relative humidity of the air is below 100%. Because of this, cold indoor surfaces can cause moisture problems if the indoor air humidity is high.

Outdoor air has a certain vapour content that varies depending on the weather. When this air is used to ventilate buildings, the same amount of vapour is transferred to the indoor air. Depending on whether the indoor air is warmer or colder than the outdoor air, the relative humidity of the indoor air will be either lower or higher, respectively, than that of outdoor air.

Indoor activities, such as cooking and washing, produce moisture. A person produces approximately 50 grams of moisture per hour through breathing and sweating (Petersson 2009). This moisture production raises the vapour content and the relative humidity of indoor air.

If an indoor moisture source, G [kg/h], is introduced at time 0, the vapour content of the air at time t will be:

$$v_i(t) = (v_i(0) - v_{out}) \cdot e^{-n \cdot t} + v_{out} + \frac{G}{n \cdot V} \cdot (1 - e^{-n \cdot t}))$$

where

v_i is the indoor water vapour content [kg/m^3]

v_{out} is the outdoor water vapour content [kg/m^3]

n is the air exchange rate [1/h]

V is the volume of the indoor air [m^3]

2.4.3 Moisture from the ground

The ground usually has a high moisture content, and building constructions in contact with the ground can absorb this moisture. Through capillary action the moisture from the ground can then be transported through the structure and further up walls. Moisture from the ground can be avoided with moisture barriers and by breaking the capillary action with gravel.

2.4.4 Construction damp

Certain building materials are produced with an excess amount of moisture that needs to dry out before the construction reaches a state of equilibrium with the climate. Depending on the amount of excess moisture and on the construction details, it takes months or even years for this construction damp to dry out. The detailing should be designed so that the construction damp can dry out once the building is finished, because if the construction remains damp it can cause moisture problems.

This applies especially to concrete which has a high initial moisture content because of water that is used when making concrete. Concrete that is cast in situ has a higher initial moisture content than prefabricated elements. When casting concrete in situ, it is important that materials that are sensitive to moisture (eg. wood) are not in direct contact with the concrete.

2.4.5 Leakages

If details and connections are not designed properly, there can be water leakages through the construction. Leakages can lead to severe moisture damages.

3 Field study

In January-February 2015 a study trip was made to Pakistan and neighboring countries in order to study existing schools as well as traditional buildings. This field study consisted of approximately three weeks in Pakistan, three weeks in Iran and one week in Bangladesh. This section summarizes the findings of the field study that are used for more detailed analysis. The analysis is supported by literature studies and the theory described in Chapter 2.

3.1 The Citizens Foundation Schools

The main goal of the field study was to visit existing schools of The Citizens Foundation (abbreviated TCF) in order to identify their strengths and weaknesses. TCF has over 1000 schools all over Pakistan and they have divided the country into four regions: South, Southwest, North and Northwest. During the study trip schools were visited in the South (Karachi), North (Lahore) and Northwest (Islamabad and Mansehra) regions and the schools in each of these regions and cities had their own characteristics. During the visits the schools were discussed with TCF’s senior architect, TCF’s regional building engineers and the school’s teachers and principals.

3.1.1 General

In 2014, an estimated 27% of primary school age and 47.6% of secondary school age children in Pakistan were not in school (UNESCO Institute for Statistics 2014). There are not enough government schools to educate everyone, and this is why non-profit organizations like TCF are needed. TCF schools are located in the poorest areas where most schools are needed such as urban slums and rural areas. The schools charge a symbolic fee because many people don’t like accepting charity, but the fee can be as low as 0.10 USD per month.

TCF builds both primary and secondary schools and both have standardized classroom sizes and numbers, while the size of the individual schools buildings varies depending on whether it has one or more units of primary and/or secondary school classrooms. Because TCF design, builds and maintains the schools themselves, optimal cost effectiveness is considered during the whole process. The designs are simple and functional and local materials are used, all of which brings down costs.

According to TCFs senior architect, climatic conditions are the main design parameter for TCF schools and the architects have also researched traditional architecture for inspiration. The schools use elements that are common in traditional architecture in the region, such as courtyards and lattice windows, and these elements contribute to passive cooling. Even though artificial lighting and ceiling fans are found in the schools, these might not work when needed because of frequent power cuts. Because of this natural daylighting and ventilation are especially important, and the schools are built and oriented to utilize dominant winds for ventilation and natural daylight.

The aesthetic quality of the schools is also important for TCF, and because of this it is also important to maintain the schools regularly. Regular maintenance such as painting is done every three years. One of the most important design factors is that the school buildings should require little maintenance, partly because it is more difficult for TCF to raise money to maintain a school than for building it. This affects what kind of materials are chosen, for example bricks are preferred over concrete blocks because they don't need to be painted, even though bricks are initially more expensive than concrete blocks. Currently, TCF is looking into alternative construction materials that would require less maintenance. TCF used to build around one school per month but today they build less new schools, and one reason for this is the high maintenance cost of the existing schools.

Some schools have two shifts, one in the morning and one in the afternoon, whereas some are only used in the morning. The dual shift maximizes the efficient use of the building because twice as many students can attend the school. A primary school class is designed for 30 students in a classroom of approximately 37 m^2 and a secondary school class for 36 students in a classroom of 42 m^2. The schools are built where they are needed the most, and in cities many schools are located in or next to slums. Security is an issue and all schools have boundary walls and a guard.

In most of Pakistan the schools have a 2,5-month summer holiday that coincides with the rainy season in July-August. In the very north in the mountains around Mansehra, the schools have 2,5-month winter holiday instead, because snowfall would make it difficult for the children to reach the school.

3.1.2 Regional designs and materials

The designs and building materials of TCF schools vary between different regions, but within a certain area the schools have a similar construction and detailing, even though the layout varies. The designs are adjusted to local conditions and locally available materials are used as much as possible.

3.1.2.1. Karachi

Karachi is the largest city in Pakistan and it is located in the south by the Indian Ocean. The schools in Karachi are built with 150 mm thick hollow concrete blocks, because bricks are not easily available in Karachi. These concrete blocks are plastered, and pigment is mixed in with the exterior plaster so that the schools don't need to be repainted in the future. TCF is also testing other materials, such as pigmented blocks and special Envicrete blocks that don’t require plastering because they have more aesthetic value than regular concrete blocks. Figure 3.1 shows a typical TCF school in Karachi.

Figure 3.1: Typical TCF school in Karach built with plastered concrete blocks.

Almost all schools in Karachi have courtyards and verandahs around the courtyard. These verandahs work as corridors and the classrooms are accessed from the verandahs. The courtyards provide light and air while the verandahs shade the courtyard-facing walls of the classrooms. The courtyards are mostly small and well-shaded which makes them reservoirs of cool air during the day. Some of the larger schools have two courtyards. The courtyard always has some type of plants, even though in some schools water is a large cost since not all schools are connected to the tap water network. Figure 3.2 shows a typical courtyard in Karachi. Some schools also have potted plants in the corridors. These plants help cool and clean the air.

Figure 3.2: A typical school courtyard with plants and surrounding verandahs.

The roofs, such as the one pictured in Figure 3.3, were accessible in most schools but not utilized. The roof surfaces were very hot during the day. However, the flat roof is ideal for long-wave radiative cooling during the night, and since this climate has large diurnal variations, the thermal inertia of the roof could be sufficient to keep the roof from heating the room below too much.

Figure 3.3: The roof of a typical school exposed to the sun.

3.1.2.2 Lahore

Lahore is the second largest city of Pakistan located in the north close to the Indian border. The schools around Lahore are built primarily with bricks, and the walls are 230 mm thick. A benefit of brick is that it doesn’t require painting, which reduces the regular maintenance of the facade. The interior wall is however plastered and painted. Figure 3.4 shows a typical school in the area.

Figure 3.4: A typical school in the Lahore area.

Lahore is an important historic city, and the design of the schools is influenced by Lahore's traditional Mughal architecture that is discussed further in Section 3.2.5. Like in Karachi, the schools generally have courtyards with plants as shown in Figure 3.5.

Figure 3.5: Mughal inspired courtyard.

3.1.2.3 Islamabad

Islamabad is the capital of Pakistan and it is located northwest of Lahore. TCF schools in Islamabad are built with bricks or concrete blocks and the walls are thicker (230 mm) than in Karachi. The walls are thicker because this is seen as a way to insulate the building from the cold, but it is questionable if this works since the schools are only used for some hours during the day and the high thermal mass means it takes a long time for the walls to heat up. Figure 3.6 shows a typical school in Islamabad.

Figure 3.6: A typical school in Islamabad.

The schools that were visited had no courtyards, only wider corridor spaces. In the school in Figure 3.6 the corridors were very dark and only had small lattice windows at the ends. In the school in Figure 3.7 below there was a covered two-story corridor area between the classrooms, and this corridor had large openings at the ends and a lot of daylight but it was very cold.

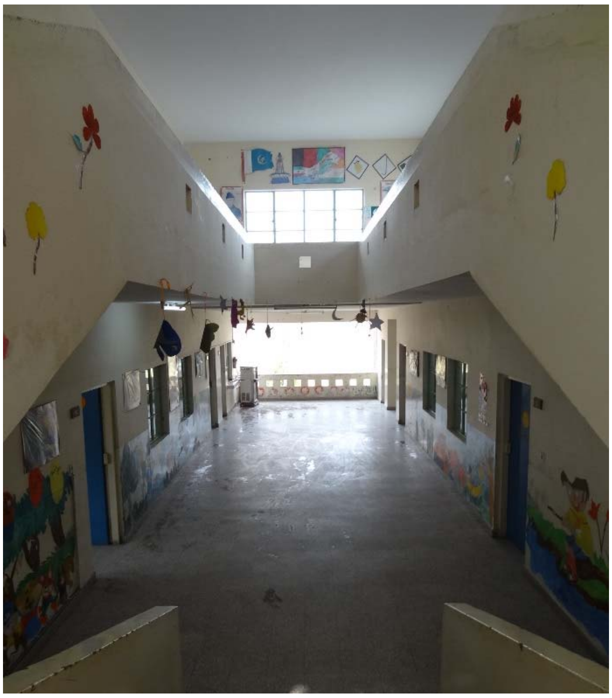


Figure 3.7: Two-story corridor space between classrooms.

3.1.3.4 Mansehra

Mansehra is located in the mountains in the north of Pakistan, and the region is prone to earthquakes. There was a major earthquake in 2005 and this earthquake caused major damage to the built environment, including schools. The earthquake is one reason why TCF has been very active in building new schools in the region since then. The schools in this region have a pitched roof because of snow and a typical school is shown in Figure 3.8. The pitched roof raises the ceiling height and provides space where warm air can be above the height of the people, which can be a benefit in the summer but a disadvantage in the winter.

Figure 3.8: Typical school in the Mansehra region.

The schools generally consist of more separate buildings that are centered on a yard. Single-story schools are quite common but some have two floors. The schools on hillsides are built with several levels following the slope of the mountain, as in Figure 3.9. The mountainous terrain makes building schools difficult, both because of structural reasons and also because in some cases the construction site hasn't been accessible by truck and materials had to be brought in by donkeys.

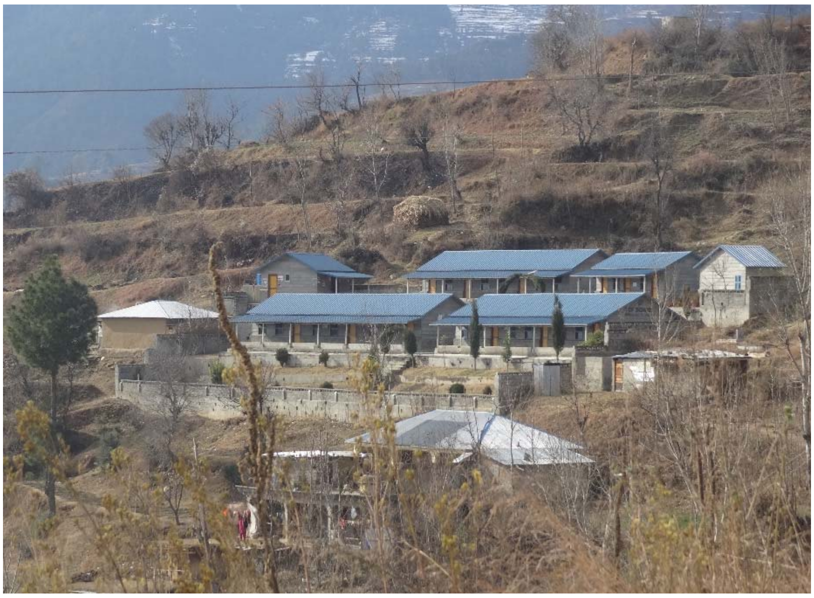


Figure 3.9: A school built on a mountainside.

The schools in the region have two types of structural systems and building envelopes. The first is a local variant with a heavy structure using loadbearing concrete block walls and columns and wooden roof beams. Expanded polystyrene (EPS), known locally as Thermopore, is placed between building parts to facilitate movement during earthquakes. A school using this structural system is shown in Figure 3.10. This school type has walls made of two concrete blocks (229 and 152 mm) with 50 mm of EPS in between.

Figure 3.10: A school with a heavy structure.

The second structural system is an imported light-gauge steel structure shown in Figure 3.11. According to the local TCF structural engineer, this structural system is better for earthquakes and it was also more common in the schools that were visited. After the earthquake, the government waived the tax on this imported system which made it cost effective to use it. Now the tax has returned which makes it difficult to build more schools with this structure and new schools are built using the local concrete-based system.

The light-gauge system has walls made of Viva Board, a type of wood cement board, on the outside, wooden boards on the inside and 50 mm of EPS in between. The insulation and the steel studs can be seen in Figure 3.12.

Figure 3.11: A school with a light-gauge structural system.

Figure 3.12: A fallen wood cement board reveals the steel studs and EPS inside the wall.

This wall is thinner and would heat up faster which is a benefit in the winter but can be a disadvantage in the summer. The steel studs create thermal bridges which reduce the effect of the insulation. The lower part of the wall has concrete blocks with no EPS in between.

The roof is typically made of two steel sheets with EPS or mineral wool in between. The steel in the interior of the roof can cause discomfort because of heat radiation. The schools that had a heavy structure had plywood on the inner surface of the ceiling. Figure 3.13 shows an unfinished roof revealing the EPS inside. In this case the studs were wooden which would create less thermal bridges.

Figure 3.13: Unfinished roof showing the EPS insulation and wooden studs.

3.1.3 Ventilation

For ventilation, the schools rely on cross-ventilation through windows and all classrooms have some windows facing the façade and some facing the courtyard or corridor. Most schools in Karachi and Lahore only had one type of window placed at the same height, as in Figure 3.14 below. This works well when there is wind but it becomes a problem during still days. When the classroom only has windows placed approximately at the center of the room height, the neutral pressure plane crosses the window and there is little air exchange due to temperature differences.

Figure 3.14: Façade-facing windows in a typical classroom in Karachi.

Figure 3.15: A typical window in Mansehra where the. higher part can be opened for ventila

The windows in Mansehra have two parts, as shown in Figure 3.15. The windows are also more air tight than in other regions. Having the top part open can be more comfortable during the colder months since less draft would be experienced at the level where the students are sitting.

One of the schools visited in Islamabad had higher ventilation windows, called ventilators, above the regular windows. The regular windows also consisted of two parts with the lower part being similar to the ventilator window. In some cases, as in the classrooms in Figure 3.16, the window had been installed upside down. This was a problem because now the ventilator opens inward and rain comes in. This also affects the natural ventilation because there is less height difference between the two ventilators, which means that both ventilators are closer to the neutral pressure plane so the air flow will be smaller.

Figure 3.16: Classroom where windows have been installed upside down.

The school in Figure 3.17 was in a donated building instead of a purpose-built school. The ceiling was higher and there was a small ventilator close to the ceiling, which can be beneficial in the summer for ventilating out hot air. The windows were closed during the visit and doors were partly closed.

Figure 3.17: Classroom of donated school showing window arrangement and high ceiling.

During the visits, most classrooms in Karachi had at least some windows open and at least the door facing the courtyard or corridor was always open. Early in the morning the windows were more likely to be closed. In some cases when all windows were closed the classrooms felt quite stuffy, even though the door was open. Some schools were quite cold in the morning and this might be the reason why the windows were closed.

Windows were more likely to be closed in Lahore and especially in Islamabad, and it was very cold indoors at this time of the year. In Lahore in particular it felt that the schools were unnecessarily cold because the weather was still quite warm outdoors during the day. A school that was under construction and didn't have windows put in yet felt warmer than the schools that were in operation. This could be a sign that the school needs to be ventilated more during the day in the winter so that warm air can heat the structure. When all windows were closed, the classrooms felt very stuffy, even if the door was open.

Figure 3.18: Corridor facing window which lets some air into the classroom even when mostly closed.

The windows are far from airtight so some air still infiltrates the classrooms even when the windows are closed. This is beneficial during the day since at least some fresh air is provided even if all the windows are closed. During the night however, cold air leaks into the building which cools down the structure which is not desired during the colder months.

Karachi has a dominant wind from the southwest and most schools are oriented east-west in order to catch as much wind as possible. In the other cities wind direction varies more and the speed is lower, which makes ventilation more challenging in the north. Even in Karachi the cross-ventilation didn't always work. Sometimes the size and shape of the available plot has forced the school to be oriented south-north instead which reduces the amount of air flow. In one case a newer neighboring building was blocking the wind, and according to one of the teacher's the classrooms in this school were hot and humid in the summer and the children were exhausted.

The schools in Karachi and some in Islamabad also use a type of lattice window that is common in traditional buildings in the region, known as *jaali*. This device lets air pass through but blocks most of the solar radiation, making it a good ventilation device in hot climates. However, these were only used in corridors, as in Figure 3.19.

Figure 3.19: Lattice window letting light and air into a corridor.

3.1.4 Thermal comfort

The thermal inertia of the concrete blocks in Karachi helps keep the schools cooler during the morning hours. Some surface temperature measurements were done during the visits and interior walls and shaded exterior walls were between 18 ºC and 23 ºC which corresponds quite well with the average daily temperatures during the visit. The coolest temperatures were on the north side and around the courtyard. Exterior surfaces in the sun had a temperature between 29 ºC and 34 ºC.

The schools in Lahore and Islamabad also have a high thermal inertia with thick walls, but during the visits they were quite cold. In one school in Islamabad the indoor surface temperatures were around 12 ºC. The teachers said the school is very cold during the winter and hot during the summer. The schools have no insulation but insulation, coupled with thermal inertia, could help both during the cold and the hot months.

In Mansehra, the walls were several degrees colder on the inside than on the outside. This was the case for both the structure with thick concrete walls and the structure with lighter wood cement board walls. The schools were not in use during the visit though and the walls would be warmer if they were. The schools are heated with gas heaters in December and March, which are coldest months during the school year.

The schools in Karachi and Lahore had shading devices above the windows, as in Figure 3.20. In Karachi, the east-west orientation that is ideal for cross-ventilation is also ideal for shading purposes because there are little windows on the east and west sides, which would be more difficult to shade than the south and north sides. The shades are designed so that they let some of the solar radiation in during the winter.

Figure 3.20: Typical window shade in Karachi.

In Mansehra, verandahs shade the classrooms and the whole facade on the side facing the yard as is shown in Figure 3.21. In some schools the roof of the verandah was insulated but this seems unnecessary. On the other side of the building there is no shading although the roof overhang shades the top floor somewhat.

Figure 3.21: Verandahs provide shading in Mansehra.

3.1.5 Moisture safety

The schools in Lahore have a severe problem with moisture damages on the interior of the exterior walls, shown in the classroom in Figure 3.22. This is a serious problem because it affects very many schools and it is a large extra costs. In some cases the moisture has caused the plaster to fall off and in other cases there is visible mould growth on the wall. The mould can also have health implications, especially during the winter months when the air change rate is low because windows are kept closed.

Figure 3.22: Classroom showing moisture damages on the façade wall.

Every three years when the schools have their regular maintenance, the damaged part is scraped off and then repainted. This doesn't solve the underlying problem and the damages return soon after the maintenance. The north walls have slightly more of the problem. This wall is the coldest and most of the wind and rain also comes from the north. The problem is present all year but it gets worse during the rainy season. The local engineer says the water comes from the groundwater, but the fact that the problem is also present on the second floor, close to the roof, seems to suggest that the water comes from the rain. In many schools the problem was actually worse on the second floor and close to the ceiling. The façade has no protection from rain. Figure 3.23 shows a particularly bad case.

Figure 3.23: Severe moisture damages.

Figure 3.24: Water damage due to inadequate drainage.

One school in Islamabad also had moisture problems and in this case it had been identified that the problem was caused by water seeping through the roof. The roof only has one drain and this is not enough to drain the rainwater during heavy rains which are typical during the rainy season. This has resulted in water damage on the top floor, shown in Figure 3.24. The damaged classrooms are not in use.

The schools in Mansehra have a problem with concrete cracking due to moisture inside the concrete freezing in the winter. This mainly affected outdoor features like stairs. A damaged part is shown in Figure 3.25. There were also some cracks caused by the setting of concrete. The schools in Lahore also have a problem with the concrete floor cracking while setting due to the movement of the earth.

Figure 3.25: Concrete cracks caused by freezing.

3.1.6 Daylight

Most schools in Karachi had enough daylight but some had problems with adequate daylight in some classrooms, and this was especially a problem during power cuts and the afternoon shift. Some schools have generators that providing electricity during power cuts but most can’t afford it.

In one school in Islamabad that had four floors, the classrooms on the 1st and 2nd floor were quite dark. The corridor, shown in Figure 3.26, was also dark and this was at least partly due to the fact that there was no courtyard and the corridors had smaller *jaali* openings than in Karachi. In general in this area sufficient amount of daylight is the most important factor when deciding which way to orient the schools.

Figure 3.26: A dark corridor in Islamabad.

3.1.7 Conclusion

The schools in Karachi perform well and climatic factors have clearly been considered in the design. However, alternative ventilation strategies could be developed so that air flow and fresh air is provided even when wind is not present for one reason or another. The chosen building materials seem to work well in this region and air pollution was the only problem causing extra maintenance.

The main challenge in Lahore is the moisture problems, and the building materials and construction details should be studied in detail to find a solution. In terms of thermal comfort the schools have similar problems as those around Islamabad.

In Islamabad the schools were cold during the visits and in some cases adequate daylight was also an issue. During the summer however the heat is a problem and the buildings are built more with this problem in mind. Strategies should be developed for how the schools should be used and ventilated in different ways in the summer and winter. Adequate protection from the rain is also important.

The schools in Mansehra were very cold (around 9 ºC). The schools were not in use at the moment because of holidays but most likely March – the first month after the winter holiday – is at least uncomfortably cold before the structure has time to heat up. During the day there is a lot of solar radiation even in the winter and this should be used more efficiently to heat the schools. Studies should be done to find the ideal building envelope system and ventilation strategies that can achieve thermal comfort in both winter and summer.

3.2 Traditional passive cooling techniques in Pakistan and Iran

Summers in Pakistan are very hot and with temperatures above 40 degrees it is difficult to create a comfortable environment in a passive way. However, people have been living in Pakistan for thousands of years and over time people have learned to deal with the heat and to adapt their traditional buildings to it. During the field study some of these traditional buildings and techniques were studied. Traditional buildings in neighboring Iran were also studied.

3.2.1 Hyderabad windcatchers

Hyderabad is a city in Sindh in southern Pakistan that has developed a simple but effective type of windcatcher that ventilates buildings by funneling in cool winds from the sea. Photos from the early 1900s, such as the one in Figure 3.27, show how these chimney-like windcatchers completely dominated the skyline. These windcatchers have been slowly replaced by mechanical cooling devices and today windcatchers in the city are rare although they still exist.

Figure 3.27: Old photo of Hyderabad. Photo from Insideflows (2015).

The climate of Hyderabad is similar to that of Karachi. It is hot and arid most of the year and there are large diurnal temperature variations. December through February are slightly cooler. For most of the year there is a relatively constant southwestern wind that brings cool air from the sea. The rainy season is between June and September and during the rainy season the wind direction changes. Figure 3.28 shows the wind rose for Hyderabad.

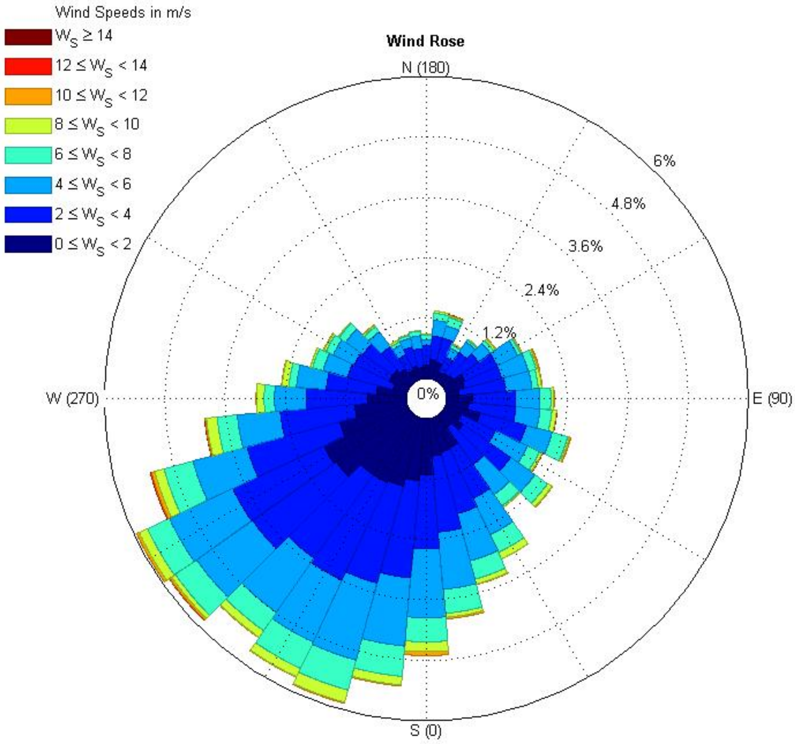


Figure 3.28: Wind rose for Hyderabad. Generated with Meteonorm data and code from Mathworks (Pereira 2014).

As can be seen from Figure 3.28 above, the dominant wind direction in Hyderabad is southwest, and because of this the windcatchers of Hyderabad are oriented towards southwest. This way they catch the dominant wind during most of the year. The air flow is illustrated in Figure 3.29 below. During the rainy season, when wind direction is changes, rain doesn't come in as the opening will be on the leeward side and the windcatcher will act as an exhaust instead. However, according to the locals there has been some rain even from the southwest in the last few years, possibly because of climate change.

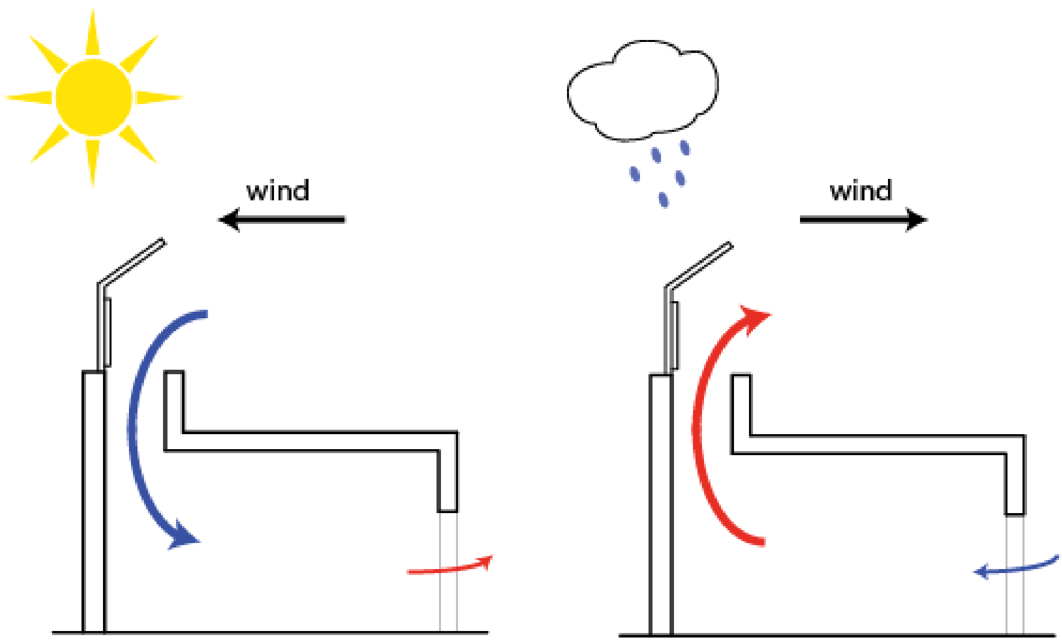


Figure 3.29: Illustration created by Hyderabad windcatchers in the dry and rainy season.

The Hyderabad windcatchers have been researched by the Hyderabad Development Authority. The windcatchers have a shutter that can be opened and shut according to need. During the summer months the windcatchers were traditionally closed during the day and opened at night which let in cool air and cooled down the structure of the building. During the winter the opposite was done and the windcatchers were open during daytime to let in warmer air. The shutter is made of wood and is not completely sealed so some air would enter through the windcatcher even when the shutter is closed, providing some fresh air.

Figure 3.30: Modern concrete windcatcher in Hyderabad.

The windcatchers were originally constructed of wooden panels but these panels have been eaten by termites over the years. Some people have replaced the wooden scoop with a construction of concrete, as in Figure 3.30, or other more permanent materials but most people have simply stopped using the windcatcher.

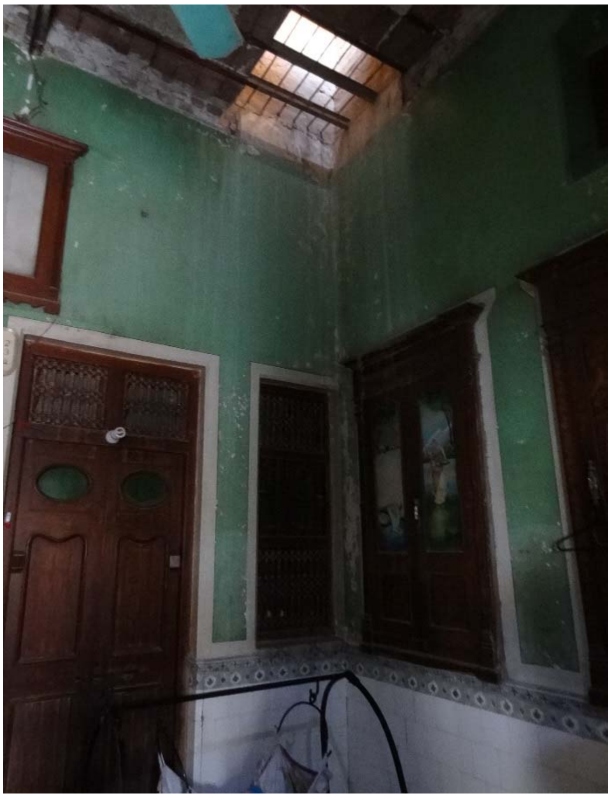


Figure 3.31: Interior of a room with a windcatcher.

With the help of Hyderabad Development Authority, a visit to a single-family house in Hyderabad was organized and it showed that the windcatchers are still in use and working. Like others, this family's original shutter had been eaten by termites. However, the family still uses the shaft without the scoop and according to them it works well. Figure 3.31 shows a picture from inside the house with the windcatcher in the corner of the room. The opening is approximately 1 × 1 meters and it also lets in daylight. The metal grid keeps away birds.

The windcatcher is opened and shut from the roof, shown in Figure 3.32. The family uses the windcatcher as was done originally, opening it during the night in the summer and during the day in the winter. The house has a mechanical ceiling fan but according to the family it is not needed.

Figure 3.32: View of the windcatcher from the roof with the shutter closed.

The house had two rooms and originally it had two windcatchers, but the second one has been sealed because rain started to enter from it.

Windcatchers have been used even in a few modern buildings in Hyderabad, such as the Aga Khan Maternity Hospital and the district administration's office, and the latter is shown in Fugure 3.33 below. However, these modern windcatchers are only decorative and both buildings have mechanical cooling devices. In the district administration's office one windcatcher is completely closed from the inside and the other opens to a small enclosed and fly-infested storage room.

Figure 3.33: Hyderabad district administration's office with decorative windcatchers.

The Hyderabad windcatchers have been researched by the Hyderabad Development Authority but they are seen as a part of cultural heritage, not as a technical device that could be used today for its original purpose. Currently Pakistan is suffering from an insufficient electricity generation capacity. Those who can afford it have their own generator, but the majority of people suffer during power cuts in buildings that are designed to use mechanical cooling. Bringing back the windcatchers would be a way to deal with this problem and to improve the comfort of the people.

3.2.2 Iranian windcatchers

Iran has one of the world's oldest continuous civilizations and over the millennia the people there have developed a distinct traditional architecture which includes a number of passive systems. Iran has a large variety of climates but there is a large hot-dry area which is comparable to that of Pakistan. Although winters are quite cold, the heat of summer is the main issue regarding thermal comfort and over time people have developed passive mechanisms that cool traditional houses and cities. Traditional cities are dense with houses shading each other, and outdoor spaces and some streets are also covered.

A typical traditional house in Iran usually has different rooms with different temperatures and these are used during different times of the day and year. Buildings are generally built with mud or mud bricks that have a high thermal inertia, which takes advantage of the large diurnal temperature variations in order to provide a more stable and comfortable indoor temperature that is close to the average daily outdoor temperature. Most houses have a courtyard and the courtyard is the center of activities with rooms opening to the courtyard. The courtyard, such as the one in Figure 3.34, usually has both water elements and plants, both of which cool the courtyard and the adjacent rooms through evaporative cooling and increased air flow. Porches shade façade openings and provide a transitional space between outdoors and indoors. (Manzoor, 1989)

Figure 3.34: Courtyard of a house in Kashan with two windcatchers.

Probably the most effective passive cooling system of traditional Iranian architecture is the windcatcher, known locally as *badgir*. These windcatchers are essentially towers with vertical openings high above the rest of the building. These towers usually are divided into several vertical shafts and have openings in different directions, and they ventilate buildings with the help of pressure differences created by both wind and temperature differences. Figure 3.35 shows some typical windcatcher cross-sections.

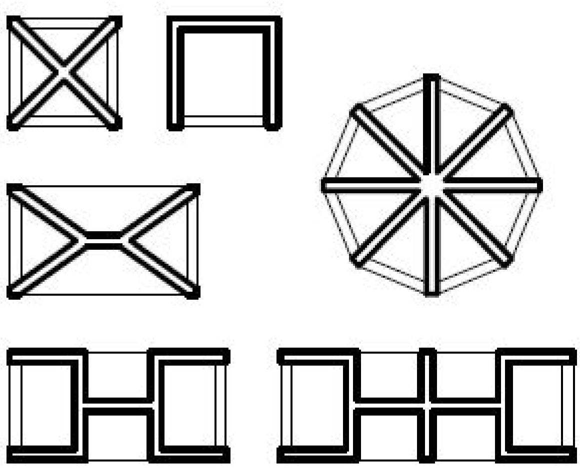


Figure 3.35. Different cross-sections of wind catchers found in Iran.

Figure 3.36 shows a typical windcatcher in Yazd, Iran that has four shafts opening in four different directions. Similar windcatchers are also found in other countries in the Middle East.

Because windcatchers are above the houses where there are less structures blocking the wind and the wind speed is higher, windcatchers can create more air flow than windows. The high location also means less dust will enter even though dust can still be an issue especially in the desert environment.

The height also creates a larger stack pressure difference between the tower and the neutral pressure plane than what could be achieved with openings only in the room height. This means that windcatchers can also be used during calm weather.

Figure 3.36: A typical windcatcher in Yazd.

The wind catcher operates differently during day and night and during windy or calm weather (Bahadori 1978). Figure 3.37 shows how the windcatcher works during calm weather. In the absence of wind, the driving force for air flow will be temperature differences. The aim of passive cooling in hot-dry climates is to keep the indoor air cooler than the outdoor air during the day. This means that during the day air will enter the building above the neutral pressure plane and exit from below it. Air will thus enter through the wind tower during the day and exit through lower openings. During the night the reverse is true because the indoor air will be warmer than the outdoor air.

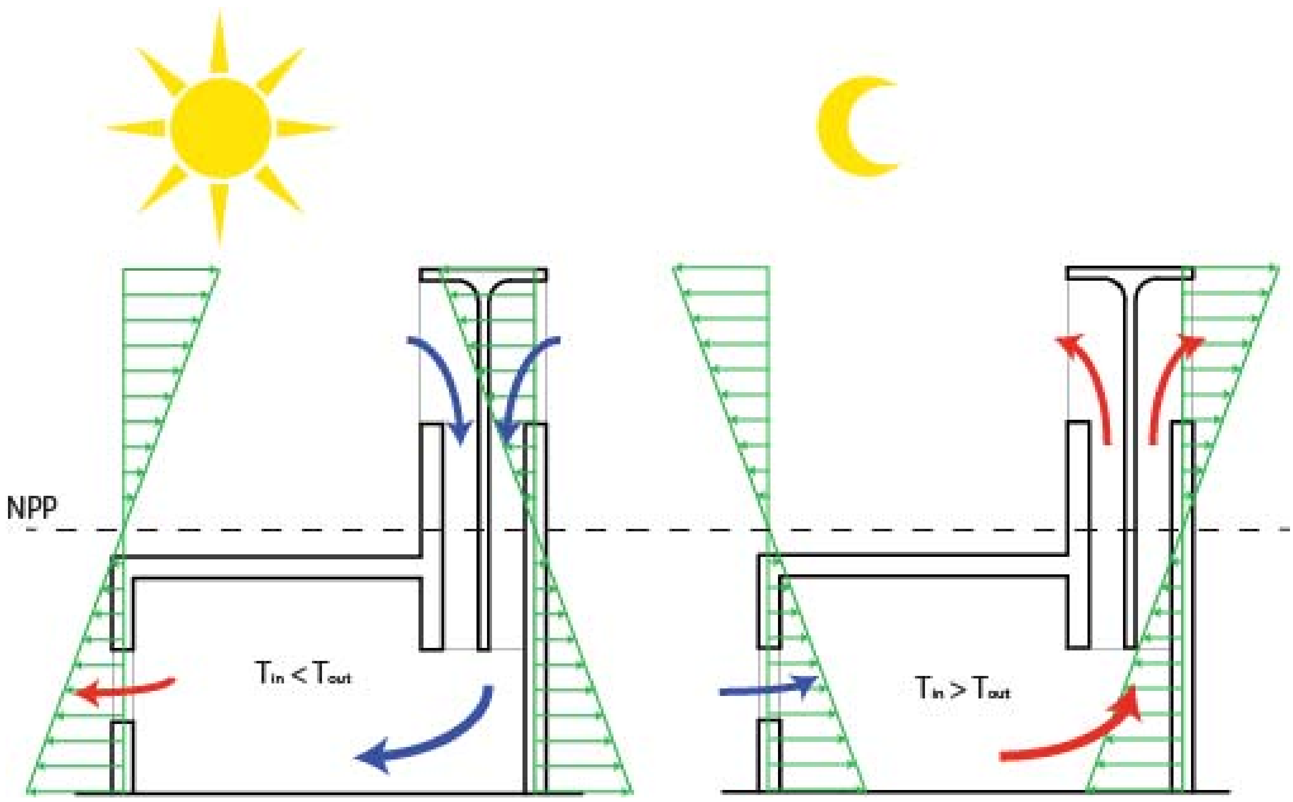


Figure 3.37: Pressure differences and air flow created by temperature differences between indoor and outdoor air.

In the presence of wind the windcatcher works in a different way, as shown in Figure 3.38. Wind will create a positive pressure on the windward side and push air into the tower from this side. A negative pressure will be created on the leeward side and air will exit the tower from this side. Air will also enter or exit through any window and door opening on the windward or leeward side, respectively. The air flow inside the building will be different depending on which side the wind catcher is located.

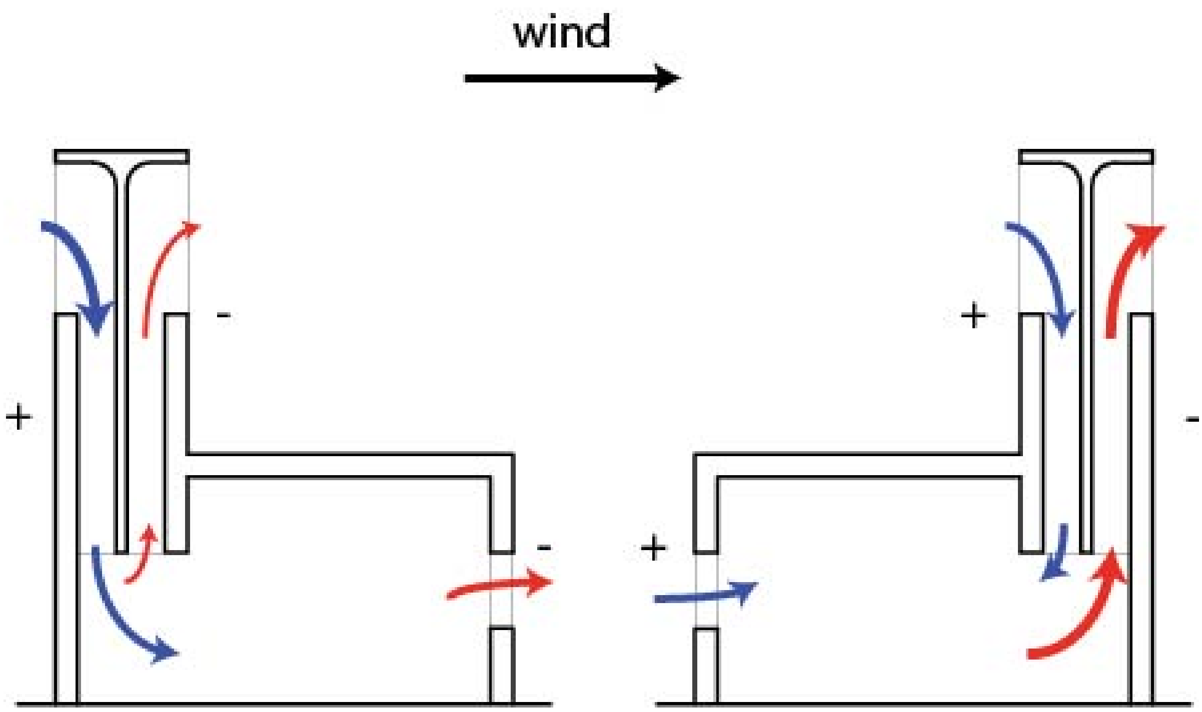


Figure 3.38: Pressure differences and air flow created by wind.

A problem with the windcatcher is that a lot of wind that enters through the windward side will exit immediately through the leeward side (Bahadori 1985). This problem can be partially solved with a controlling system such as in Figure 3.39. This control system makes the windcatcher more flexible and it can work more efficiently during different types of weather. Keeping the windward or leeward side closed makes it possible to control whether air exits or enters through the tower, and this can be useful for example when cooler air from the courtyard is preferred.

When there is a dominant wind direction, the windcatcher can only have an opening on one side, such as in the town shown in Figure 3.40. This eliminates the problem of air escaping from the leeward side but is less flexible.

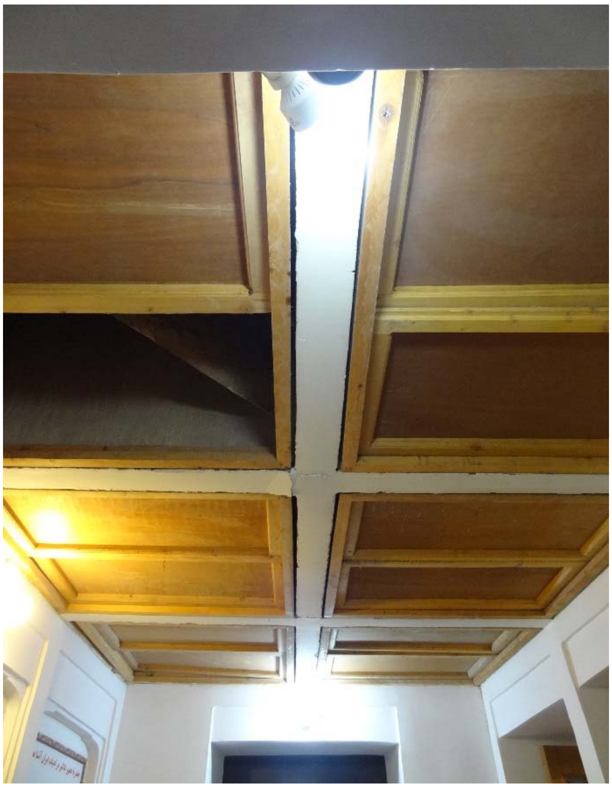


Figure 3.39: A system for opening and closing shafts of a windcatcher.

Figure 3.40: One-sided windcatchers in Meybod.

Combining wind and the stack effect, as in Figure 3.41, shows that during the day the flow in through the windward side of tower will be increased, and during the night the flow out through the leeward side will be increased. However, at high wind speeds the effect of wind will dominate and stack effect will be negligible.

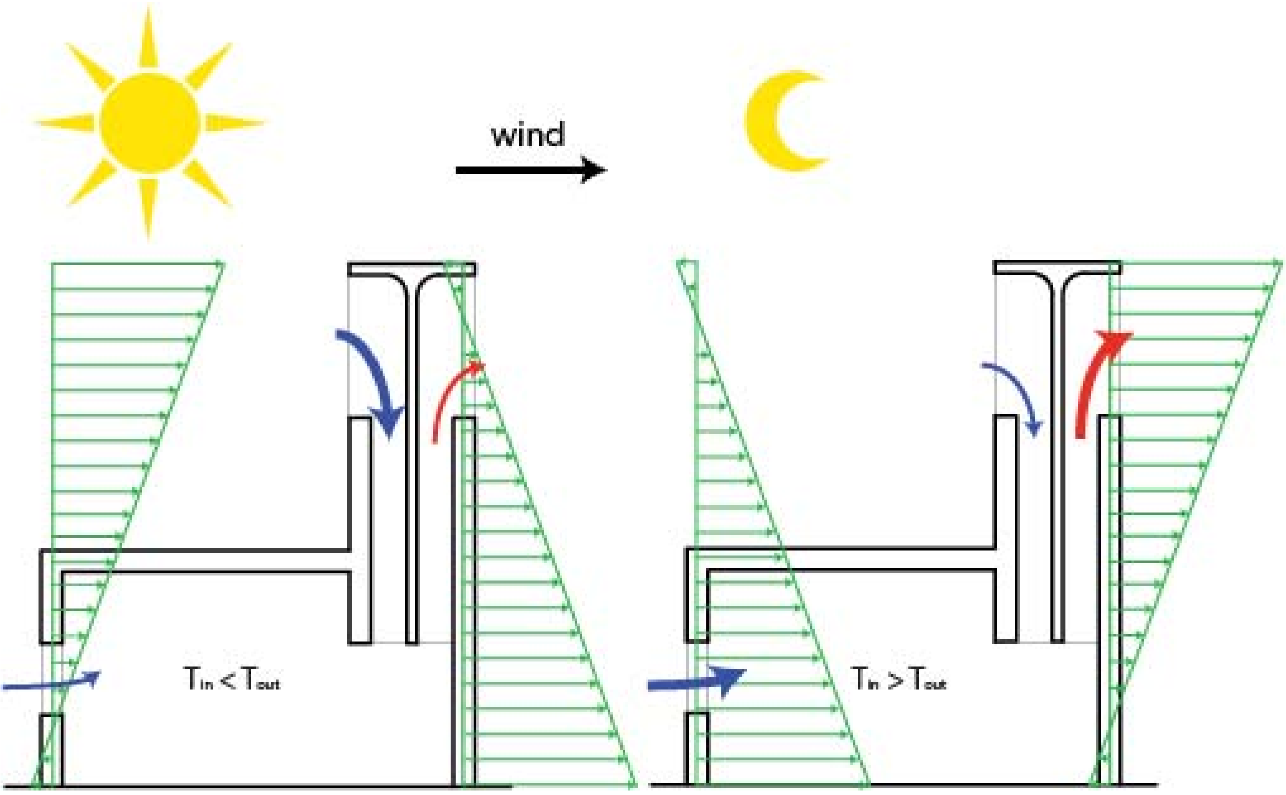


Figure 3.41: Combination of wind and stack effect.

Combining windcatchers with water elements enhances the cooling effect. Having a fountain under the windcatcher, such as in Figure 3.42, means the air around the fountain is cooled through evaporative cooling.

This cooler air is then pushed into the room by the air entering from the tower. In some cases windcatchers work together with underground water channels that have been built to provide water to the desert cities (Bahadori 1978). When only the leeward side of the windcatcher is open, the windcatcher will draw air out of the water channel and this cooler air will flow through the house.

Figure 3.42: Fountain in a room directly under a wind catcher.

One way to enhance the windcatcher would be to keep the tower surface moist or to provide a wetted net that the air passes through. This would cool the air through evaporative cooling and this principle has also been used traditionally in Iran with wetted palm leaves. Water also helps keep dust away. (Bahadori 1985).

3.2.3 Domes and air vents

Domes are another common feature of Islamic architecture. When compared with flat roofs, domes have a higher surface area and they increase the air flow around them, meaning that domes lose more heat through convection. Before reinforced concrete, domes were also efficient structurally since they don’t required wooden beams in an area where there is little wood. (Bahadori 1978).

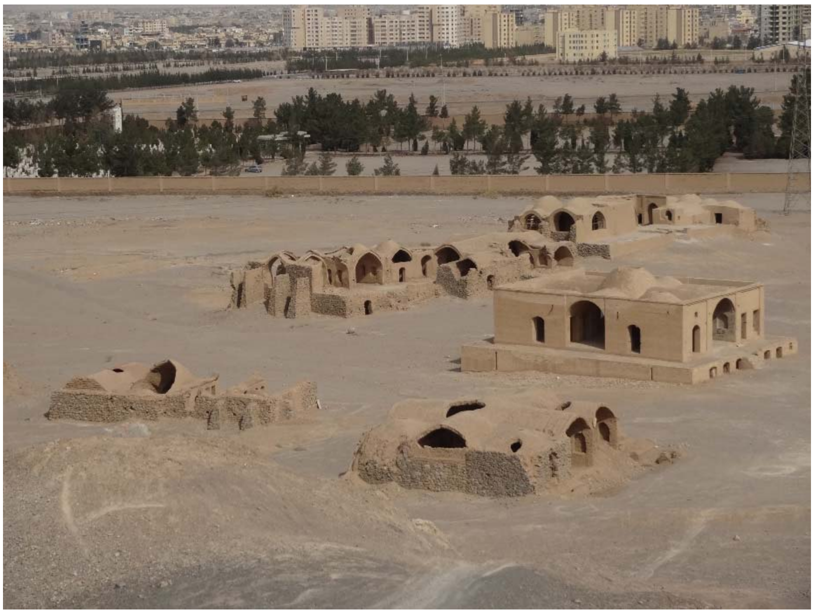


Figure 3.43: Abandoned domed houses near Yazd, Iran.

Domes raise the height of a room and provide space for the lighter warmer air above the height where people are. When warm air gathers at the top, there is also less heat transferred from the outdoor air through conduction because the temperature difference is smaller across the roof (Bahadori 1978). When a dome has an opening at the top, warm air can escape while cooler air is drawn into the house from lower openings such as windows and doors. In Iran a specific type of air vent, such as is shown in Figure 3.44, has developed to ventilate rooms with domed roofs (Bahadori 1978).

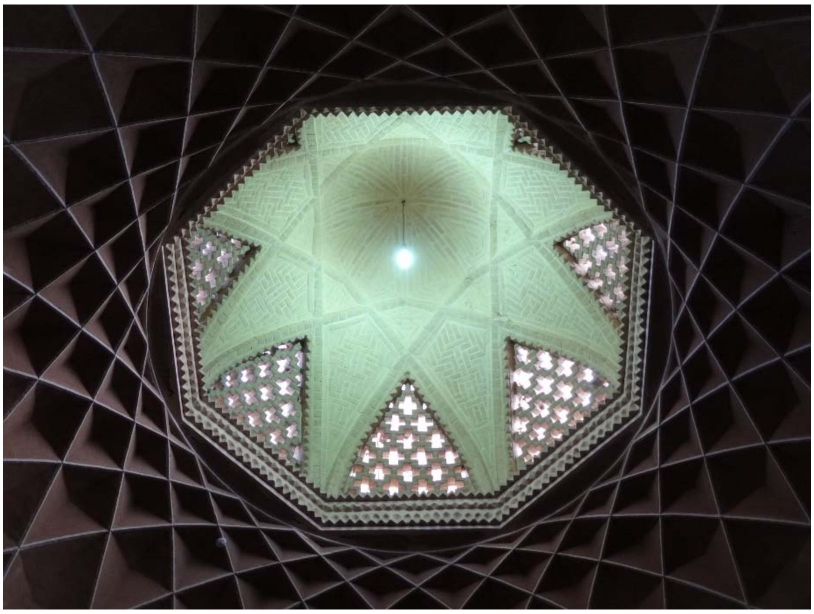


Figure 3.44: Interior view of a dome with an air vent.

As the sun heats up the dome and the air vent, the air next to these will also heat up creating a region of lower pressure. Air from the rest of the house will start to flow up and the air will flow out through the air vent. Wind enhances this effect by drawing air out from the leeward side of the vent. When wind passes over a dome, the velocity is highest at the top and this also reduces the density of the air at the top, creating more outflow than if the roof was flat (Bahadori 1978). Figure 3.45 shows how the air flows in this type of house.

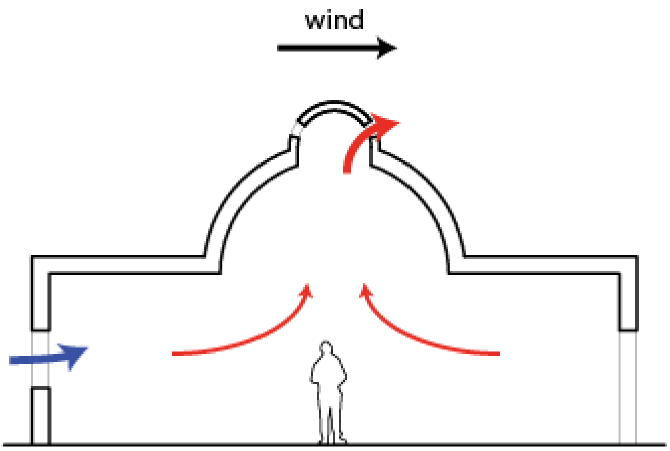


Figure 3.45: Illustration of air flow in a building with a dome and air vent.

The air vent lets in less dust than a windcatcher because air is always channeled out through the vent and in through lower openings (Bahadori 1978). The air vents also let in indirect daylight.

3.2.4 Iranian ice houses

In arid climates the sky is usually clear and this makes it possible to take advantage of long-wave radiation exchange with the sky for cooling purposes, as was explained in Section 2.2.4. A clear night sky has a much lower temperature than the air which means heat from the earth radiates to the night sky. Roofs of buildings are cooled in this way, but in Iran the same principle has even been used to make ice, which was then stored in an ice house such as the one in Figure 3.46. The ice was made during the winter months and it could last until the end of summer.

Figure 3.46: Ice house in Meybod, Iran.

In front of the ice house there are ponds, shown in Figure 3.47, and these are located on the side that is most shaded during the winter. These ponds were filled with water in the evening on clear winter days when temperatures are a few degrees above zero in the night. During the night heat from the water radiates to the night sky, lowering the temperature of the water, and eventually ice will form. This means ice could be made even though the temperatures rarely drop below zero. On colder nights more water can be put in the pool and thus more ice generated. Walls around the pond protect the water from winds that would heat the water through convection. Conduction from the ground heats the water to some extent and because of this it is important that the pond is shaded during the day. (Bahadori 1978)

Figure 3.47: Pond outside ice house for making ice, located on the shaded side of the ice house.

The ice was then harvested before sunrise and stored inside the ice house with alternating layers of ice and hay for insulation. The house itself has very thick walls and a domed room. The ice cools down the air inside and the thick walls prevent heat from entering while the dome assures that warmer air stays at the top, furthest from the ice. The ground also helps insulate the ice during the summer. (Bahadori 1978)

The top of the dome has a hole and this hole was covered with a piece of marble. This meant that the indoor air that is cooled by the ice doesn’t escape and hot air doesn’t enter. But at the same time the marble lets in daylight, meaning that people who enter the ice house don’t need to carry a lamp that would heat up the space.

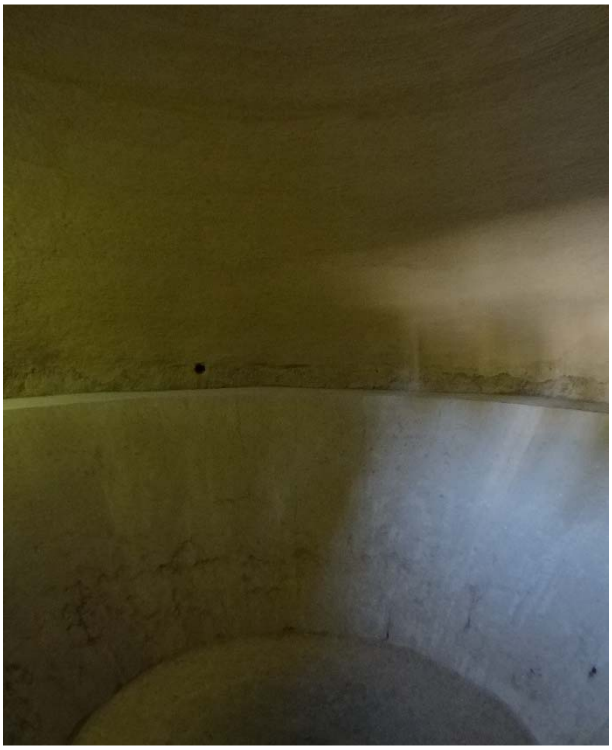


Figure 3.48: Storage pit inside the ice house.

The ice houses are not used anymore but the fact that the technique works shows how powerful a cooling effect can be achieved using only passive systems. In this case the ice was used in the summer for human consumption but it could also have been used for cooling buildings.

3.2.5 Mughal architecture

Mughal architecture developed in the Indian subcontinent between the 16th and 18th centuries, and it combines Islamic architecture with Indian architecture. Lahore was one of the most important Mughal cities and because of this the city has some fine examples of Mughal architecture. Mughals generally used marble and red sandstone as building materials, but in Lahore bricks were also used.

Mughals used water and plants to improve the microclimate through evaporative cooling and water elements were used both indoors and outdoors (Ali 2013). When fountains spray water, evaporation is enhanced and the air is cooled more. The evaporation of water also improves the thermal comfort during the dry season by increasing humidity. A prime example of this is Shalimar Gardens in Lahore, pictured in Figure 49, where a system of small channels carries water through the garden from a tank placed outside the garden on higher ground. The water flows slowly which means the storage tank needs less refilling, which is important during the dry season in the semi-dry climate.

Figure 3.49: Shalimar Gardens in Lahore.

In the middle of the fountain in Figure 3.49 is the scene where dance performances were held. The king's seat at the bottom of the figure had water around it but also underneath and behind it there was a fountain and a waterfall, shown in Figure 3.50. The abundance of water on all sides made the King's seat the most comfortable.

Figure 3.50: Waterfall and fountain behind king's seat. The narrow inlet at the top means that only a thin layer of water can pass, enhancing the rate of evaporation.

Mughals also used other passive cooling techniques. Shaded outdoor spaces like the verandah in Figure 3.51 provided escape from the intense sun while the openness ensured that air flow was maximized. Courtyards with water elements and plants were also a common feature. During the day the center of the courtyard that is exposed to the sun is heated and this creates an upward draft, which draws in cooler air from shaded areas. (Ali 2013).

Figure 3.51: Verandah and courtyard at Lahore Fort.

Window openings were shaded and often the whole façade was shaded. The windows often had a lattice screen, known as *jaali*, such as in Figure 3.52. This lattice ensures privacy and blocks solar radiation while letting in air and daylight. (Ali 2013).

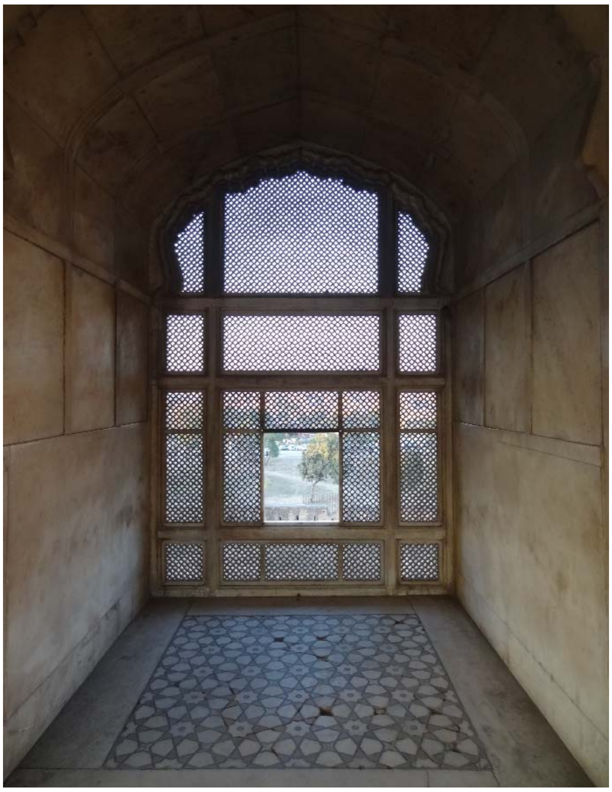


Figure 3.52: Jaali *window at Lahore Fort.*

4 Simulation of thermal comfort and natural ventilation

This chapter describes the computer simulations done to assess the thermal comfort and natural ventilation of TCF schools. A model has been developed in MATLAB/Simulink that is based on the existing schools in the four cities studied. These reference schools are then modified to see the effect that different changes have on the indoor temperature and air change rate. The aim is to see which type of building design and operation performs best in each city.

4.1 Model and assumptions

A calculation model has been built with Simulink and MATLAB. The outputs that are studied are hourly values for indoor temperature and air change rate. This section describes the how the model is built and what assumptions are made.

4.1.1 General

The model calculates the free-running indoor temperature during one year without any cooling or heating devices. Once the net heat transfer, $Q(t)$, between the indoor and outdoor has been computed for each time step, the indoor temperature for each time step, $T_{in}(t)$, is computed from the equation

$$Q(t) = C \cdot \frac{dT_{in}(t)}{dt}$$

where C is the volumetric heat capacity of the building, computed according to Section 2.2.1.

When calculating the net heat transfer between the building and the exterior, the following are considered:

- Ventilation losses/gains
- Transmission losses/gains through the building envelope
- Solar gains through windows
- Internal gains

The following sections describe the details of how these phenomenon are included in the model.

The outputs of the simulation are hourly values for indoor temperature and air change rate. The results are represented with statistical box plots that illustrate how much the data varies throughout the year. Figure 4.1 below illustrates how the box plots should be interpreted.

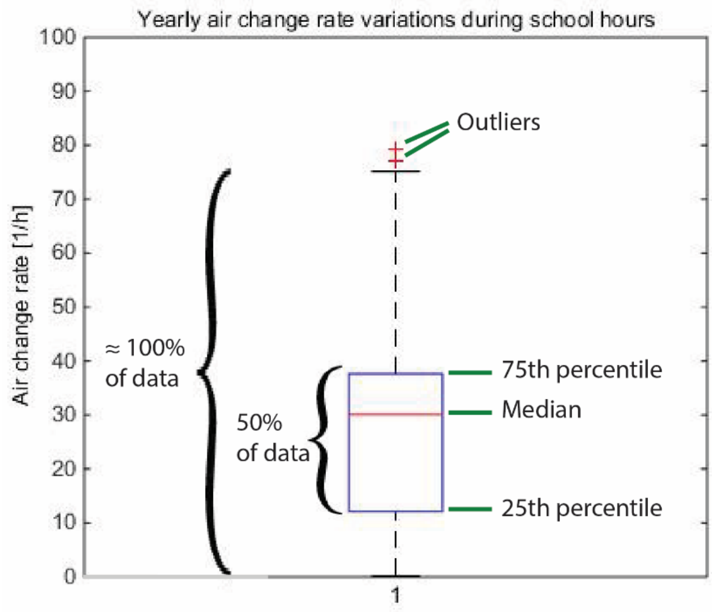


Figure 4:1 Explanation of statistical box plot.

The simulation is run for the whole year but in the resulting box plots only schools hours are considered. This means that nights, weekends and school holidays are not considered in the box plots. This is done because only the thermal comfort and ventilation rate during school hours is relevant.

4.1.2 Ventilation

The simulation of natural ventilation is the most important and complex part of the model. The simulation computes the natural ventilation created by wind and temperature differences between indoor and outdoor air. The model includes the possibility to control when openings are open and closed, so that it can be used to study for example night ventilation.

The simulation calculates pressure differences caused by wind and stack effect over each opening, as described in Section 2.3.1 and 2.3.2. The air flow through each opening is then calculated based on the total pressure difference. The air flow is calculated as described in Section 2.3.3, and it is calculated separately for all openings and then the flows are added together to find the total flow in and the total flow out. Figure 4.2 shows this part of the Simulink model that calculates the air flow in and out.

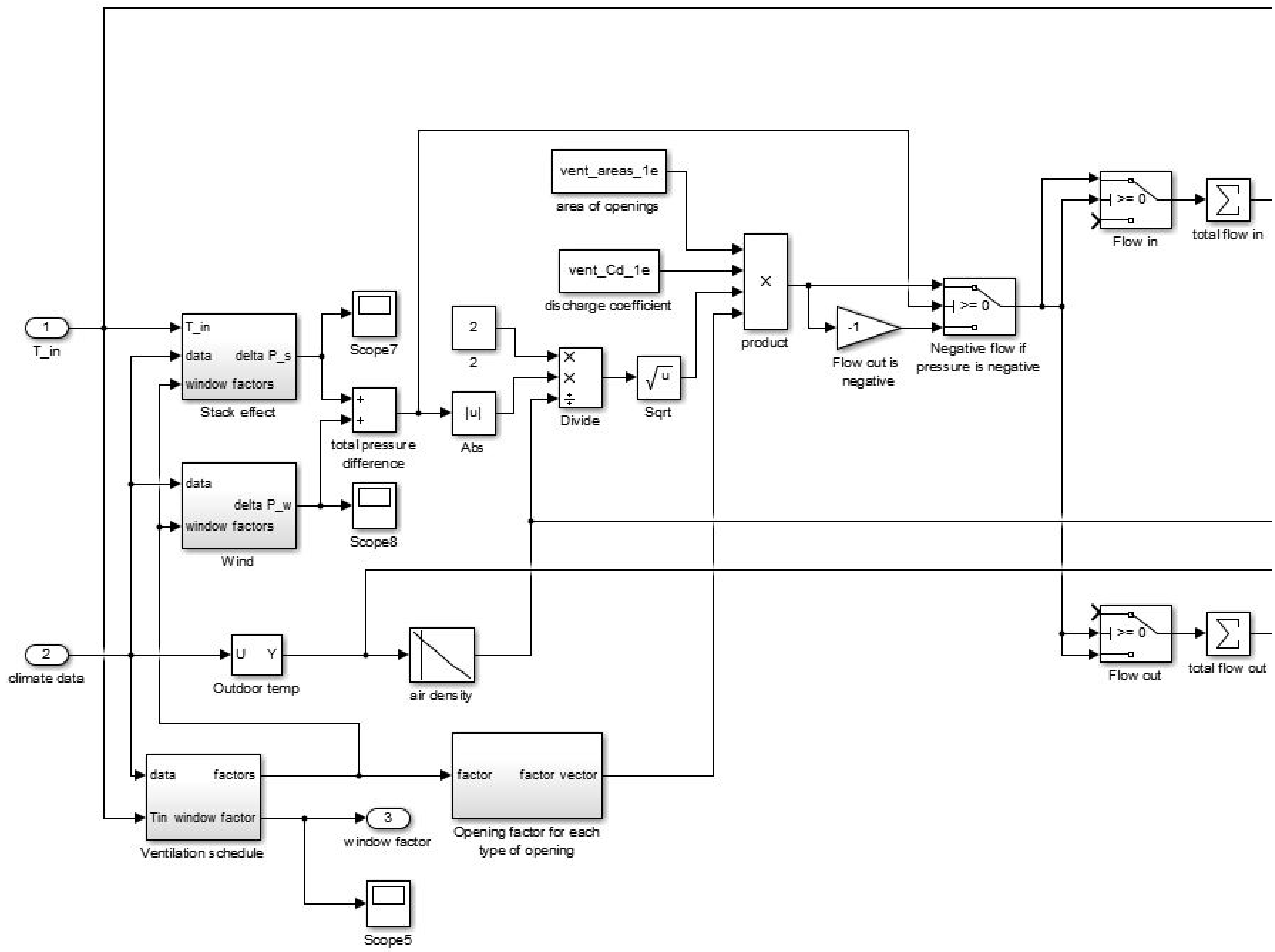


Figure 4.2: Calculation of air flow rate through each opening to find the total air flow in and out.

An average of the flow in and flow out is used when calculating the air change rate and the heat transfer through ventilation. Complete mixing of indoor air is assumed. The air change rate and heat transfer are calculated as described in Sections 2.3.3 and 2.3.4. Figure 4.3 below shows how the air change rate and heat transfer are calculated with Simulink, once the total air flow in and out is known. The model includes the possibility to set a minimum air change rate that represents air leakages that occur even when openings are closed.

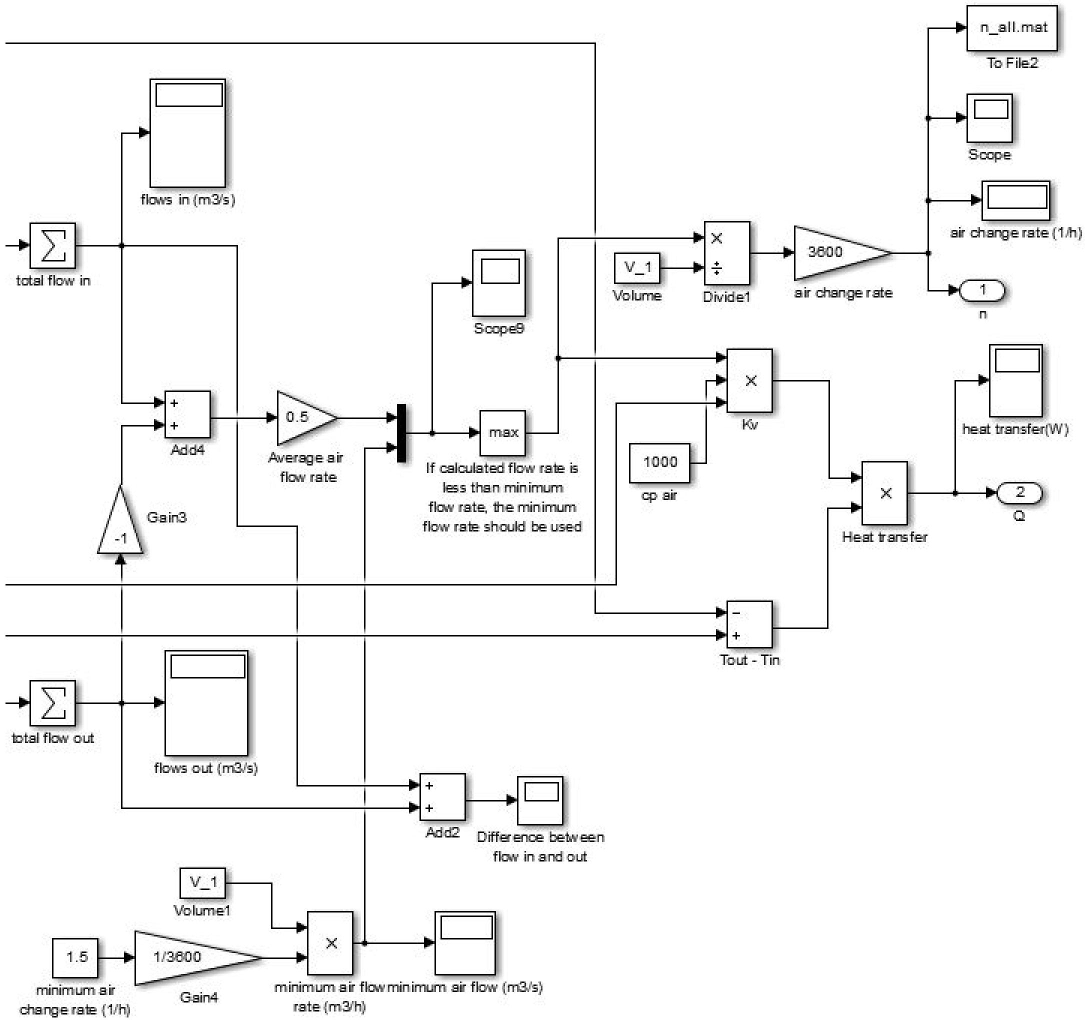


Figure 4.3: Calculation of air change rate and heat transfer through ventilation.

With a desired fresh air intake of 8 l/s per person and 0.35 l/s per m^2 of floor area, the desired air change rate becomes approximately 9 1/h for a typical classroom. More air flow is beneficial though because of thermal comfort reasons, since air flow improves thermal comfort when it is hot. Air flow is also required to remove heat produced by the students.

4.1.2.1 Openings

Different types of openings are modeled in order to improve the accuracy of the ventilation calculation. The model has five categories of openings: windows, doors, *jaali*, ventilators and other openings. Windows are the most common type, and the existing schools rely almost only on windows. Doors are modeled separately because of the different size and because they are almost always open during the school hours. *Jaali* is the local screened lattice opening that is used in corridors of some schools. Ventilators are smaller ventilation windows placed above regular windows that were found in some schools in Islamabad and Mansehra. Other openings include for example windcatchers.

Each opening is defined by four parameters: the area, middle height, discharge coefficient, and the direction the opening is facing. Openings that have identical parameters (eg. windows that face the same direction at the same height) are grouped together and treated as one opening with a larger area. Table 4.1 below presents the values used for standard openings.

Table 4.1: Properties of openings

	Area [m^2]	Middle height [m^2]	Discharge coefficient
Window	1.4	1.35	0.60
Door	2	1	0.60
Jaali	1	1.35	0.65
Ventilator	0.3	2.4	0.62

Each opening type can be set as opened or closed during school hours, during the night, or at all times. The openings can also be partially open. The effect that closing an opening has on the discharge coefficient is neglected. An opening factor is used to describe how open an opening is and the opening factor varies between 1 (fully open) and 0.05 (fully closed but with some leakage).

4.1.2.2 Wind

The wind induced pressure difference over each opening is calculated as described in Section 2.3.1. The meteorological wind speed from the climate date is adjusted for the height of the opening. The wind pressure coefficient, C_p, is calculated for each opening based on the angle between the normal of the opening and the current wind direction. The values from table 4.2 are used.

Table 4.2: Wind pressure coefficients

Angle between wind and normal of wall	C_p [-]
0	0.4
45	0.1
90	-0.3
135	-0.35
180	-0.2
225	-0.35
270	-0.3
315	0.1

For the roof, a C_p of -0.4 is used.

Since the amount and size of openings is not equally distributed in every direction, the internal pressure coefficient, C_{pi}, varies depending on the wind direction and on the opening factor of the openings. The model calculates the internal pressure coefficient separately for each major time step. The model calculates how many percentage of the current total opening area, A_{tot}, each opening j represents and then multiplies the C_p of the opening with this percentage.

$$C_{pi} = \sum_{j=1}^{n} \frac{A_j}{A_{tot}} C_{pj}$$

Figure 4.4 shows an example of how the internal pressure coefficient varies throughout the year in one case.

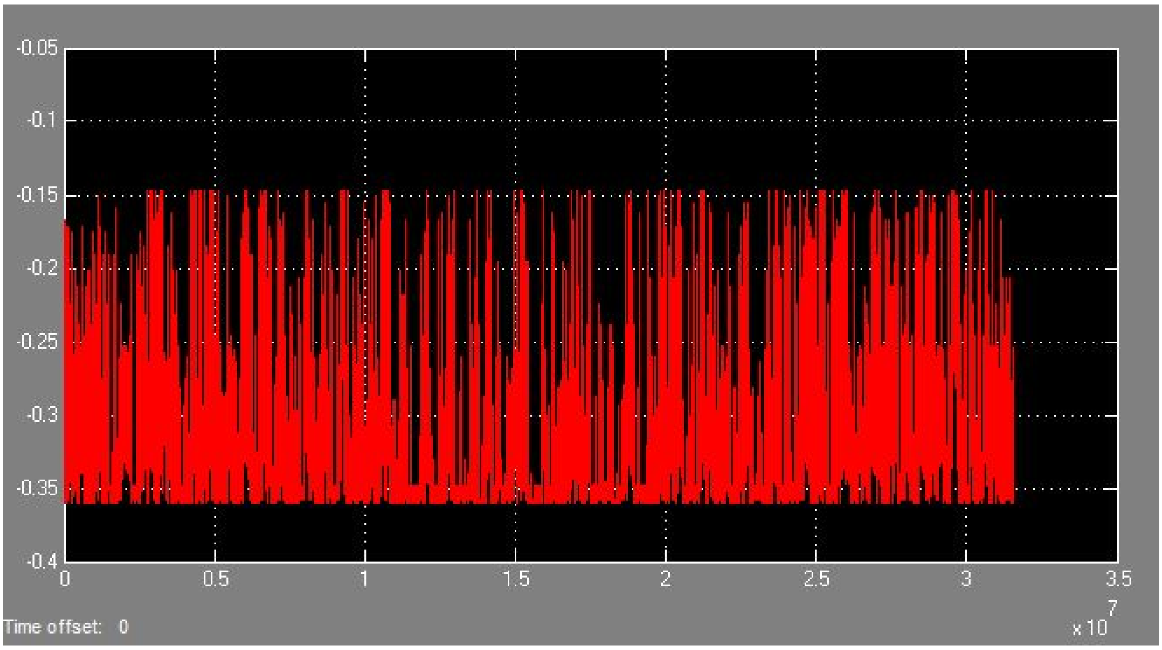


Figure 4.4: Variation of internal wind pressure coefficient throughout the year.

4.1.2.3 Stack effect

The pressure difference due to stack effect is calculated as described in Section 2.3.2. The location of the neutral pressure plane is determined from mass balance so that the total flow in through all openings equals the total flow out. The location of the neutral pressure plane varies depending on which openings are open and closed, and the location is calculated separately for each major time step

The height of the neutral pressure plane, z, is determined through iteration. The model uses the average of the height between openings to determine an initial guess for the height of the neutral pressure plane. The pressure difference and the air flows through each external opening is then calculated as described in sections 2.3.2 and 2.3.3. The flows are added together and if the absolute value of the sum of flows is more than 0.1 m^3/s, the calculation is repeated with a new guess for z. A new value of z is calculated based on the whether the net flow is negative or positive and whether the indoor or outdoor temperature is higher.

If the outdoor temperature is lower than the indoor temperature, air flows in from below the indoor pressure plane and out from above it. If the net flow is negative and the absolute value is more than 0.1 m^3/s, the model increases the height z by 0.01 m. If the net flow is positive and the absolute value is more than 0.1

m^3/s, the model decreases the height z by 0.01 m. If the outdoor temperature is higher than the indoor temperature, the reverse happens.

The iteration is stopped if the value of z starts escalating between two values, i.e. if the value of z is the same as two iterations ago. In this case the actual location of the neutral pressure plane would be between the two values, but the accuracy of 0.01 m is not enough to determine the exact location.

Figure 4.5 shows an example of how the location of the neutral pressure plane varies throughout the year in one case.

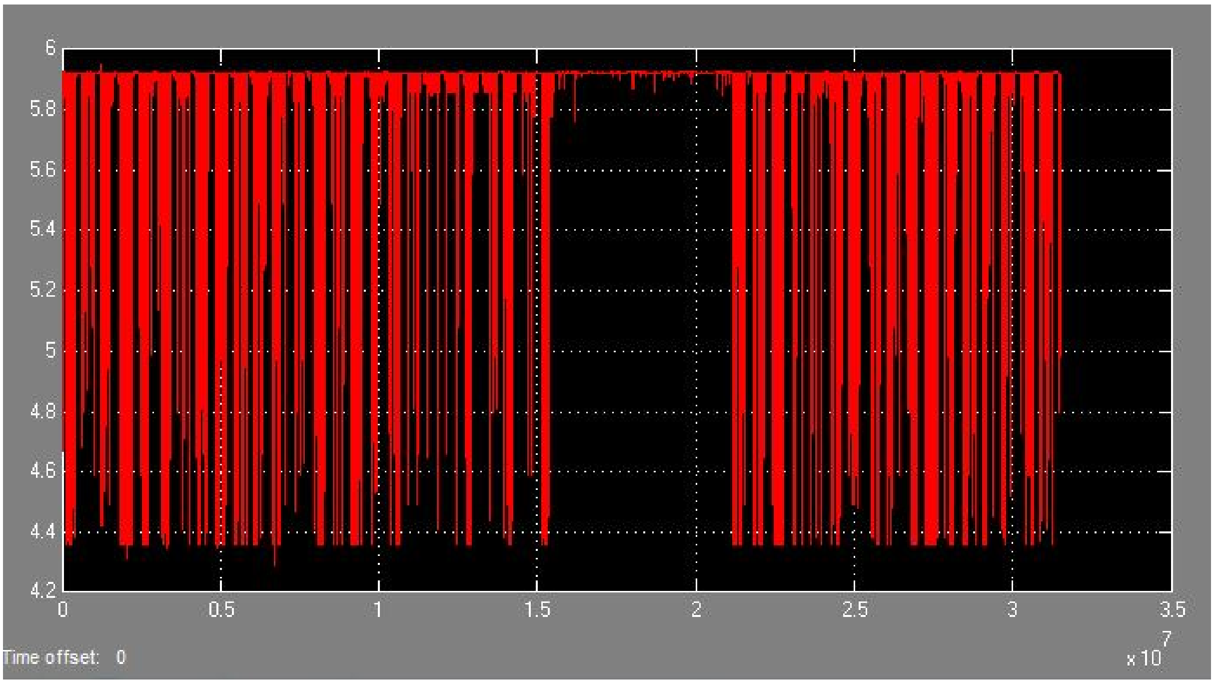


Figure 4.5: Variation of the location of the neutral pressure plane.

4.1.3 Transmission losses and gains

Transmission losses and gains through the building envelope are calculated as described in Section 2.2.2. An equivalent outdoor temperature, T^e, is used instead of the outdoor temperature, and this considers convective heat transfer, long-wave radiation exchange with the sky and solar radiation. These are calculated as describe in Sections 2.2.3, 2.2.4 and 2.2.5 respectively. The equivalent temperature becomes:

$$T^e = T_{out} + \frac{1}{\alpha_e}\left(I_{sol} \cdot \alpha_{sol} + \left(T_{sky} - T_{out}\right) \cdot \alpha_r\right)$$

where $\alpha_e = \alpha_c + \alpha_r$ is the effective heat transfer coefficient.

Transmission losses/gains through windows are not considered since windows are often open for ventilation purposes, and even when the windows are closed air leakages will have a greater effect on the overall heat transfer. Transmission losses/gains to/from the ground are also neglected.

4.1.4 Solar gains

Solar gains through windows are considered and calculated as described in Section 2.2.5. Some of the solar radiation hitting a window is reflected, and in this case a transmission value is 0.86 is assumed for direct solar radiation and 0.78 for diffuse radiation. This means that when the windows are fully open, 86% of the direct solar radiation and 78% of the diffuse solar radiation hitting a vertical surface in that orientation is considered as solar gains. The transmission of direct solar radiation varies with the angle of incidence and the maximum value 0.86 occurs when the angle of incidence is 0°. However, since the windows are mostly open, this reduction in solar radiation is only considered once the windows are at least half closed. That is, when the windows are more than half open, the transmission of solar radiation is assumed to be 100%. Figure 4.6 shows how this part is modeled in Simulink.

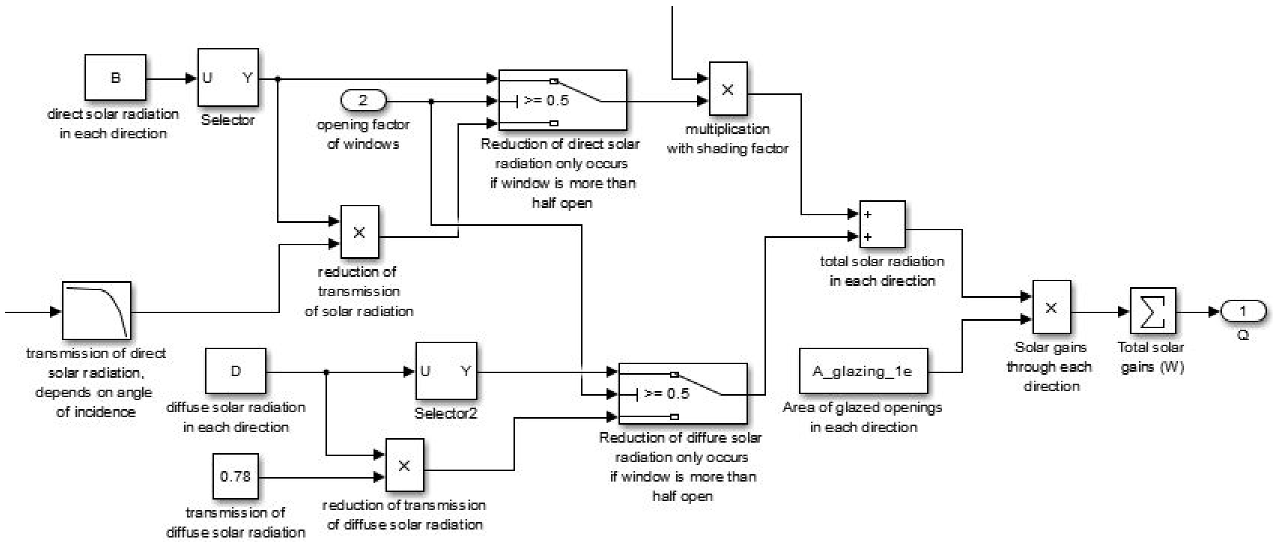


Figure 4.6: Calculation of solar gains depending on angle of incidence, orientation, shading factor and opening factor.

The model also has a built in shading system that reduces the direct solar radiation. There are three types of shades, one is a shading device (as used in Karachi and Lahore) and the other is a roof overhang (used in Mansehra) and the third is a longer overhang which corresponds to a verandah (found on the side with the doors). The size of the existing overhangs has been used to determine how much of the window is shaded depending on the height of the sun. The shading factor also considers how the solar azimuth affects the shading since the shade/overhang is only fully effective if the azimuth is normal to the surface.

The calculation of the shading factor for a window shade is illustrated in Figure 4.7. The model reads the angles between the surface normal the height of the sun (α) and the azimuth (β), and uses these to determine two shading factors that vary from 1 (fully shaded) to 0 (no shade), S_1 and S_2 respectively. The total shading factor, S is then given by:

$$S = 1 - S_1 \cdot S_2$$

For the total shading factor, 0 corresponds to fully shaded and 1 to no shading. If β is greater than 90°, the shading factor is 0.

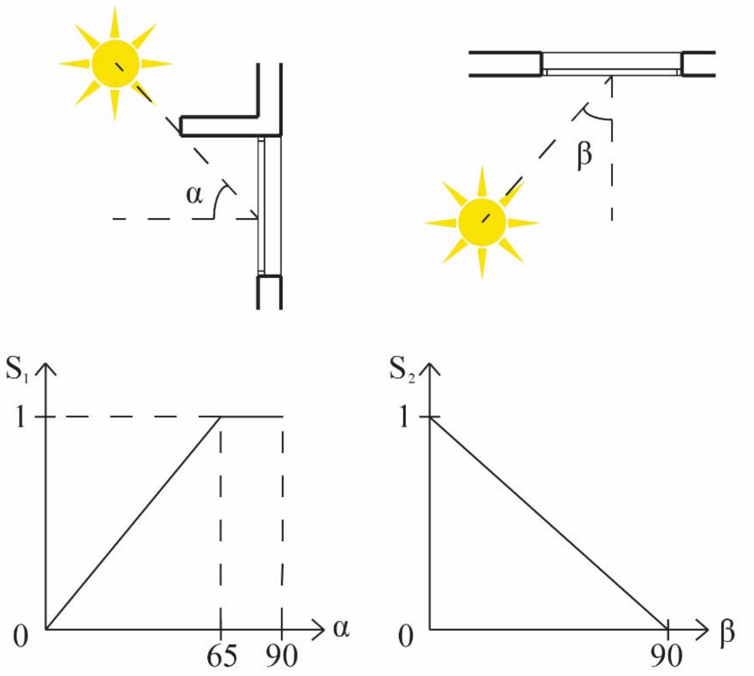


Figure 4.7: Calculation of shading factor for a regular window shade.

Shading caused by surrounding buildings is neglected.

4.1.5 Internal gains

Only internal gains from people are considered as there are very few other gains or they are small in comparison. The schools have energy efficient lighting and it is only used later in the afternoon, or in certain classrooms that have less daylight. The only other appliance that would contribute to internal gains is ceiling fans but since the study looks only at passive methods of providing air flow, ceiling fans are also neglected from the internal gains. Frequent power cuts further decrease the amount of internal gains from appliances.

The primary school classrooms are designed for 30 students and in the calculation this maximum number of occupants is used. Each person is assumed to generate 100 W of heat. Internal gains are present only during school hours which are 8 to 12 for the morning shift and 13 to 17 for the afternoon shift. There are no internal gains on two days of the week (weekend) and during the two-month summer or winter break.

4.1.6 Climate data

Climate data from Meteonorm is used. For Mansehra, climate data for nearby Balakot is used. The wind direction is simplified so that there are only 8 possible directions (N, NE, E, SE, S, SW, W, NW).

According to Meteonorm, the wind direction is defined clockwise from north (N=0°, E=90°, S=180°, W=270°). Comparing the Meteonorm data with data from other sources shows that this definition seems to match for Lahore, Islamabad and Balakot, but not for Karachi. Karachi is located by the sea and according to other climate data and according to the local people, the dominant wind direction is from the sea, i.e. southwest, west and south. Using Meteonorm definition of wind direction would give the dominant wind direction as northwest, west and north instead. Because of this the wind direction is redefined for Karachi to be counterclockwise from south instead (S=0°, E=90°, N=180°, W=270°). This decision is further backed up by Meteonorm's data for nearby Hyderabad, which is known to have an even more dominant wind direction from southwest and which according to Meteonorm's definition would instead have a dominant wind direction from northwest.

From Meteonorm, only the horizontal and normal solar radiation is obtained. The direct radiation for vertical surfaces is calculated by multiplying the direct normal radiation with the cosine of the angle of incidence. The diffuse radiation for vertical surfaces is calculated according to Perez et al (1990).

4.2 Reference schools

In order to create more reliable data that is easy to compare, a simple reference school is used for the majority of simulations. This school, shown in Figure 4.8, has four classrooms with sizes according to existing TCF primary school classrooms. All classrooms are studied together as one interior zone and it is assumed that the temprature is the same in all classrooms. There is an exterior verandah on the side where the doors are. The results are also compared with a more complex school that has several zones and a courtyard, and this is described in Section 4.3.6.

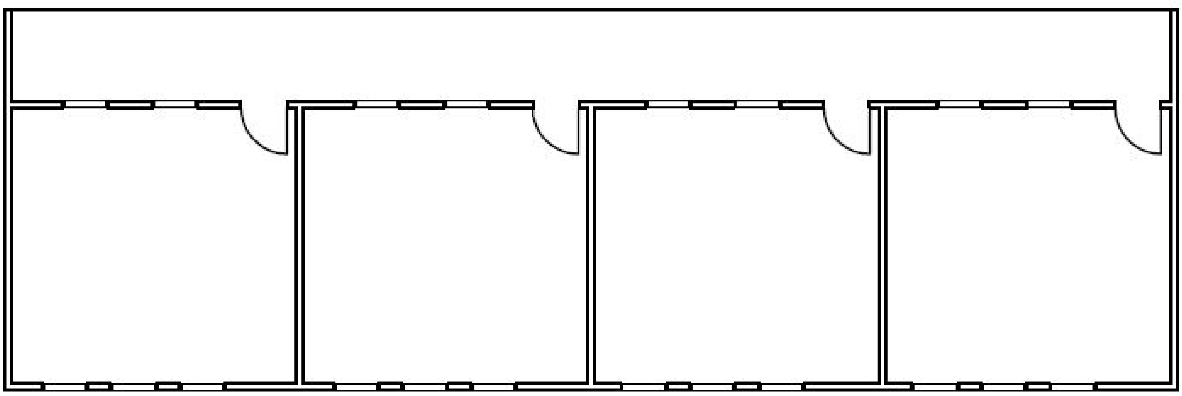


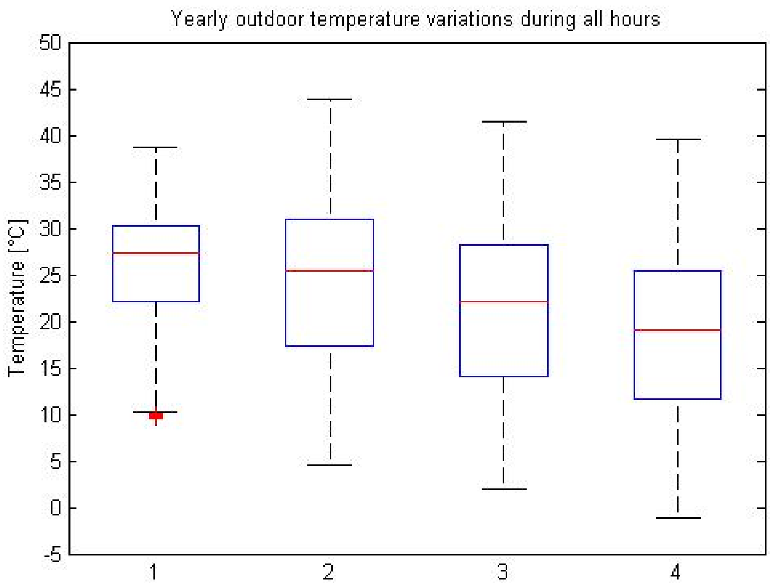
Figure 4.8: Plan of simplified school used in the simulations.

The details of the reference school are shown in Table 4.3. Around Mansehra there are two types of schools with different materials. Since the first type has a much greater thermal inertia, the schools behave differently and are thus studied separately.

Table 4.3: Details of design and operation of reference schools.

	Karachi	Lahore	Islamabad	Mansehra type 1	Mansehra type 2
Operation	Double shift (8:00 to 18:00) and summer vacation (July, August)			Double shift (8:00 to 18:00) and winter vacation (January, February)	
Orientation	Long sides facing north and south, with doors facing north and all windows facing south or north				
Shading	Almost always shaded on the north side (verandah) and a shading device on the south side		Almost always shaded on the north side (verandah) and no shading on the south side	Almost always shaded on the north side (verandah) and a roof overhang on the south side	
Materials	152 mm concrete block wall and 152 mm concrete roof	229 mm brick wall and 152 mm concrete roof	229 mm concrete block wall and 152 mm concrete roof	Wall with two layers of concrete blocks (152 mm on the inside and 229 mm on the outside) with 50 mm EPS in between & pitched roof of corrugated metal with a wooden ceiling and 50 mm of EPS in between	Wall with wood cement board on the outside, wooden board on the inside and 50 mm EPS in between & pitched roof of two sheets of corrugated metal with 50 mm of EPS in between
Ventilation	Windows opened during school hours according to need (usually open but gradually closed if indoor temperature drops or if the wind speed is very high) and doors always open during school hours.				

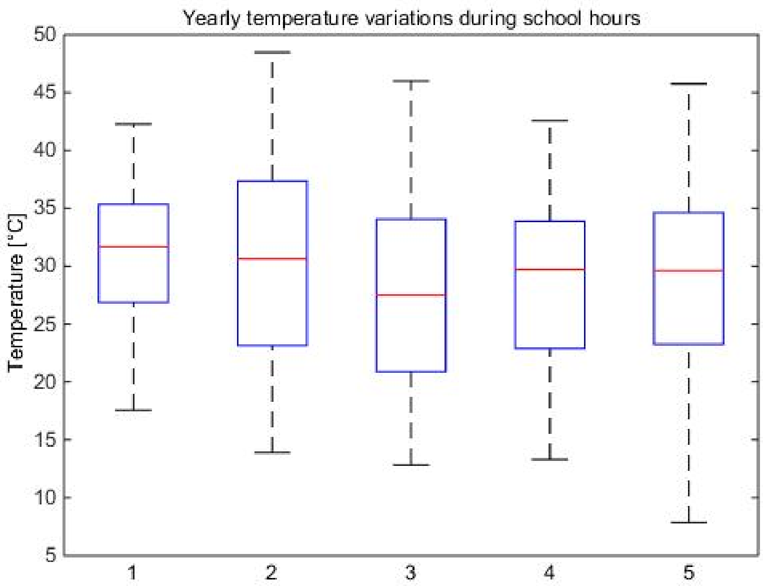
Figures 4.9, 4.10 and 4.11 show how the outdoor and indoor temperature and the air change rate vary in the cities and the reference schools studied.



1 – Karachi
2 – Lahore
3 – Islamabad
4 – Mansehra (Balakot)

Figure 4.9: Yearly outdoor temperature variations for the four cities studied.

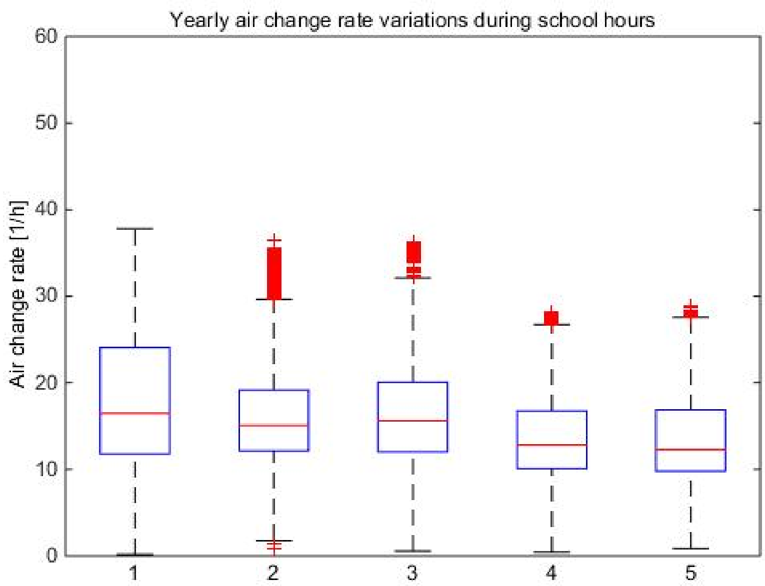
Comparing Figure 4.9 above and Figure 4.10 below shows that the variation in indoor temperature is similar to the variation in outdoor temperature, but the indoor temperature values are higher. The average temperature is about 5°C more indoors than outdoors. This seems unnecessary because with enough ventilation, the indoor temperature should be the same as the outdoor temperature. The two schools types in Mansehra have about the same average temperature, but the school that hass less thermal inertia (type 2) has more extreme peak temperatures



1 – Karachi
2 – Lahore
3 – Islamabad
4 – Mansehra type 1
5 – Mansehra type 2

Figure 4.10: Temperature variations in the reference schools for one year during school hours.

From Figure 4.11 below it is clear that on average Karachi has the highest air change rates, and this is also expected because wind speeds are also highest in Karachi, as seen from Figure 2.5 in Section 2.1.1. However, Karachi also has the lowest minimum air change rates, which suggests that the schools there don't perform optimally during varying weather conditions.



1 – Karachi
2 – Lahore
3 – Islamabad
4 – Mansehra type 1
5 – Mansehra type 2

Figure 4.11: Air change rate variations in the reference schools for one year during school hours.

Figure 4.12 below shows the monthly temperature variations for Islamabad. It is clear that the thermal comfort varies a lot throughout the year with the average monthly temperature varying between approximately 18°C and 39°C. There are no values for July and August because the summer holiday is then and the figure only considers school hours.

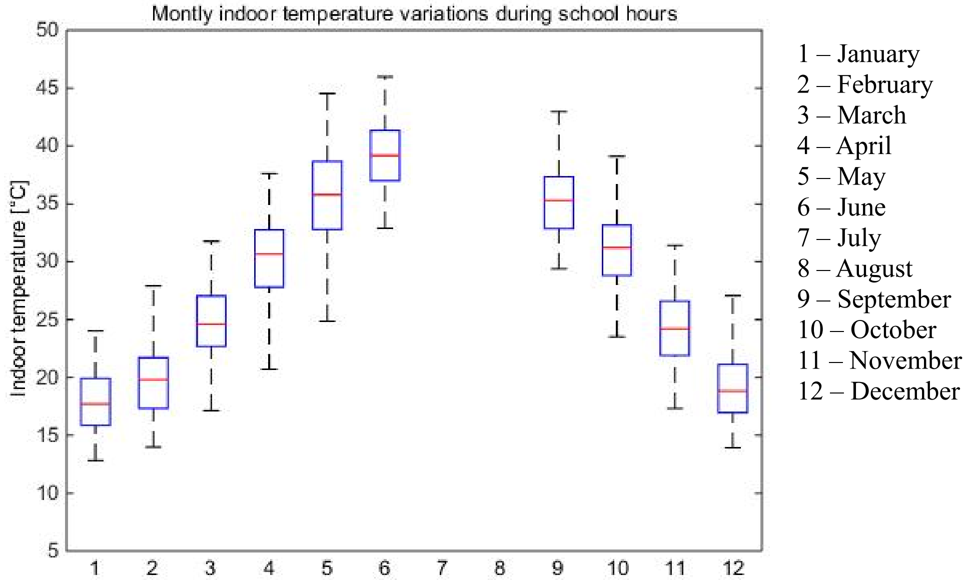


Figure 4.12. Temperature variations in the reference school for Islamabad for each month and during school hours.

Figure 4.13 shows that the air change rate varies less from month to month. During the colder months the windows are closed more often which reduces the air change rate.

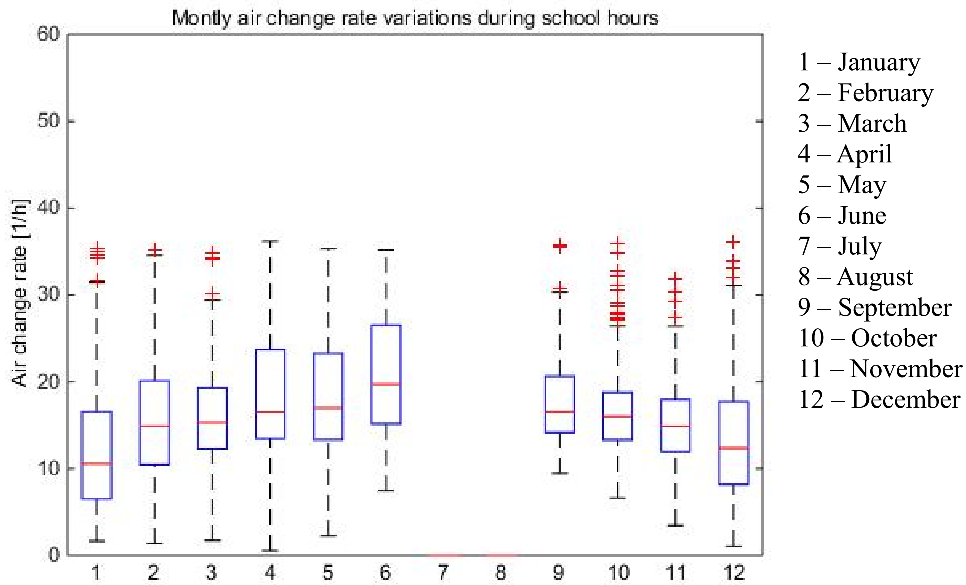


Figure 4.13: Air change rate variations in the reference school for Islamabad for each month and during school hours.

4.3 Operation, design and materials

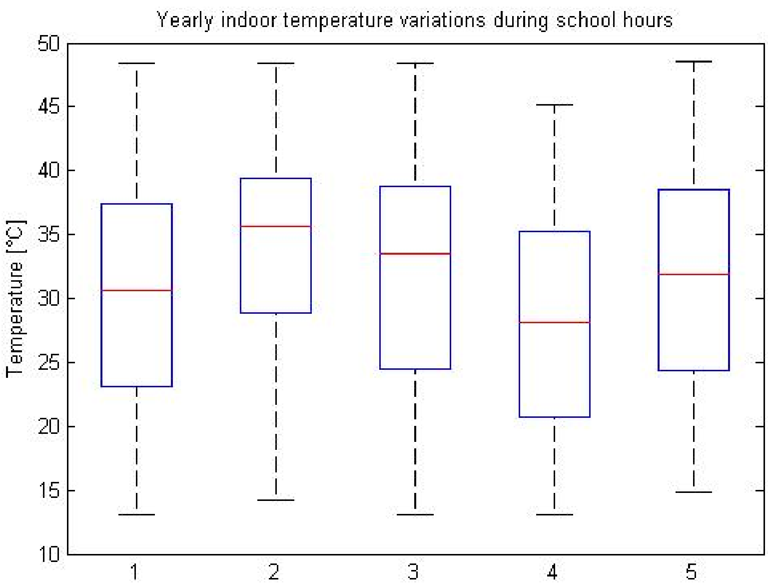
This section presents results from studies on the effect of different school hours, orientation, shading, internal gains and materials. The effect of the courtyard is also studied and this is done with a more complex Simulink model.

4.3.1 Operation

TCF schools are used in morning and afternoon shifts with a different set of student in each shift. Some schools are only used during one shift, but in the reference cases two shift are used as this is more common. The shifts in the model are from 8 to 13 and 13 to 18. Breaks during the school day are neglected from the model, but they would have a positive effect on thermal comfort by allowing for heat to be removed more efficiently.

The schools have either a summer vacation or a winter vacation. A summer vacation is more common and it coincides with the rainy season. A winter vacation is common practice in the colder mountain regions because snowfall makes going to school difficult. In the model the vacation is simplified to two months, which are July – August for the summer vacation and January – February for the winter vacation. Summer vacation is the reference for Karachi, Lahore and Islamabad, and winter vacation is the reference for Mansehra.

Figure 4.14 shows the indoor temperature variations in Lahore when the operation of the school is changed. The effects are similar in the other cities.



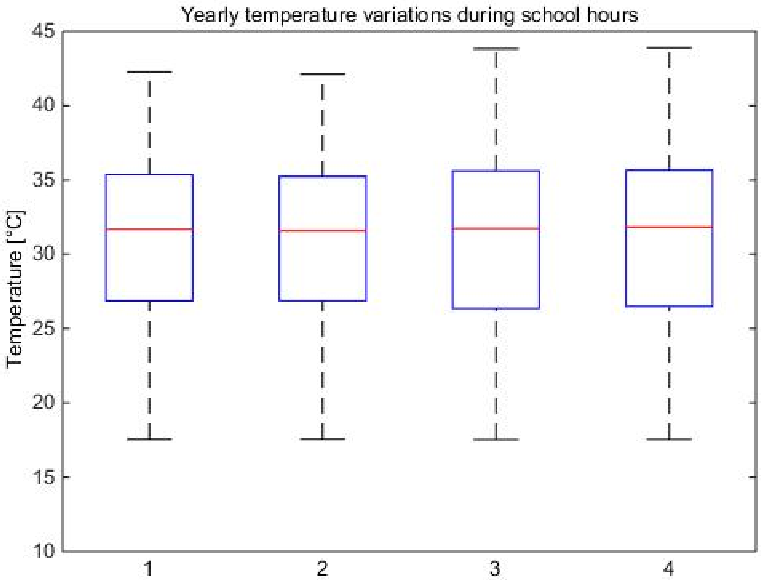
1 – Reference (summer vacation and double shift)
2 – Winter vacation
3 – No vacation
4 – Only morning shift
5 – Only afternoon shift

Figure 4.14: Temperature variations for one year during school hours in Lahore for cases with different school operation.

The morning shift clearly has lower indoor temperatures than the afternoon shift, and schools that only have one shift should have the morning shift. In the winter however, the afternoon shift could be more beneficial since the mornings can be too cold. In cases 1 and 2 the peak temperature is the same which suggest that even with the summer vacation the school is being used during the hottest time of the year, even though a summer vacation clearly lowers the average temperatures.

4.3.2 Orientation

In the reference cases the schools are oriented so that the long sides are facing south and north. Figure 4.15 below shows how the indoor temperature would vary in Karachi if the school was oriented in differently. The effects are similar in the other cities.

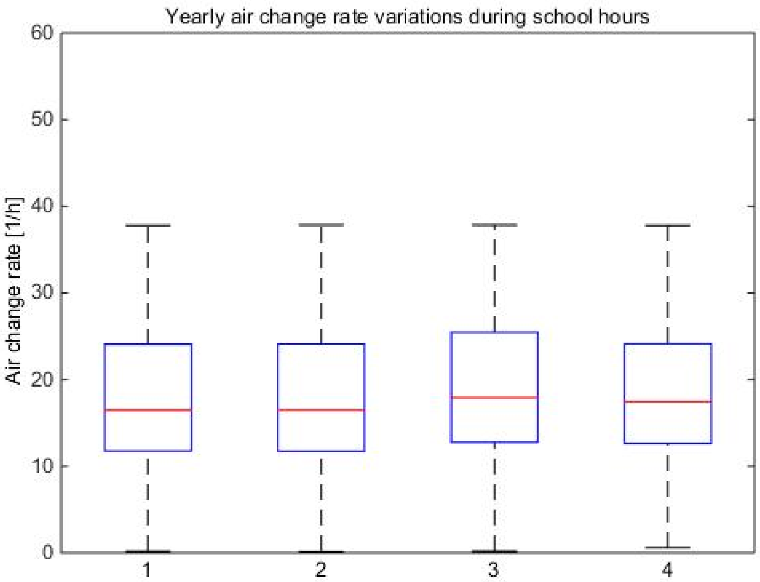


1 – Reference (doors and the side with most shade facing north)
2 – Doors facing south
3 – Doors facing west
4 – Doors facing east

Figure 4.15: Temperature variations for one year during school hours in Karachi for cases with different building orientations.

Orientation has a very small impact on the indoor temperature, but having the long sides face east and west would increase temperatures a little, probably because these sides receive more solar radiation because of the lower angle of the sun.

Figure 4.16 below shows that orientation also has a very small effect on the air change rate in Karachi. According to TCF, Karachi has a dominant wind from the south and this is why the schools are oriented with long sides facing south and north. However, the wind data from Meteonorm shows a wider spread with winds from south, southwest, west and northwest. If the wind direction varies more, the orientation also has less significance for the air change rate. In other cities the air change rate was even less affected by the orientation.

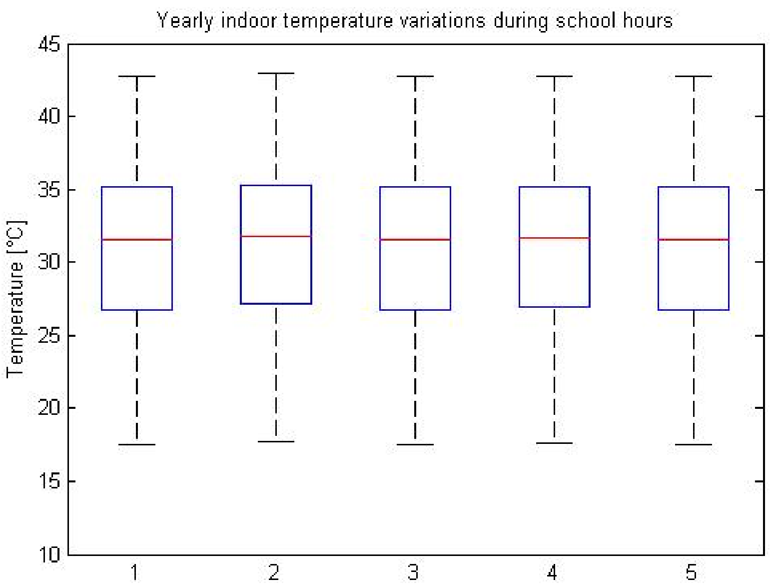


1 – Reference (doors and the side with most shade facing north)
2 – Doors facing south
3 – Doors facing west
4 – Doors facing east

Figure 4.16: Air change rate variations for one year during school hours in Karachi for cases with different building orientations.

4.3.3 Shading

The model has the possibility to change between different overhangs and the effect of this shading has been studied. Figure 4.17 shows the effect on temperature in Karachi, but the effects are similar in other cities.



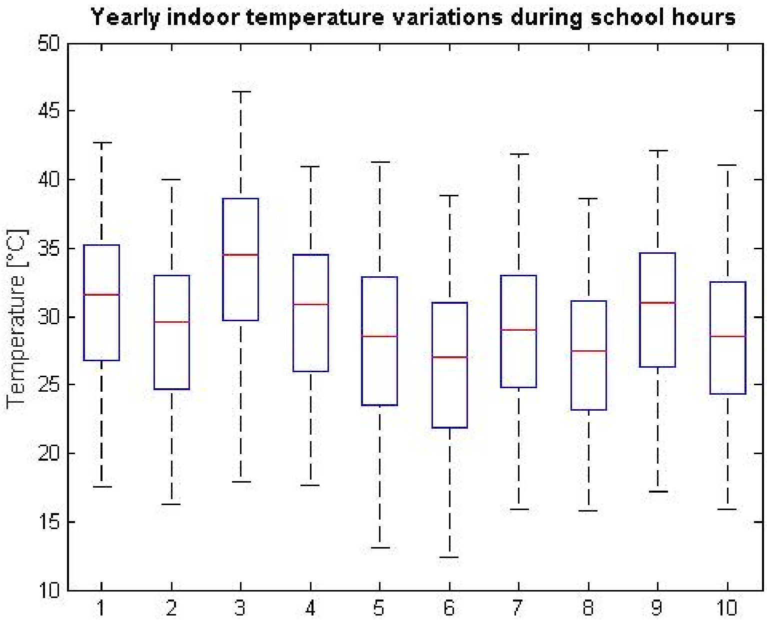
1 – Reference (almost always shaded on the north side (verandah) and a shading device on the south side)
2 – No shading
3 – Shading device on both sides
4 – Long shade (verandah) on both sides
5 – Long shade (verandah) on north side and short roof overhang on the south side.

Figure 4.17: Temperature variations for one year during school hours in Karachi for cases with different shading devices.

Figure 4.17 shows that shading windows has a negligible effect on the indoor temperature. This is surprising because the amount of solar radiation is high, but the effect can be explained by the fact that the sun is high most of the year and this means that the angle of incidence is high for vertical surfaces which reduces the amount of solar radiation. Also, shading doesn’t affect diffuse solar radiation in the model.

4.3.4 Internal gains

In the reference case internal gains are considered to be 100 W per person. This is a standard value used in energy calculations, but since the occupants are mostly children, the amount of heat produced is probably less. Also, even though the classrooms are designed for 30 students, they were not as full during the visits. Figure 4.18 below shows the effect that internal gains has on the indoor temperature in Karachi and the effects are similar in other cities. Constant air change rates and different ventilation strategies are also tested to see how ventilation and internal gains work together.



1 – Reference
2 – No internal gains
3 – Internal gains as in reference, n=1.5 1/h
4 – No internal gains, n=1.5 1/h
5 – Internal gains as in reference, n=20 1/h
6 – No internal gains, n = 20 1/h
7 – Internal gains as in reference, seasonal night ventilation and ventilation according to need during school hours
8 – No internal gains, seasonal night ventilation and ventilation according to need during school hours
9 – 75% internal gains, ventilation according to reference
10 – 75% internal gains, seasonal night ventilation and ventilation according to need during school hours

Figure 4.18: Temperature variations for one year during school hours in Karachi for cases with different internal gains and air change rates.

Internal gains clearly have a significant effect on the indoor temperature. Without internal gains (case 2) the indoor temperature variations would be closer to the outdoor temperature variations.

This study also shows how important ventilation is for removing the heat produced by the people, as can be seen from the cases 3 and 4 where a constant air change rate on 1.5 1/h is used. There is only a small rise in temperature between cases 2 and 4 when the air change rate is lowered in the absence of internal gains. But between cases 1 and 3 where internal gains are present, there is a much more significant rise in temperature when the air change rate is lowered.

In traditional buildings that rely on passive cooling it is common to keep the building closed during the day to avoid heat gains from the outdoor air. This can however not be done in this case where so many people are using the relatively small space during the day.

4.3.5 Materials

The materials used in the schools vary regionally, and the purpose of this study is to see if these regional materials are appropriate of if alternatives would perform better. The following building envelope constructions, described from exterior to interior, are tested to study their effect on the indoor temperature:

Wall 1: 152 mm hollow concrete blocks
Wall 2: 229 mm hollow concrete blocks
Wall 3: 229 mm hollow concrete blocks + 50 mm EPS + 152 mm hollow concrete blocks
Wall 4: 1/3 (the bottom) is the same as wall 3, rest 15 mm wood cement board + 50 mm EPS + 15 mm wooden board
Wall 5: 229 mm bricks
Wall 6: 15 mm wood cement board + 50 mm EPS + 152 mm hollow concrete blocks
Roof 1: 152 mm concrete
Roof 2: Steel sheet, 50 mm EPS, 15 mm wooden board
Roof 3: Steel sheet, EPS 50 mm, Steel sheet
Roof 4: 152 mm concrete, 50 mm EPS, 152 mm concrete
Roof 5: Steel sheet
Roof 6: 50 mm EPS +152 mm concrete

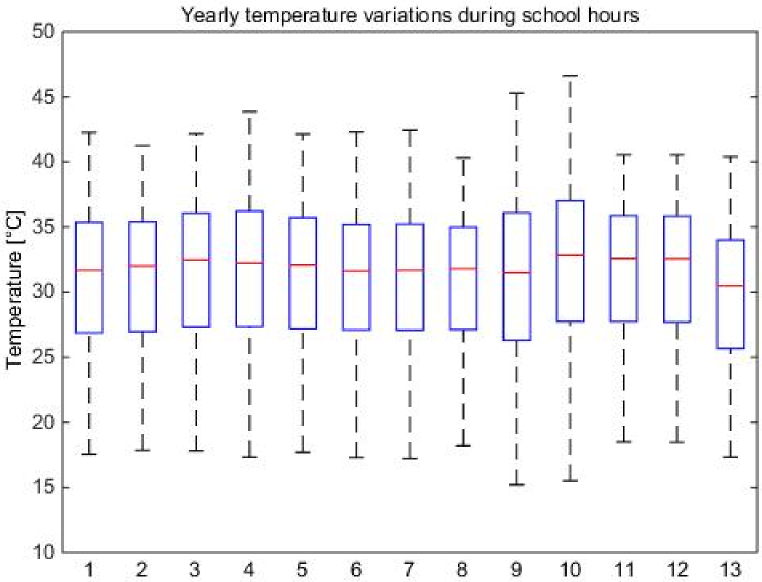
Most of these are constructions that are found in existing schools, except for wall 6 and roofs 4, 5 and 6. The material properties used are presented in Table 4.4.

Table 4.4: Material properties used

	Thermal conductivity [W/mK]	Density [kg/m^3]	Specific heat capacity [J/kgK]	Emissivity [-]	Absorptivity for solar radiation [-]
Concrete block	0.9	2000	900	0.85	0.6
Concrete	1.7	2200	900	0.85	0.6
Brick	0.6	1500	850	0.85	0.68
Wood cement board	0.25	-	-	0.85	0.6
EPS insulation	0.04	-	-	-	-
Wooden board	0.13	500	1400	-	-
Steel sheet	50	7850	500	0.3	0.4

4.3.5.1 Karachi

Figure 4.19 below shows the effects that different material combinations would have on the indoor temperature in Karachi.



1 – Reference (wall 1 and roof 1)
2 – Wall 2
3 – Wall 3
4 – Wall 4
5 – Wall 5
6 – Roof 2
7 – Roof 3
8 – Roof 4
9 – Roof 5
10 – Wall 4 + Roof 3 (insulation but little thermal mass)
11 – Wall 3 + Roof 4 (insulation and thermal mass)
12 – Wall 6 + Roof 6 (insulation and thermal mass but less materials than in 11)
13 – Reference but with white paint (α_{sol}= 0.35)

Figure 4.19: Temperature variations for one year during school hours in Karachi for cases with different materials.

The existing materials seem to work well in Karachi. Thermal inertia (case 1) is more important than insulation (case 10) in this climate since it reduces temperature peaks. Having both insulation and thermal mass (cases 8,11 and 12) would reduce temperature peaks somewhat, both during summer and winter, but this wouldn't have a very large effect and the average temperature would remain the same. If insulation would be added, it would make most difference in the roof (case 8). However, adding insulation increases the average temperatures slightly, and this could be because insulation would reduce the amount of heat lost during the night due to long-wave radiation exchange with the sky.

Reducing absorption of solar radiation with a lighter surface color, case 13, would have the greatest effect. This would protect from the heat of the sun, and it wouldn't reduce the effect of night sky radiation like insulation would. While reflective metallic surfaces would also reduce the absorption of solar radiation, white paint has a higher emissivity value than metallic surfaces and this means that a white roof can lose more heat during the night due to night sky radiation (Koenigsberg et al 1973).

In the reference case the absorptivity for solar radiation is 0.6 and for white surface it is 0.35, and Figure 4.20 shows how the equivalent temperature at the roof surface varies in these two cases. The temperature differences varies between approximately 10°C and 20°C which is a significant difference. During the night the temperature in both cases drops to that below outdoor temperature, showing the effect of night sky radiation. The roof is clearly a major heat source. A lower absorptivity than 0.35 could also be achieved, depending on the surface finish, and this would be beneficial.

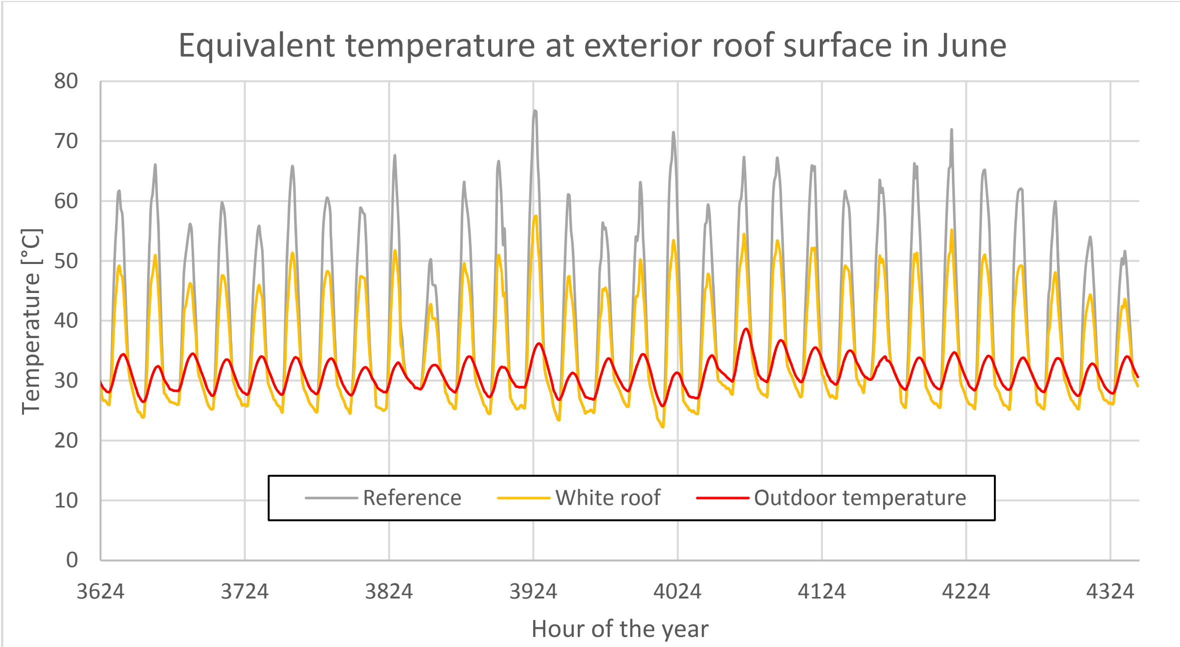
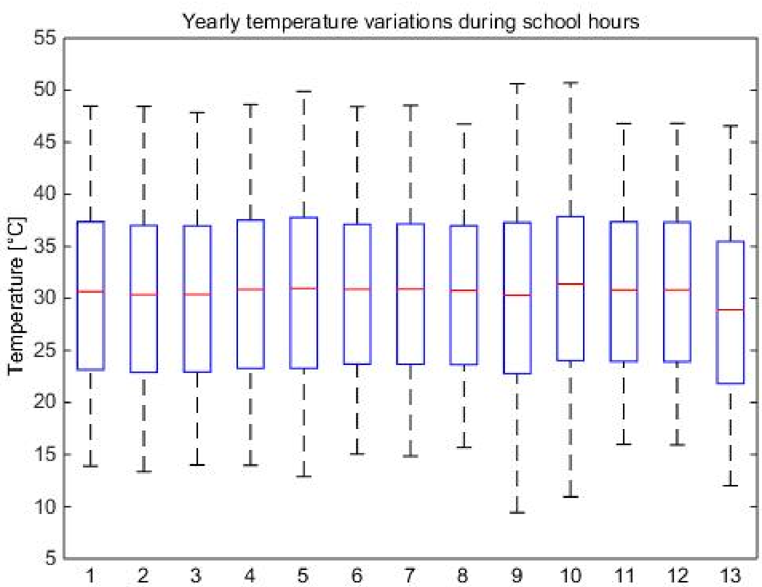


Figure 4.20: Variation of exterior roof surface temperature in June in Karachi without and with white paint.

4.3.5.2 Lahore

Figure 4.21 shows the effect of different materials on indoor temperature in Lahore. The effects are similar to Karachi, although insulation would be slightly more beneficial here because of the colder winter temperatures. A lighter surface color would also reduce temperatures the most in this case, but it also reduces the minimum temperatures in winter which is not desirable. A lighter surface color on the walls would be in practice more difficult since the schools here are built with bricks, but the roof makes the largest difference.

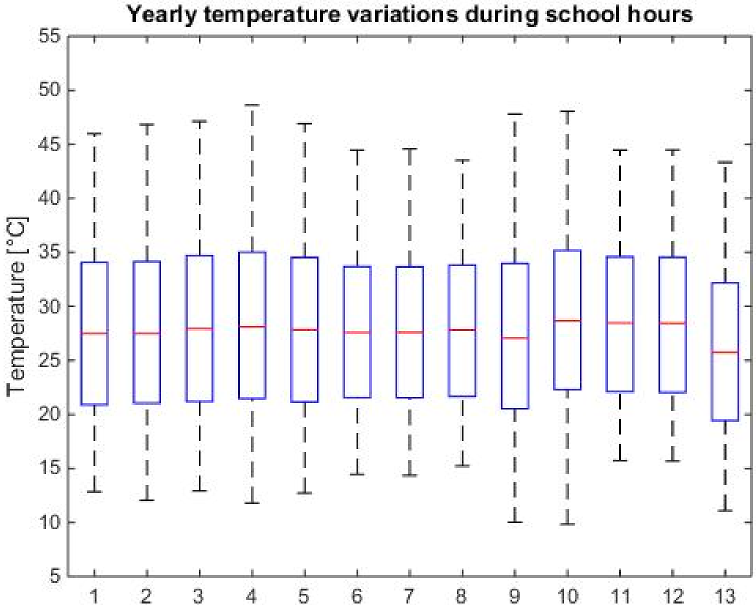


1 – Reference (wall 5 and roof 1)
2 – Wall 1
3 – Wall 2
4 – Wall 3
5 – Wall 4
6 – Roof 2
7 – Roof 3
8 – Roof 4
9 – Roof 5
10 – Wall 4 + Roof 3 (insulation but little thermal mass)
11 – Wall 3 + Roof 4 (insulation and thermal mass)
12 – Wall 6 + Roof 6 (insulation and thermal mass but less materials than in 11)
13 – Reference but with white paint (α_{sol}= 0.35)

Figure 4.21: Temperature variations for one year during school hours in Lahore for cases with different materials.

4.3.5.3 Islamabad

Figure 4.22 shows how different materials would effect the indoor temperature in Islamabad.



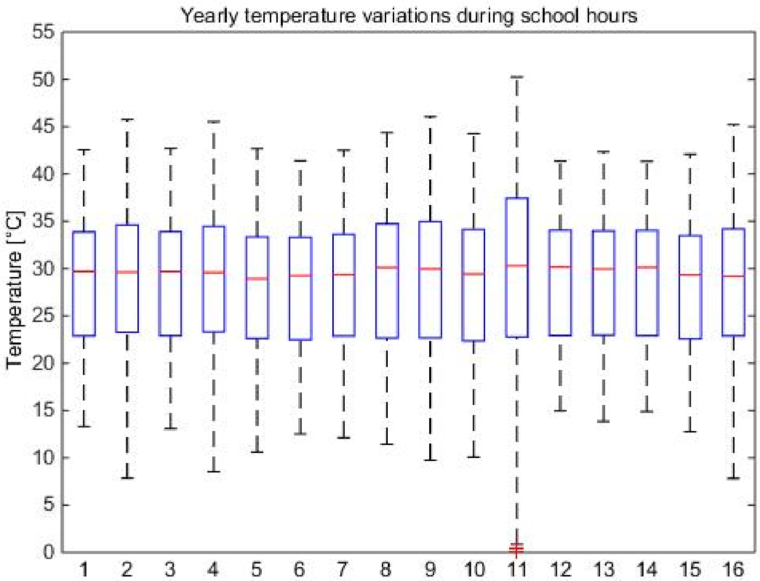
1 – Reference (wall 2 and roof 1)
2 – Wall 1
3 – Wall 3
4 – Wall 4
5 – Wall 5
6 – Roof 2
7 – Roof 3
8 – Roof 4
9 – Roof 5
10 – Wall 4 + Roof 3 (insulation but little thermal mass)
11 – Wall 3 + Roof 4 (insulation and thermal mass)
12 – Wall 6 (insulation and thermal mass but less materials than in 11)
13 – Reference but with white paint (α_{sol}= 0.35)

Figure 4.22: Temperature variations for one year during school hours in Islamabad for cases with different materials.

Using a 229 mm concrete block wall instead of 152 mm wall doesn't seem to have much effect. The reason behind the thicker wall is that it is thought to insulate better, but it raises the minimum temperature by only about 1°C while the average temperature remains the same, so it is questionable whether the thicker wall is worth the extra cost. The effect of materials is otherwise similar to Lahore.

4.3.5.4 Mansehra

Figure 4.23 below shows the effect of different materials in Mansehra.



1 – Reference type 1 (wall 3 and roof 2)
2 – Reference type 2 (wall 4 and roof 3)
3 – Wall 3 + Roof 3
4 – Wall 4 + Roof 2
5 – Wall 1 + Roof 2
6 – Wall 2 + Roof 2
7 – Wall 5 + Roof 2
8 – Wall 3 + Roof 1
9 – Wall 4 + Roof 1
10 – Wall 1 + Roof 1
11 – Wall 4 + Roof 5
12 – Wall 3 + Roof 6
13 – Wall 4 + Roof 6
14 – Wall 6 + Roof 6
15 – Type 1 with white paint (α_{sol}= 0.35)
16 – Type 2 with white paint (α_{sol}= 0.35)

Figure 4.23: Temperature variations for one year during school hours in Mansehra for cases with different materials.

Both insulation and thermal inertia help in this climate to reduce temperature peaks, both in summer and winter. This can be seen from the difference between reference type 1 and 2. Insulation has a greater effect in this climate than in the other cities because it raises the minimum temperatures more. Insulating the roof is very important as can be seen from case 11 without roof insulation or thermal inertia. Adding thermal mass to the roof (cases 12, 13 and 14) would improve thermal comfort but the effect is not major when comparing with reference type 1. The similarities of cases 1 and 15 and cases 2 and 16 shows that reducing the absorption of solar radiation with a lighter color would have less effect in this case because the insulation is already helping keep solar radiation out.

The existing walls of school type 1 have concrete blocks on both sides of the insulation. Since thermal inertia is only beneficial if it is on the interior side, the exterior concrete blocks could be replaced with a lighter façade (wall 6) to save materials. It would be more beneficial to add the extra concrete to the ceiling as in roof 6 so that both the wall and the roof would have both thermal inertia and insulation. In reality, the existing roofs have a lot of thermal bridges that are not accounted for in this calculation and the roof construction 6 would also help solve this problem.

Comparing cases 5, 6 and 7 that have thermal mass in the walls but no insulation and the first reference school shows that the insulation in the walls does very little in the summer and only raises the minimum winter temperatures slightly. In reality, the existing insulated walls include a lot of thermal bridges cause by steel studs, and these thermal bridges further reduce the effectiveness of wall insulation. Using thick concrete blocks (case 6) or bricks (case 7) could be almost as effective as using concrete blocks and insulation (case 1). However, removing the insulation from the roof (case 10) would have a greater effect on both maximum and minimum temperatures so the roof insulation should be kept.

4.3.6 Courtyard

Most existing TCF schools have two floors and schools in Karachi and Lahore usually also have a courtyard. This affects the natural ventilation and also the amount of solar radiation received. In order to study the effect of the courtyard and the second floor, a more complex Simulink model has been built. This model has five zones, four of which have classrooms and one of which contains the courtyard. The courtyard in this case is thus assumed to act like an interior space that has a large horizontal opening at the top.

Figure 4.24 below shows the layout of one floor of this courtyard school with the different zones color coded, and the second floor is identical. The courtyard zone extends both floors while the classroom zones only have one floor. The courtyard zone also includes the corridors which have *jaali* openings in the ends. The classrooms located to the sides of the courtyard (marked white in the figure) are not studied, but their thermal inertia is included in the courtyard zone.

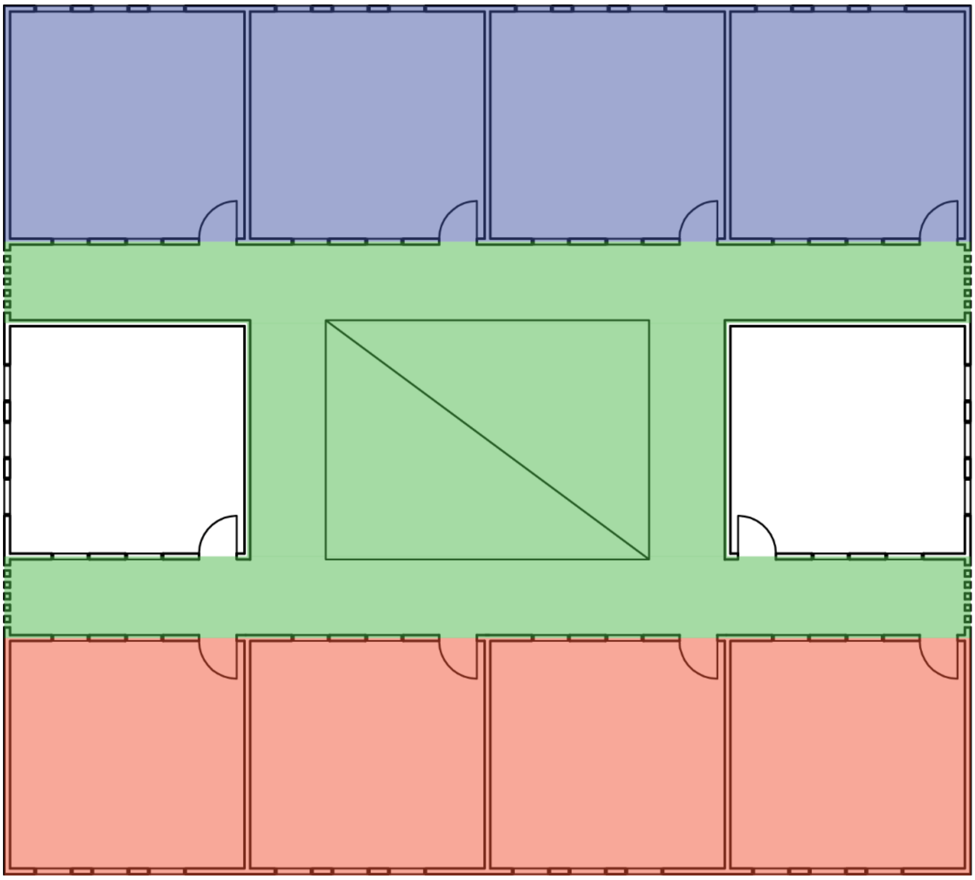


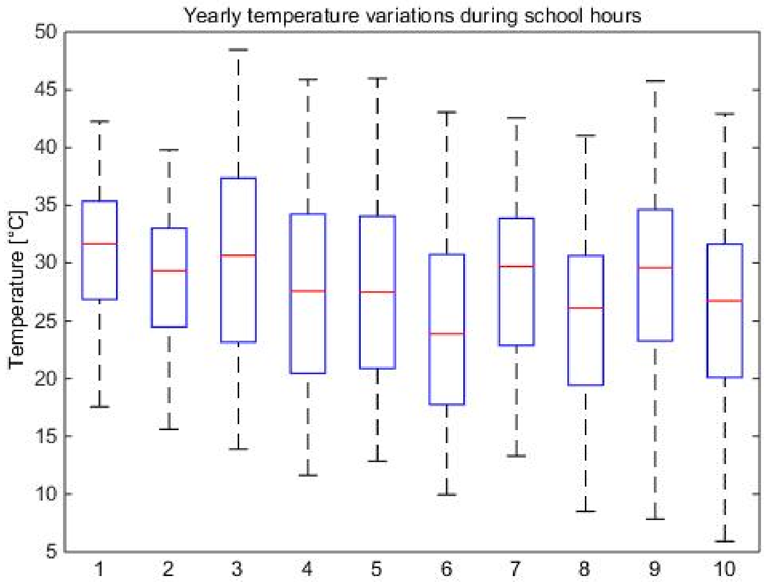
Figure 4.24: Plan of school with courtyard showing the different zones.

The courtyard is assumed to act like an atrium that raises the neutral pressure plane and creates a negative wind pressure coefficient, which draws air out of the building through the roof opening. When calculating the neutral pressure plane, only exterior openings are considered and the interior temperature is assumed to be the same everywhere (an average of all zones, including the courtyard). The flow is first calculated separately for each classroom zone and based only on the exterior openings. The net flow from or to the exterior is then assumed to be equal to the net flow to or from the courtyard.

The courtyard roof opening is assumed to have an air flow similar to windows and other openings, but in reality there will be more turbulent flow and two-way flows. The discharge coefficient of the courtyard roof opening is also difficult to estimate because of its large size. However, a sensitivity study showed that the discharge coefficient has a negligible effect on the temperature and air flows of the classroom zones, and since the courtyard itself is not studied in detail, this error is acceptable. A discharge coefficient of 0.5 is used.

The walls of the classrooms facing the courtyard are shaded because there are walkways along the courtyard. These walls thus receive no solar radiation, but the courtyard itself receives heat gains from the sun as the surfaces warm up. How much solar radiation is received depends on the angle of the sun and how much of the walls are shaded. The model calculates how much surface area is facing the sun at each timestep depending on the angle of the sun, and this area is then multiplied with the total solar radiation in that orientation at that timestep.

Figure 4.25 below shows the indoor temperature variations in the schools without and with a courtyard. The average of all classroom zones is studied.

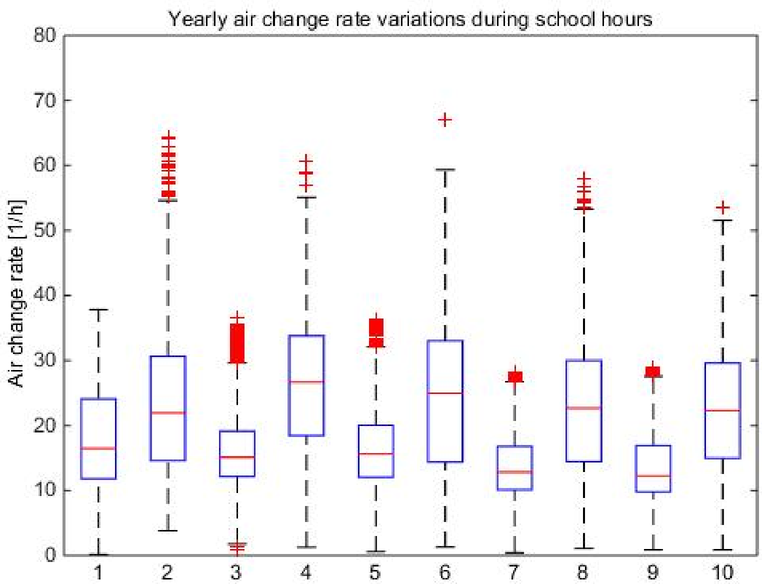


1 – Karachi reference
2 – Karachi with courtyard
3 – Lahore reference
4 – Lahore with courtyard
5 – Islamabad reference
6 – Islamabad with courtyard
7 – Mansehra type 1 reference
8 – Mansehra type 1 with courtyard
9 – Mansehra type 2 reference
10 – Mansehra type 2 with courtyard

Figure 4.25: Temperature variations for one year during school hours in cases without and with courtyard.

From this figure we can see that the courtyard lowers both the average and peak temperatures. This can be explained with an increased air change rate and with a decrease in exterior heat gains because the exterior surface area to volume ratio has decreased.

Figure 4.26 below shows the effect the courtyard has on the air change rate in the different cities.

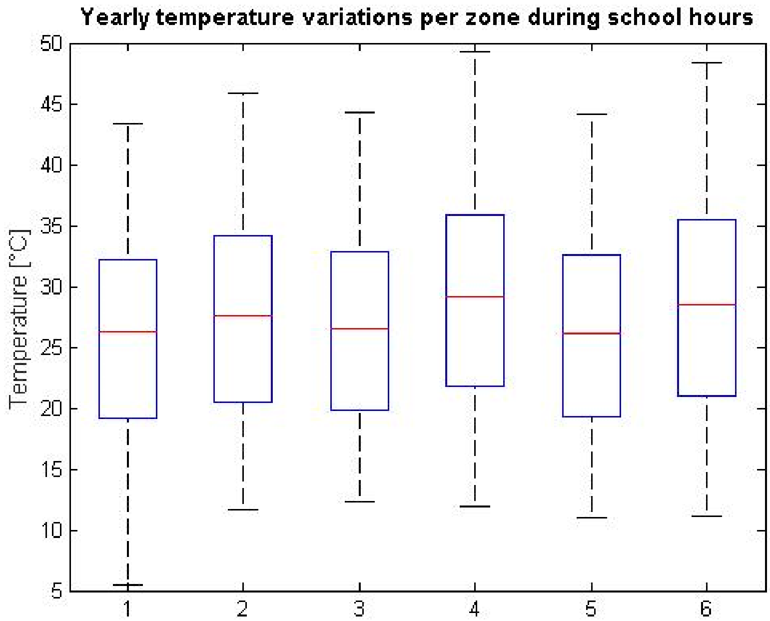


1 – Karachi reference
2 – Karachi with courtyard
3 – Lahore reference
4 – Lahore with courtyard
5 – Islamabad reference
6 – Islamabad with courtyard
7 – Mansehra type 1 reference
8 – Mansehra type 1 with courtyard
9 – Mansehra type 2 reference
10 – Mansehra type 2 with courtyard

Figure 4.26: Air change rate variations for one year during school hours in cases without and with courtyard.

Figure 4.26 shows that the courtyard clearly raises the air change rate. The courtyard raises the neutral pressure plane considerably which means that stack effect becomes more significant. In Karachi the effect is less significant because ventilation relies less on stack effect, although the minimum air change rate is raised considerably.

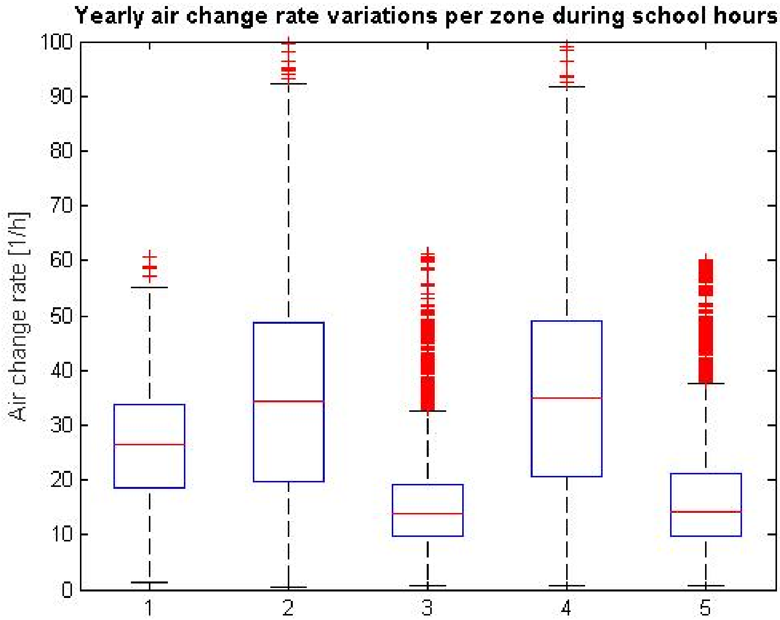
However, the courtyard doesn't affect all zones equally. Figure 4.27 below shows the temperature variations in different zones in a courtyard school in Lahore.



1 – Outdoor temperature
2 – Average indoor temperature
3 – First floor south
4 – Second floor south
5 – First floor north
6 – Second floor north

Figure 4.27: Temperature variations for one year during school hours per zone in courtyard school in Lahore

The second floor receives transmission gains through the roof that is exposed to large amounts of solar radiation, and this eplains the higher indoor temperature on the second floor. The difference between zones is even greater when looking at the air change rate, shown for Lahore in Figure 4.28 below. On the second floor the air change rate is lower because the windows there are closer to the neutral pressure plane, which is located at a high level because of the courtyard. The lower air change rate also contributes to higher temperatures on the second floor.



1 – Average
2 – First floor south
3 – Second floor south
4 – First floor north
5 – Second floor north

Figure 4.28: Air change rate variations for one year during school hours per zone in courtyard school in Lahore

The effect of the courtyard on the air change rate is similar in Islamabad and Mansehra, but the effect is less significant in Karachi where ventilation relies more on the wind than on the stack effect. In the existing schools, courtyards are primarily used in Karachi, but according to this study courtyards could be even more beneficial in other cities.

4.4 Ventilation

The studies before have already shown that ventilation is very important for removing heat, and a low air change rate correlates with higher indoor temperatures. This section presents studies done to test different ventilation strategies. Some of these strategies can be implemented in existing schools, while others test alternative designs of openings.

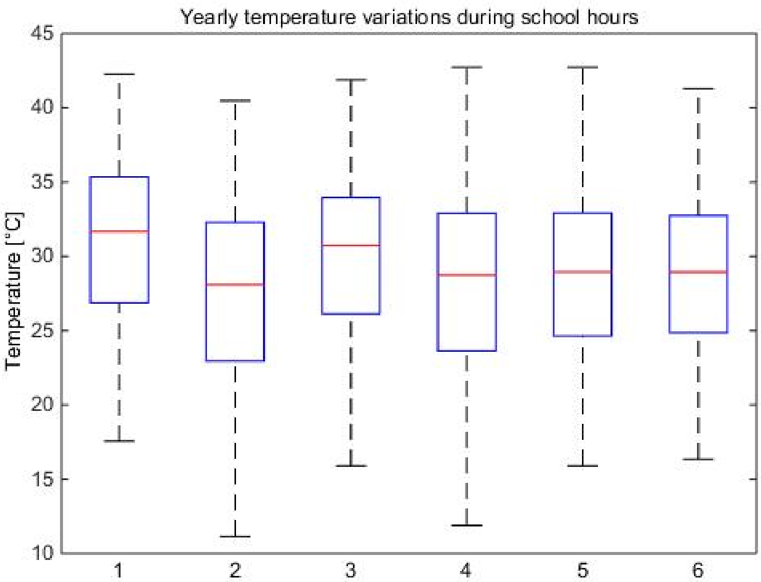
The reference case for ventilation is based on teachers opening and closing windows according to need. When the window is completely closed, there is still 5% of the maximum flow through the window, since the windows used are not very airtight. How open a window is in the model depends on the wind speed and on the indoor temperature. When the wind speed is below 1 m/s the window is fully open and after that it is gradually closed until it is fully closed at 4 m/s wind speed. Similarly, when the indoor temperature is above 20°C, the window is fully open and after this it gradually closed until the window is completely closed when the indoor temperature is 15°C.

Night ventilation is also tested, and the night ventilation times are set to be from 21:00 to 8:00. The model has the possibility to vary the ventilation seasonally so that night ventilation is not used during the coldest months of the year. In this schedule night ventilation is not used during months when the average outdoor temperature is below 22°C.

It is also possible to set openings as being always open during school hours, and this is the reference case for doors.

4.4.1 Operation of windows

In this study different opening schedules for the existing windows are tested. Figure 4.29 shows the resulting indoor temperature variations in Karachi.

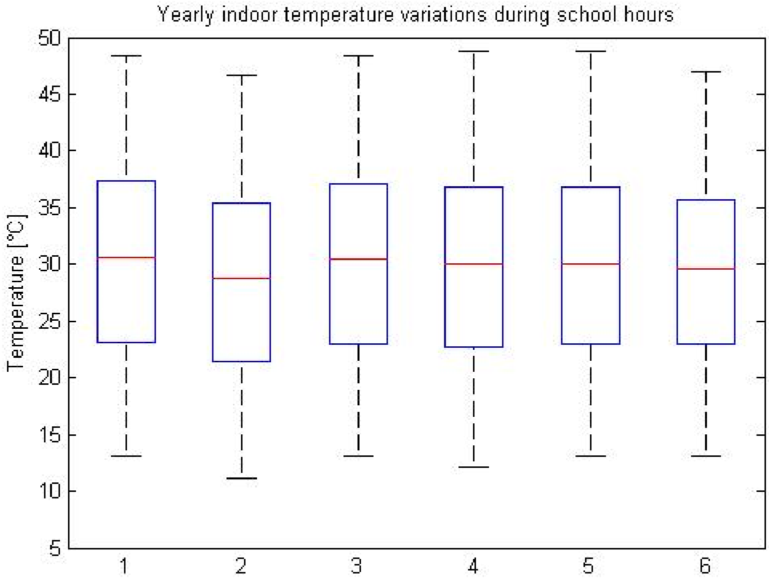


1 – Reference (windows open during the school hours according to need)
2 – Windows always open
3 – Windows always open during daytime
4 – Windows always open during nighttime, only doors open during the day
5 – Windows open during the day or night, depending on the season (night ventilation when the average monthly temperature is above 22°C)
6 – Windows seasonally open during the night, and also open during school hours according to need

Figure 4.29: Temperature variations for one year during school hours in Karachi for cases with different window operation..

Night ventilation is clearly effective in lowering the temperature even during the daytime. But even in this hot climate, night ventilation should only be done seasonally and not during the coolest months (in this case December, January and February), because otherwise the indoor temperature will be unpleasantly cold in the mornings, as can be seen from the low minimum values in cases 2 and 4. Comparing cases 4 and 6 shows that ventilation during the day doesn't raise temperatures, even though the outdoor air is hotter than the nighttime air that has cooled down the building, and this is probably due to the large effect of internal gains as discussed in Section 4.3.4.

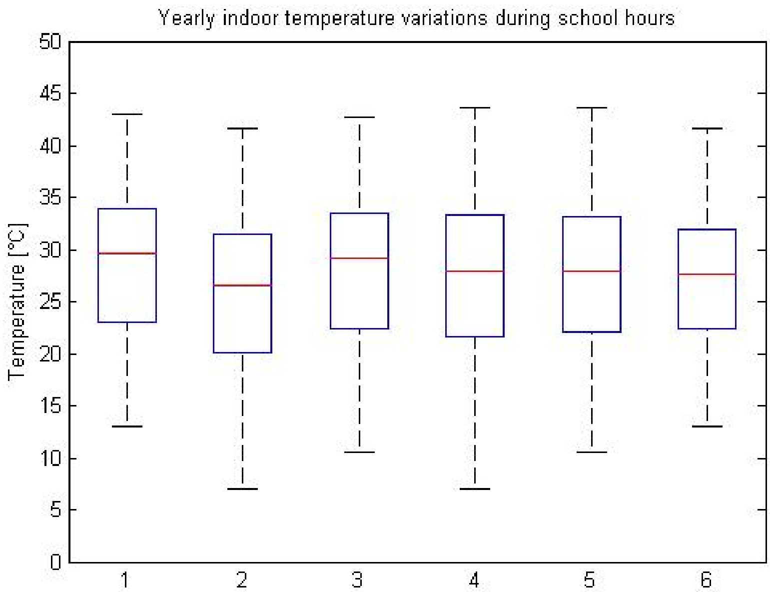
Figure 4.30 shows the indoor temperature results for Lahore. Although night ventilation is also beneficial in Lahore, here the effect is less significant, probably because air change rates are lower because of lower wind speeds. The situation is similar for Islamabad.



1 – Reference (windows open during the school hours according to need)
2 – Windows always open
3 – Windows always open during daytime
4 – Windows always open during nighttime, only doors open during the day
5 – Windows open during the day or night, depending on the season (night ventilation when the average monthly temperature is above 22°C)
6 – Windows seasonally open during the night, and also open during school hours according to need

Figure 4.30: Temperature variations for one year during school hours in Lahore for cases with different window operation.

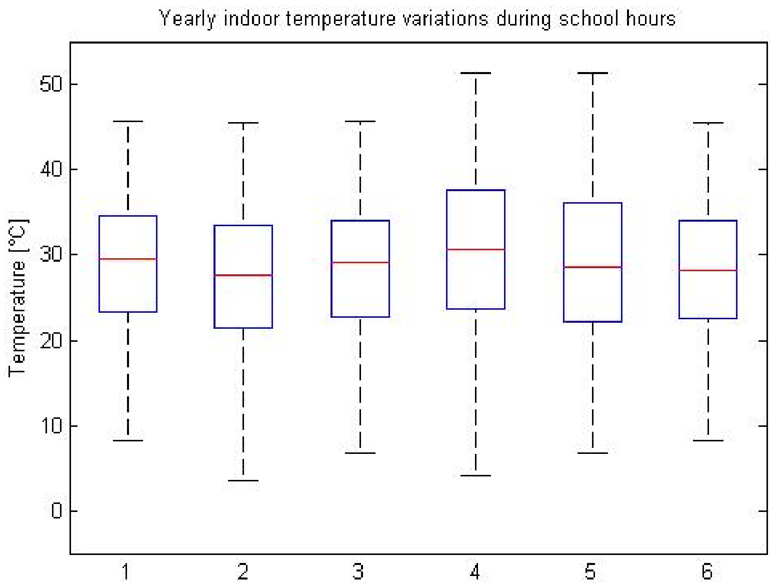
Figure 4.31 shows that the effects are also similar in Mansehra for type 1 school. However, it is more important here that windows are kept closed during the cold season, otherwise morning temperatures become very low.



1 – Reference (windows open during the school hours according to need)
2 – Windows always open
3 – Windows always open during daytime
4 – Windows always open during nighttime, only doors open during the day
5 – Windows open during the day or night, depending on the season (night ventilation when the average monthly temperature is above 22°C)
6 – Windows seasonally open during the night, and also open during school hours according to need

Figure 4.31: Temperature variations for one year during school hours in Mansehra type 1 school for cases with different window operation.

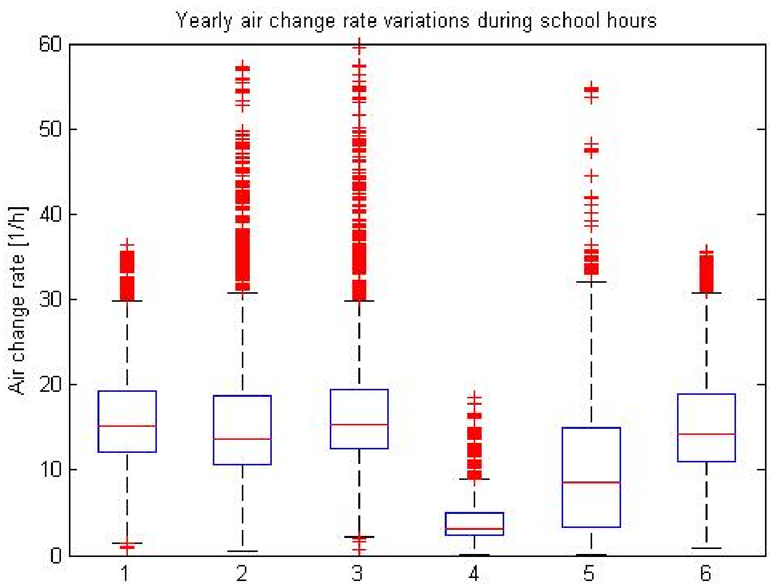
Figure 4.32 shows the effect in Mansehra type 2 school. This school has a much smaller thermal inertia, and because of this night ventilation is also less effective. In this school it is also more important that there is enough ventilation during the day because there is no thermal mass that can absorb the heat from the people (case 4).



1 – Reference (windows open during the school hours according to need)
2 – Windows always open
3 – Windows always constantly open during daytime
4 – Windows always open during nighttime, only doors open during the day
5 – Windows open during the day or night, depending on the season (night ventilation when the average monthly temperature is above 22°C)
6 – Windows seasonally open during the night, and also open during school hours according to need

Figure 4.32: Temperature variations for one year during school hours in Mansehra type 2 school for cases with different window operation.

Ventilation during the day is important to provide enough fresh air, and Figure 4.33 shows how the air change rate varies in Lahore. In case 4, when only doors are open during the day, the air change rate is below the desired 9 1/h minimum air change rate.



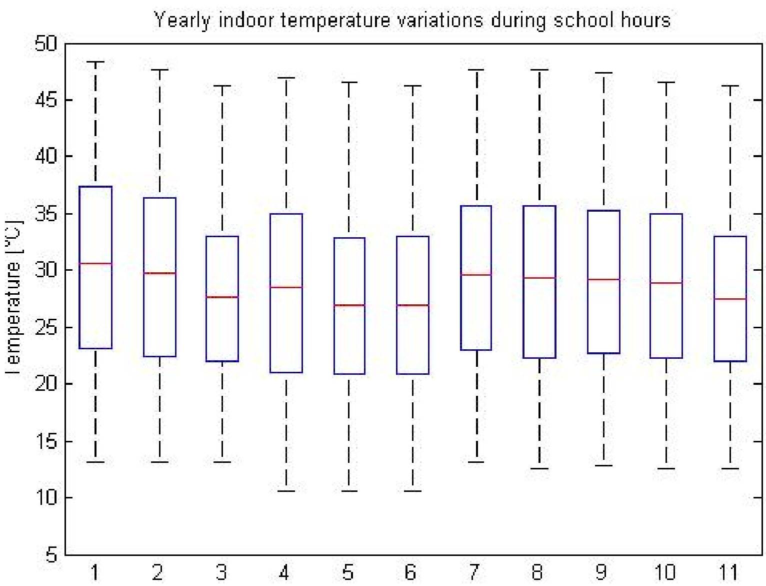
1 – Reference (windows open during the school hours according to need)
2 – Windows always open
3 – Windows always open during daytime
4 – Windows always open during nighttime, only doors open during the day
5 – Windows open during the day or night, depending on the season (night ventilation when the average monthly temperature is above 22°C)
6 – Windows seasonally open during the night, and also open during school hours according to need

Figure 4.33: Temperature variations for one year during school hours in Lahore for cases with different window operation.

4.4.2 Ventilators

Some existing schools in Islamabad and Mansehra have higher ventilator windows on top of the regular windows. These ventilators increase the total area of openings, and they also move the neutral pressure plane so that there is more flow even through the regular windows. This study tests what effect this type of ventilators could have and how they could be used.

Figure 4.34 below shows the effect of ventilators in Lahore.



1 – Reference (no ventilators, windows open according to need during school hours)
2 – Ventilators and windows opened according to need during school hours
3 – Ventilators and windows open seasonally during the night, and according to need during school hours
4 – Ventilators always open, normal windows according to need during school hours
5 – Ventilators always open, normal windows seasonally during the night
6 – Ventilators always open, normal windows according to need during school hours and also seasonally during the night
7 – Ventilators open seasonally during the night, normal windows according to need during school hours
8 – Ventilators open during day or night depending on season, normal windows according to need during school hours
9 – Ventilators open during the night, normal windows during the day or night depending on the season
10 - Ventilators open the during the day, normal windows according to need during school hours and seasonally also at night
11 - Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night

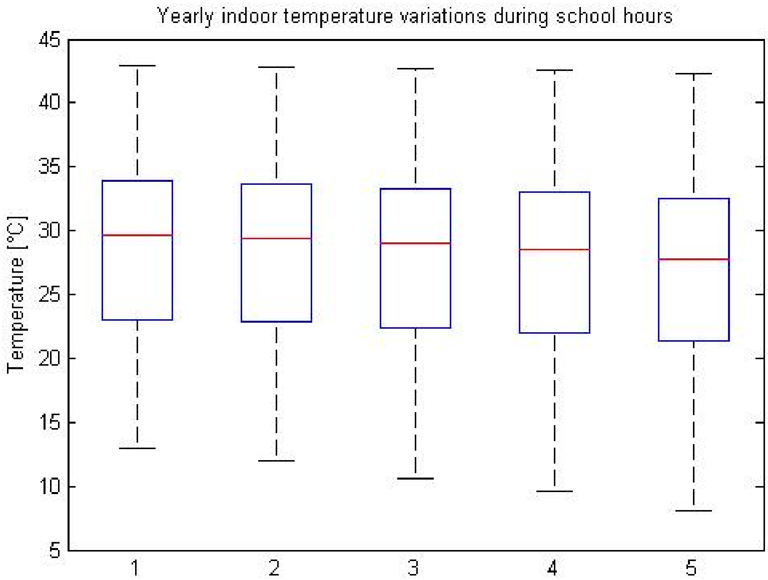
Figure 4.34: Temperature variations for one year during school hours in Lahore for cases with different window and ventilator operation.

The difference between cases 2 and 11 shows that having the ventilators always open is a benefit during the day, even if the normal windows would be closed for comfort reasons. There isn't much difference between cases 3 (ventilators closed according to need) and 11 (ventilators always open during school hours) but the air change rate is more stable in case 11. During cold weather, ventilators could be a more comfortable way of providing fresh air than regular windows, because there would be less draft at the level where people are sitting.

The effects of ventilators are similar in other cities. In Mansehra it is more important that the ventilators, as well as the regular windows, are properly closed during the night during the cold season.

4.4.3 Air leakages

In the reference case, when all windows and doors are closed, there is still a flow that corresponds to 5% of the flow that would occur if all openings were open. This somerimes gives the air change rate as close to 0 1/h, but in reality there are more air leakages when the windows are closed because the windows are far from air tight. Because of this the impact of adding a minumum air lekagae rate was tested. Figure 4.35 below shows the results for Mansehra type 1 school where the impact was the greatest.



1 – Reference, no minimum air change rate
2 – Minimum air change rate 1 1/h
3 – Minimum air change rate 1.5 1/h
4 – Minimum air change rate 2 1/h
5 – Minimum air change rate 3 1/h

Figure 4.35: Temperature variations for one year during school hours in Mansehra type 1 school for cases with air leakages.

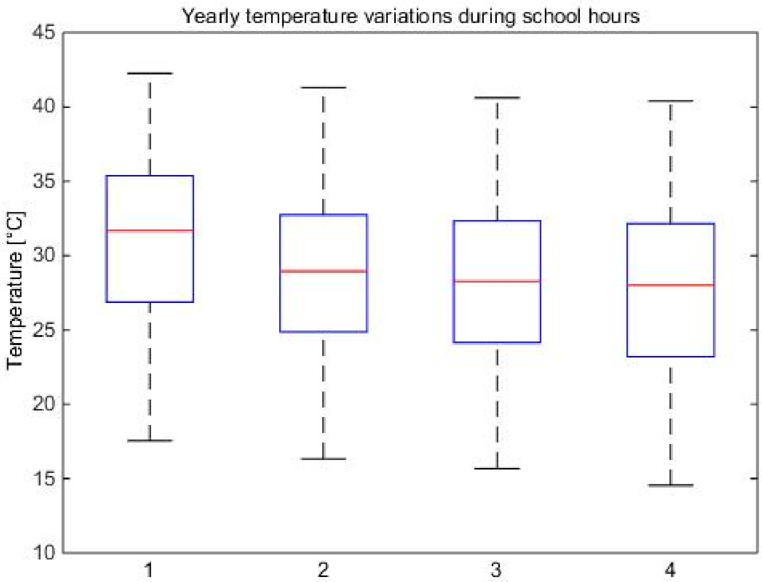
Air leakages lower the temperature because there are leakages when the windows are closed for comfort reasons (i.e. when it is cold indoors) and also during the night in the winter. Especially the minimum temperatures are effected and become very cold, which shows the importance of air tight windows during the winter. In other cities adding minimum air leakages has less affect because the air change rate is already higher and the windows are closed less often because the weather is warmer.

4.4.4 Detailed comparison of ventilation strategies

In this section the best cases from Sections 4.4.1 and 4.4.2 are compared. Also added is a case with a windcatcher. These cases are studied with box plots, but a more detailed study is also done that looks at the hourly temperature and air change rate variations during the hottest and the coldest day of the year. The hottest and the coldest day are defined from the indoor temperature of the reference case for each city.

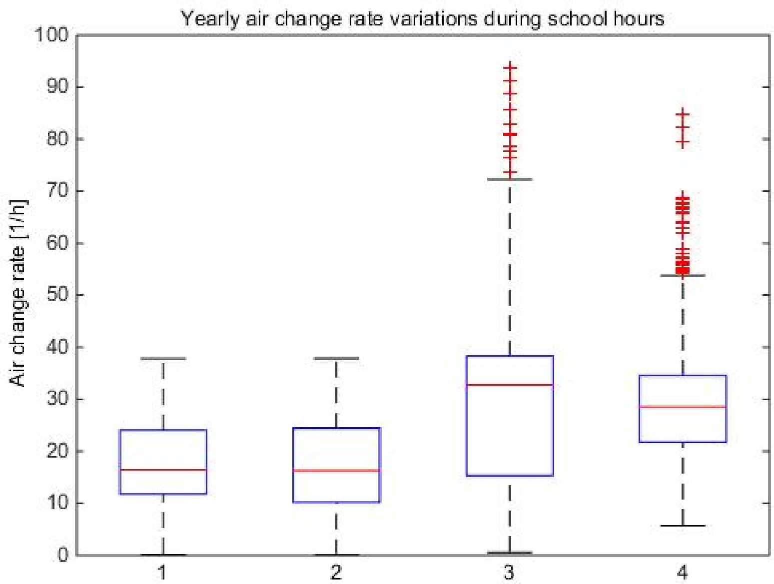
4.4.4.1 Karachi

Figures 4.36 and 4.37 below show the temperature and air change rate variations for the different cases in Karachi.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.36: Temperature variations for one year during school hours in Karachi for cases with different ventilation strategies.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.37: Air change rate variations for one year during school hours in Karachi for cases with different ventilation strategies.

In terms of temperature, night ventilation with regular windows is just as effective as adding ventilators or windcatchers in this climate. For security reason ventilators could be better however. The average air flow is sufficient in all cases, but ventilators and windcatchers have the potential to increase the minimum air flow, especially during still weather. Figure 4.37 above shows that a windcatcher would be particularly effective in raising the minimum air change rates.

Figures 4.38 and 4.39 show the temperature and air change rate variations on the coldest day. The reference case and night ventilation are identical because night ventilation is not used during the cold season.

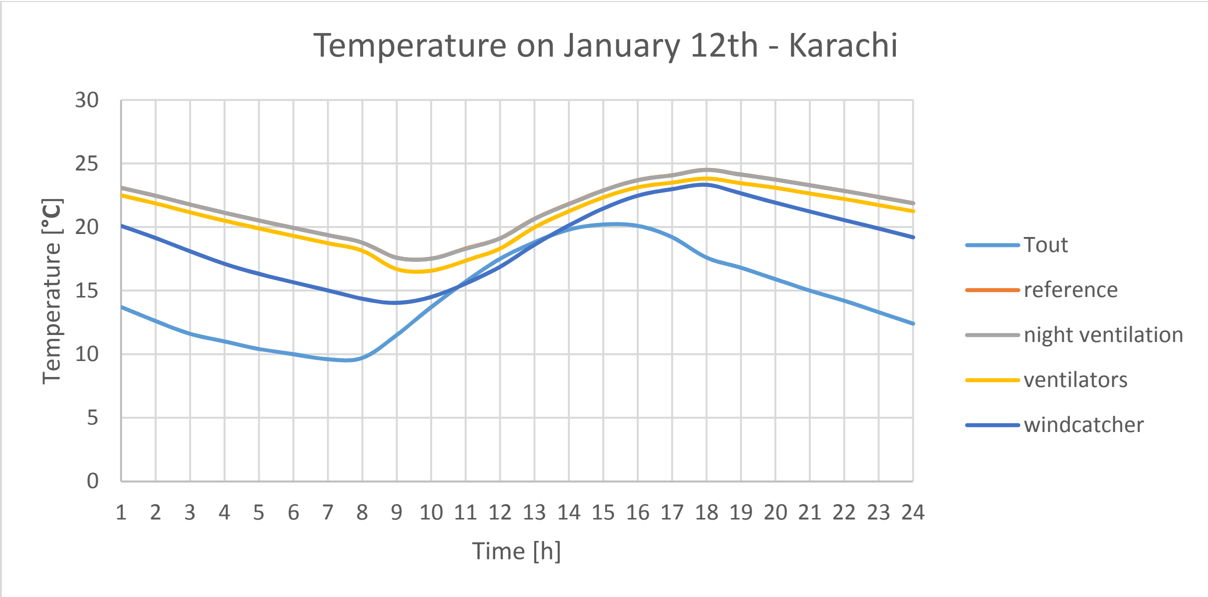


Figure 4.38: Hourly temperature variations on a cold day in Karachi with different ventilation strategies.

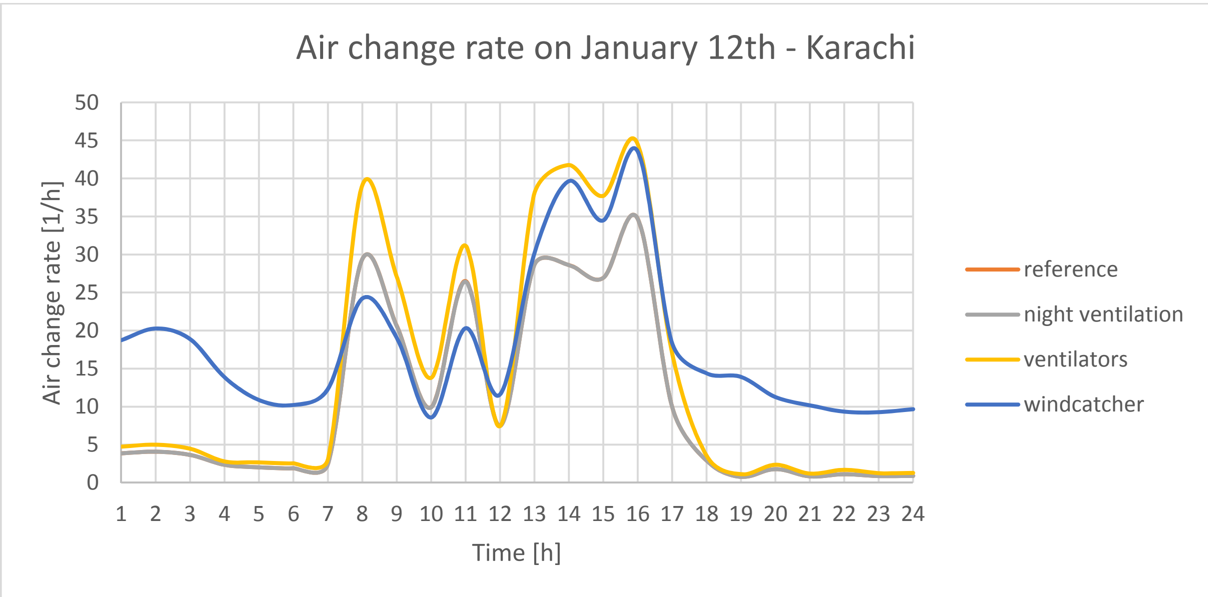


Figure 4.39: Hourly air change rate variations on a cold day in Karachi with different ventilation strategies.

On the coldest day the temperatures during school hours are still mostly comfortable in the reference case. Ventilators would increase air leakages during the night and because of this they would make it slightly less comfortable during the cold season. Interestingly, ventilators provide a higher air change rate during the day than windcatchers, probably because in the model the total area of the windcatcher openings is smaller than the total area of the ventilators (4 m^2 vs 6 m^2).

Figures 4.40 and 4.41 show the temperature and air change rate variations on the hottest day.

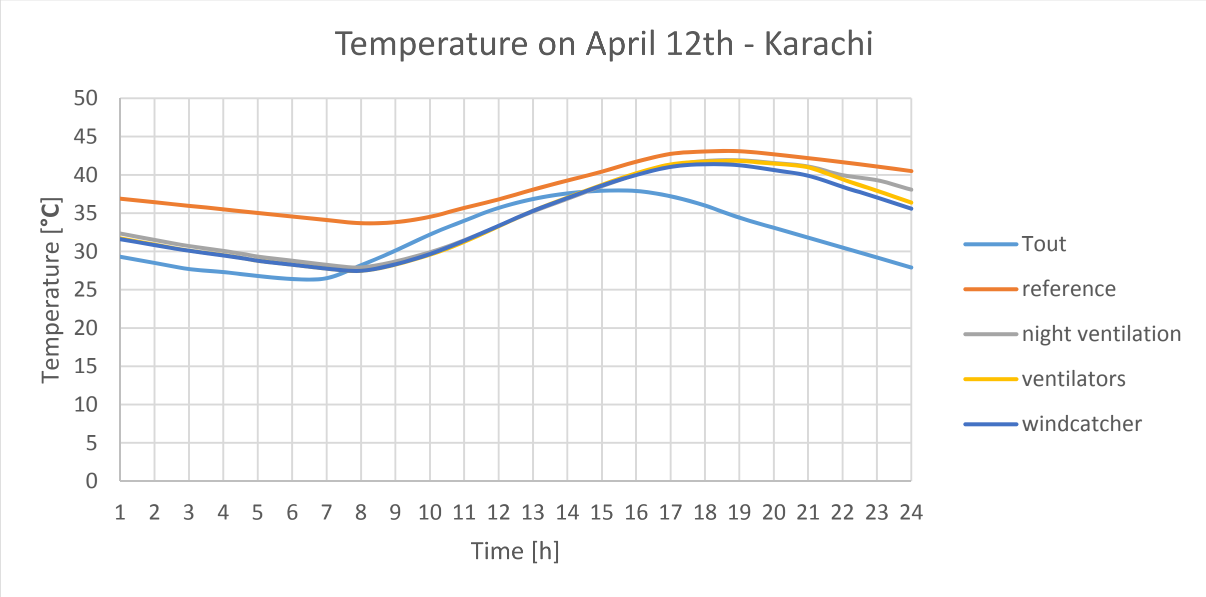


Figure 4.40: Hourly temperature variations on a hot day in Karachi with different ventilation strategies.

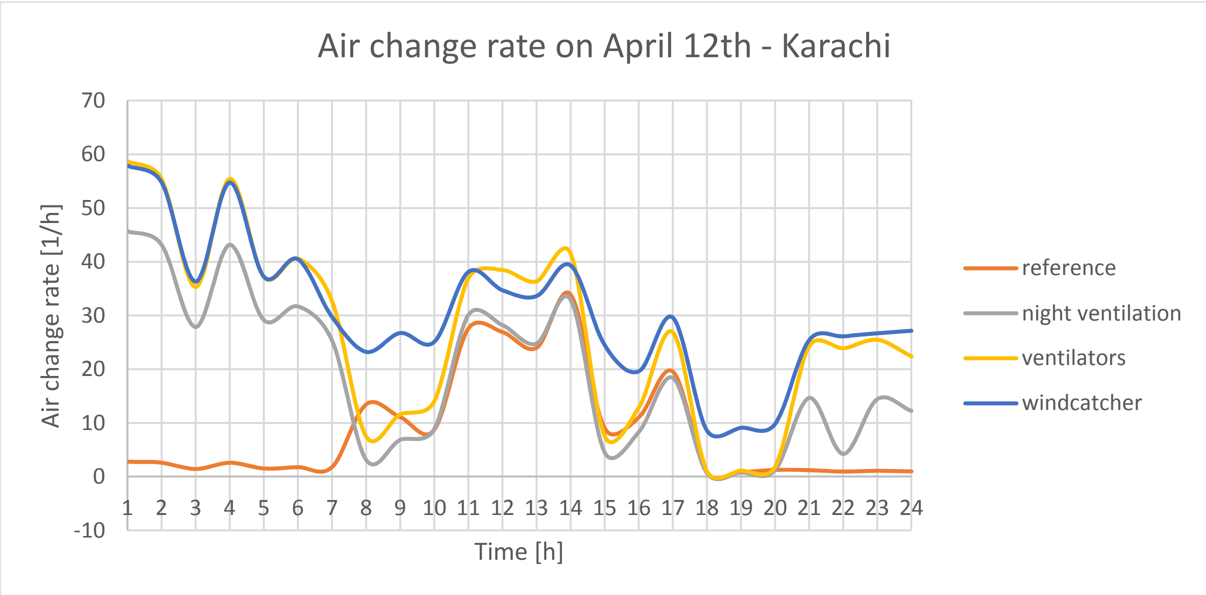


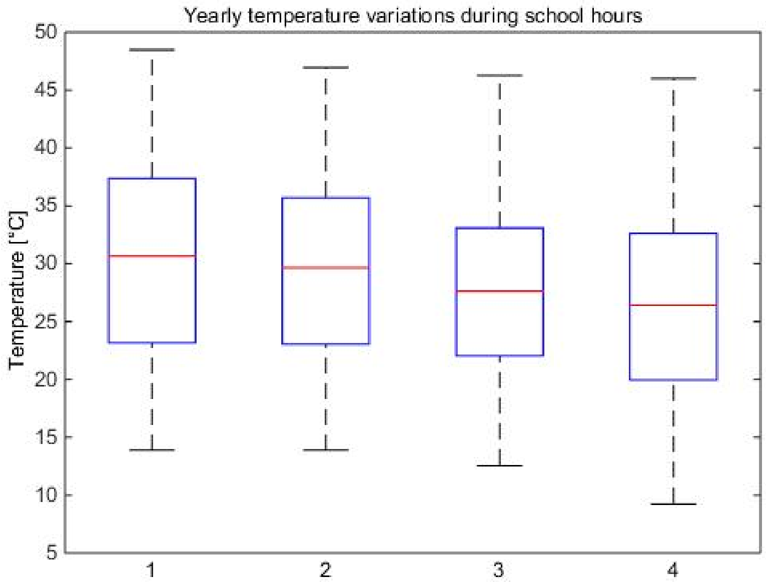
Figure 4.41: Hourly air change rate variations on a cold day in Karachi with different ventilation strategies.

Night ventilation, ventilators and windcatchers provide virtually the same benefit when looking at Figure 4.40 and the temperature on the hottest day. During the morning shift it is possible to keep the indoor air temperature below that of outdoor air, while in the reference case the indoor temperature is always higher than outdoor temperature. Figure 4.41 shows that the provision of fresh air would be more stable and reliable with alternative openings such as ventilators or a windcatcher.

Figure 4.40 shows that the indoor temperature at 18:00, when school finishes, is higher than the outdoor temperature. This means it could be beneficial to start night ventilation immediately at 18:00 instead of 21:00 as in the simulation.

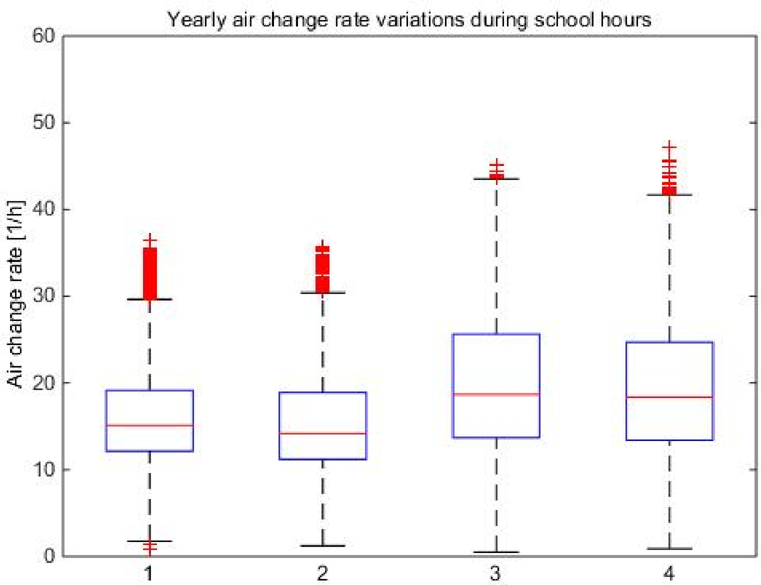
4.4.4.2 Lahore

Figures 4.42 and 4.43 below show the temperature and air change rate variations for the different ventilation cases in Lahore.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.42: Temperature variations for one year during school hours in Lahore for cases with different ventilation strategies.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.43: Air change rate variations for one year during school hours in Lahore for cases with different ventilation strategies.

The differences between case 2 and cases 3 and 4 shows that ventilators and windcatchers could be more beneficial in this climate than in Karachi, probably because there is less wind and ventilation relies more on stack effect.

Figures 4.44 and 4.45 show the temperature and air change rate variations on the coldest day in Lahore.

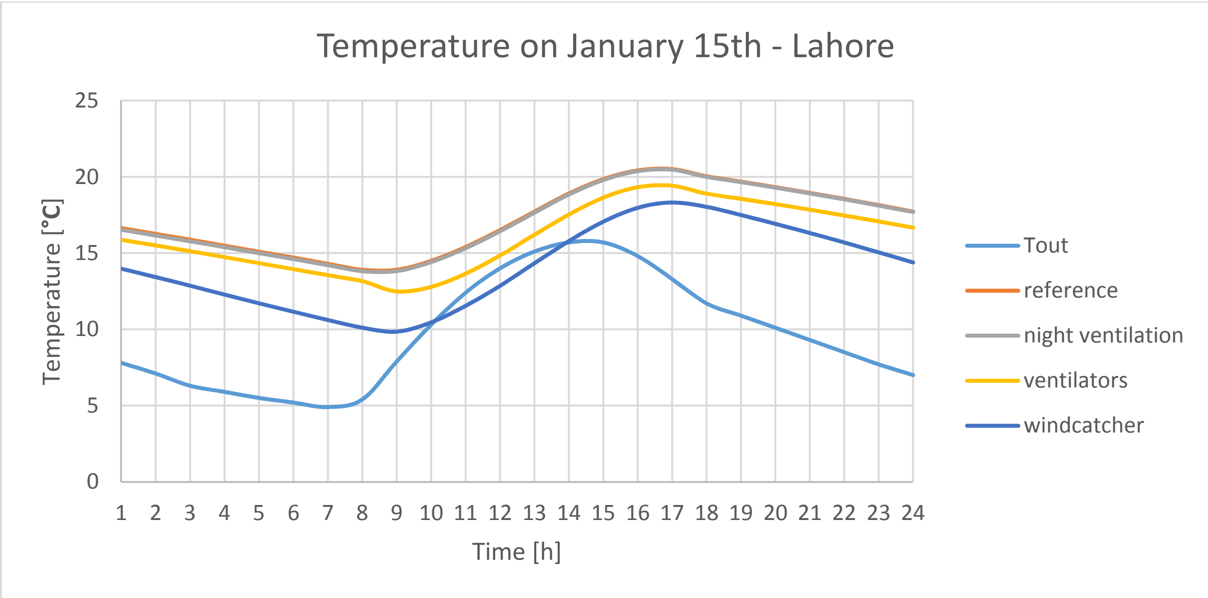


Figure 4.44: Hourly temperature variations on a cold day in Lahore with different ventilation strategies.

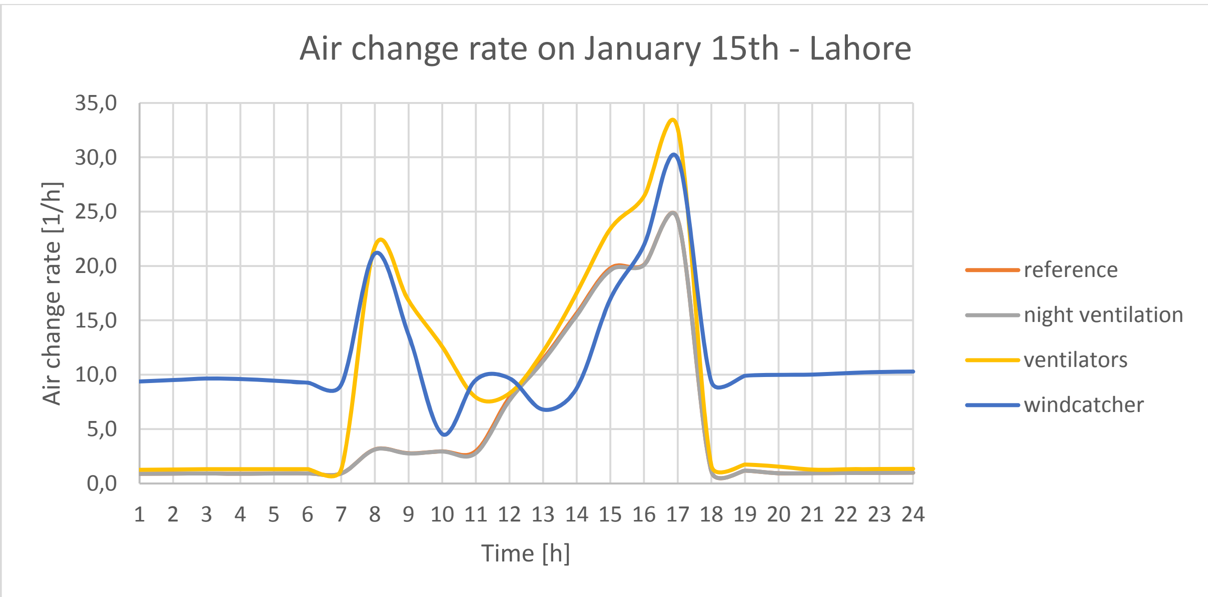


Figure 4.45: Hourly air change rate variations on a cold day in Lahore with different ventilation strategies.

The morning temperatures are very cold in all cases and especially with the windcatcher because it is open all the time. In the afternoon the temperature becomes more comfortable, but the building is not able to keep this heat during the night. In the reference case the windows are kept closed during the cold morning, and the resulting air change rate (approximately 3 1/h) is far below the desired 9 1/h minimum.

Figures 4.46 and 4.47 show the temperature and air change rate variations on the hottest day.

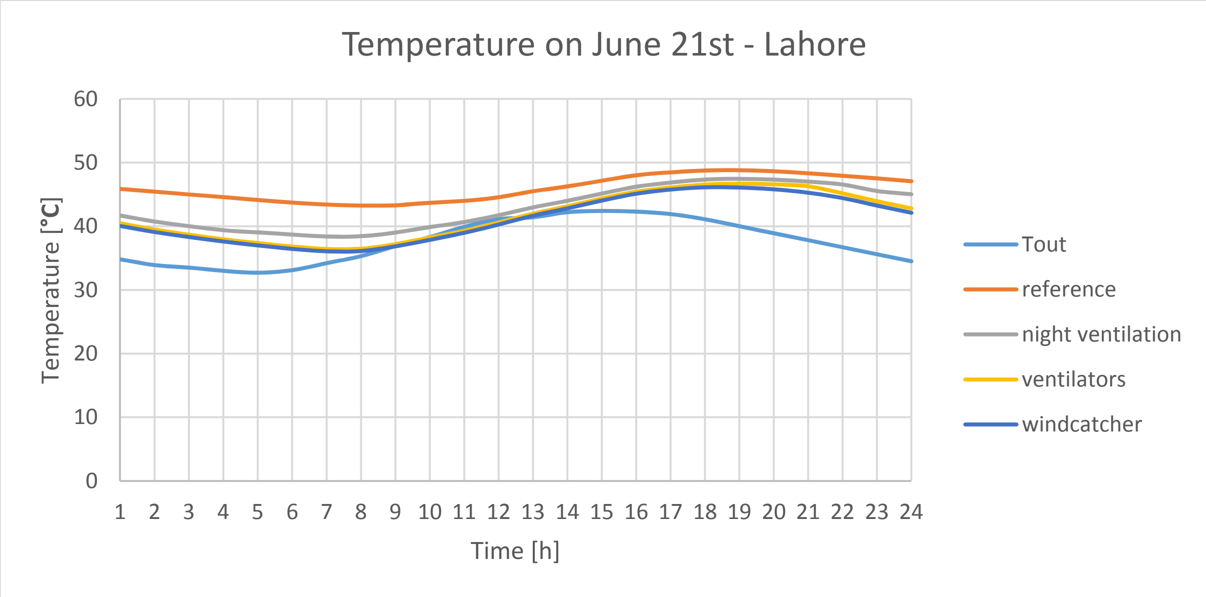


Figure 4.46: Hourly temperature variations on a hot day in Lahore with different ventilation strategies.

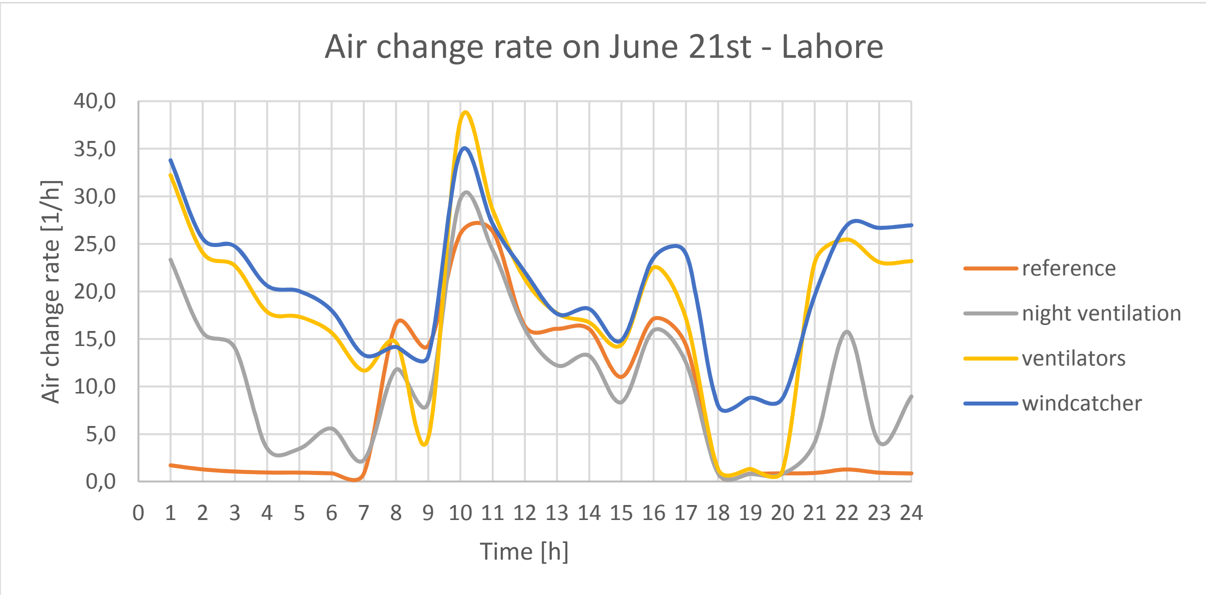
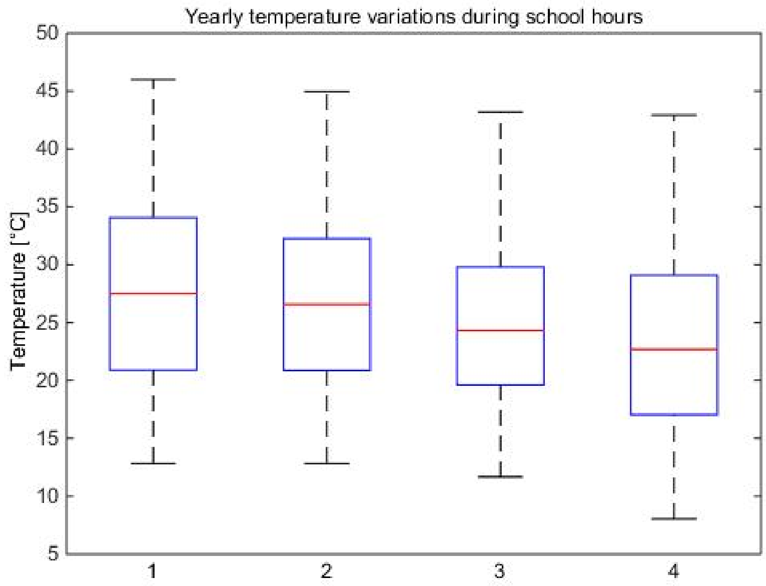


Figure 4.47: Hourly air change rate variations on a hot day in Lahore with different ventilation strategies.

On the hottest day night ventilation is not enough to reach temperatures below the outdoor temperature even in the morning, and Figure 4.47 shows that the night ventilation rate is very low on this day during the early morning before school. Ventilators and windcatcher can just barely reach below the outdoor temperature. Night ventilation should be enhanced somehow, and starting it immediately after school hours would probably be beneficial, as was already seen in Karachi.

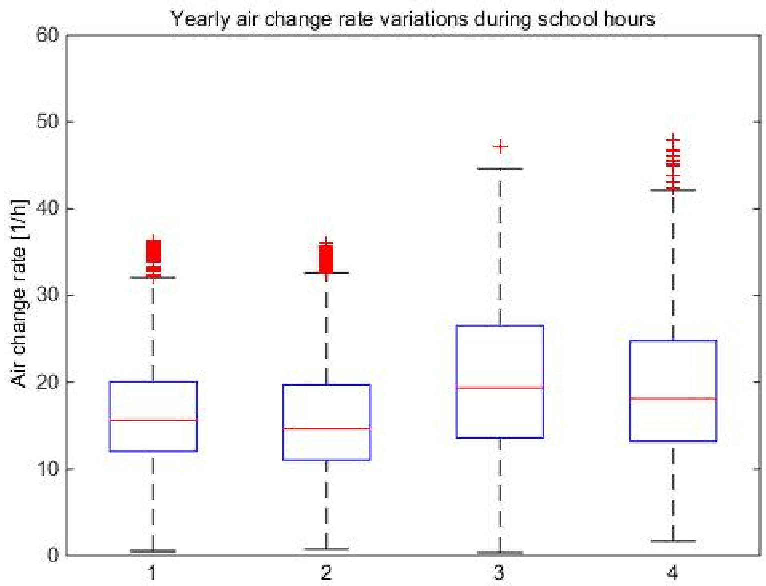
4.4.4.3 Islamabad

Figures 4.48 and 4.49 below show the temperature and air change rate variations for the different cases in Islamabad.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.48: Temperature variations for one year during school hours in Islamabad for cases with different ventilation strategies.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.49: Air change rate variations for one year during school hours in Islamabad for cases with different ventilation strategies.

The results are similar to Lahore, and adding ventilators or a windcatcher would be more beneficial in lowering temperatures and increasing the air change rate than just adding night ventilation.

Figures 4.50 and 4.51 show the temperature and air change rate variations on the coldest day.

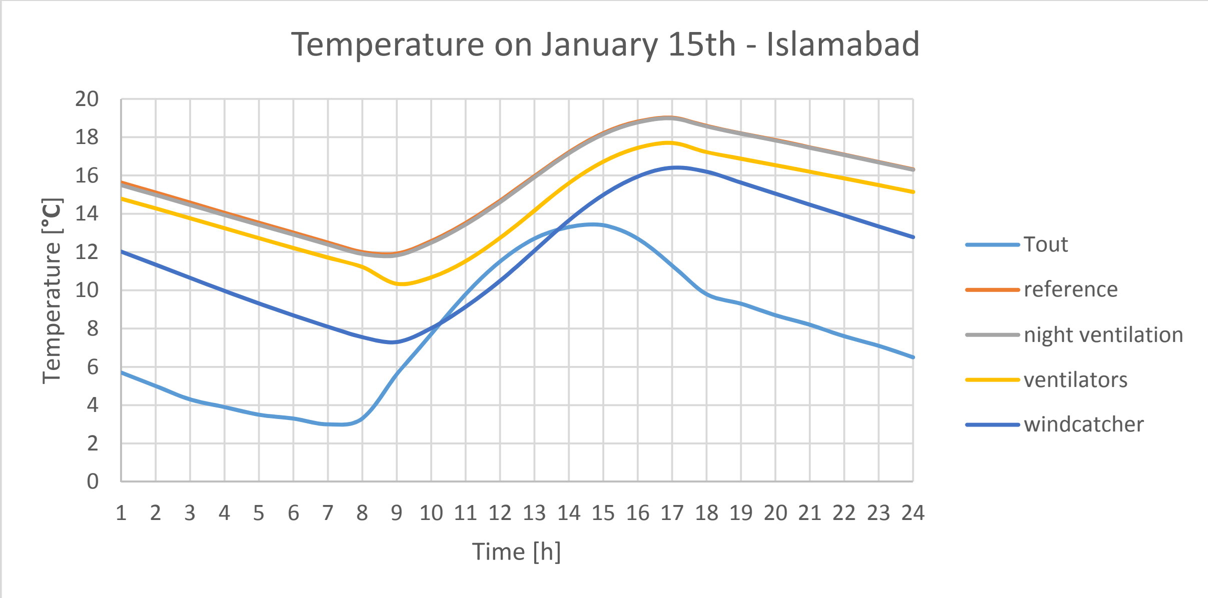


Figure 4.50: Hourly temperature variations on a cold day in Islamabad with different ventilation strategies.

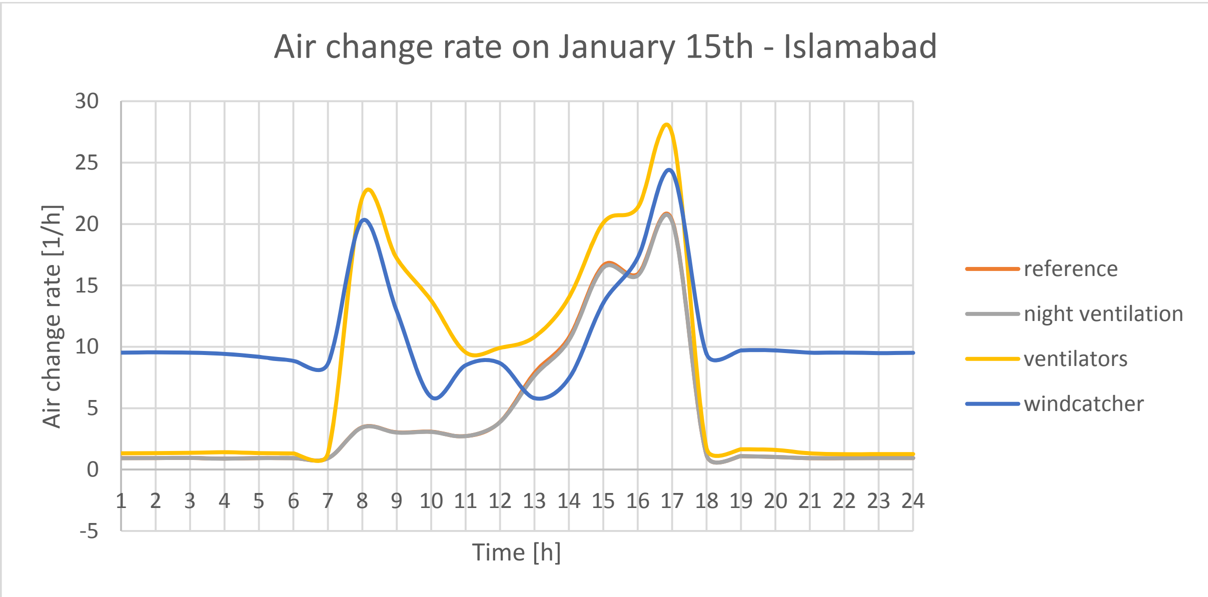


Figure 4.51: Hourly air change rate variations on a cold day in Islamabad with different ventilation strategies.

In Islamabad the temperatures on the coldest day are even lower than Lahore, and keeping openings shut during the night is even more important. As in Lahore, the air change rate in the morning is below the desired minimum.

Figures 4.52 and 4.53 show the temperature and air change rate variations on the hottest day.

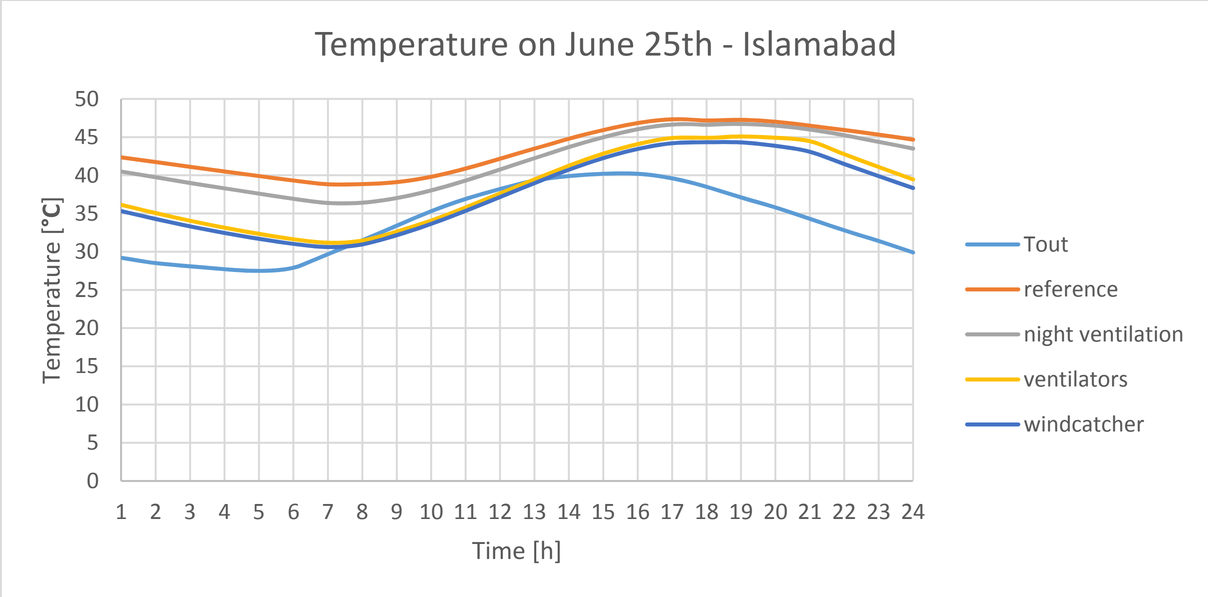


Figure 4.52:. Hourly temperature variations on a hot day in Islamabad with different ventilation strategies.

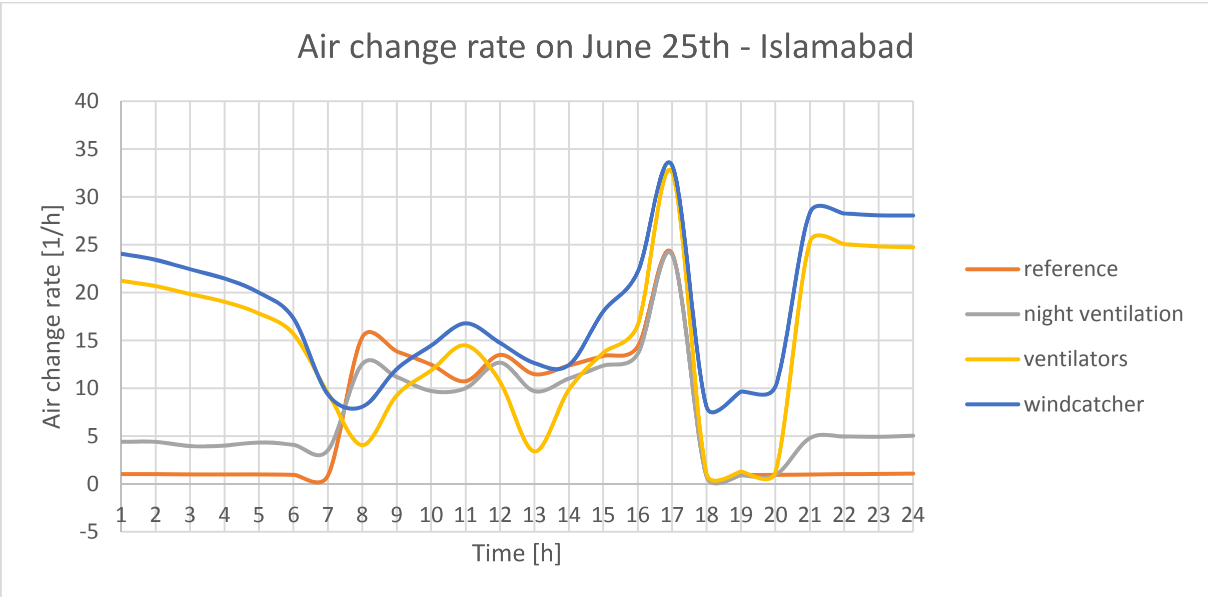
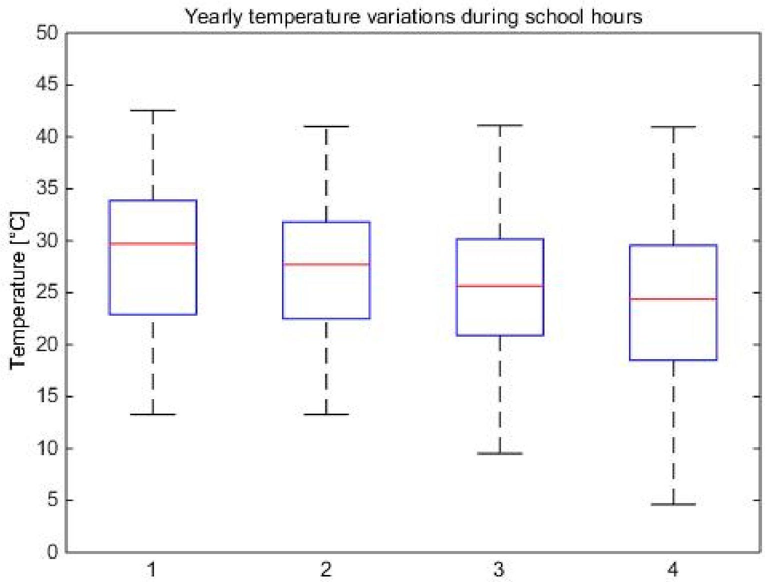


Figure 4.53: Hourly air change rate variations on a hot day in Islamabad with different ventilation strategies.

In this case, ventilators and windcatchers can provide a much higher air change rate during the night than regular windows can. Because of this the temperatures are also lower throughout the day.

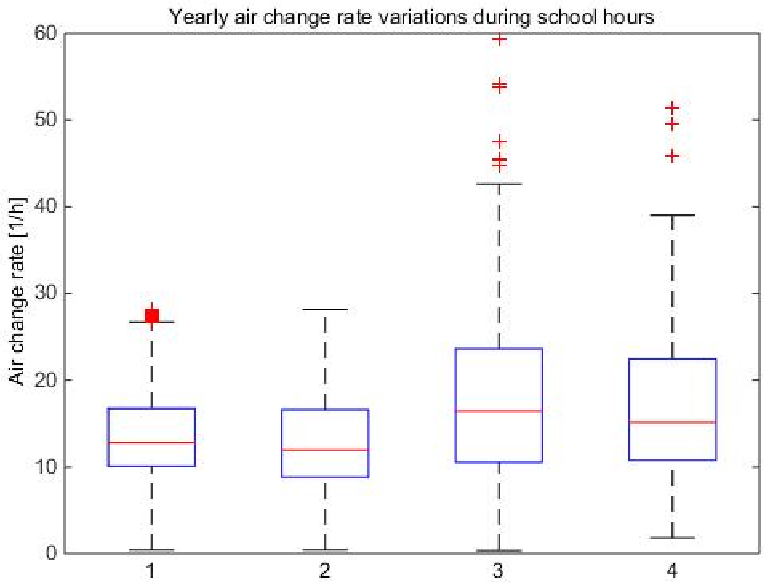
4.4.4.1 Mansehra type 1 school

Figures 4.54 and 4.55 below show the temperature and air change rate variations for the different cases in Mansehra type 1 school.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.54: Temperature variations for one year during school hours in Mansehra type 1 school for cases with different ventilation strategies.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.55: Air change rate variations for one year during school hours in Mansehra type 1 school for cases with different ventilation strategies.

Here night ventilation helps somewhat and the other strategies would lower the temperatures more, but the minimum temperatures would become very uncomfortable.

Figures 4.56 and 4.57 show the temperature and air change rate variations on the coldest day.

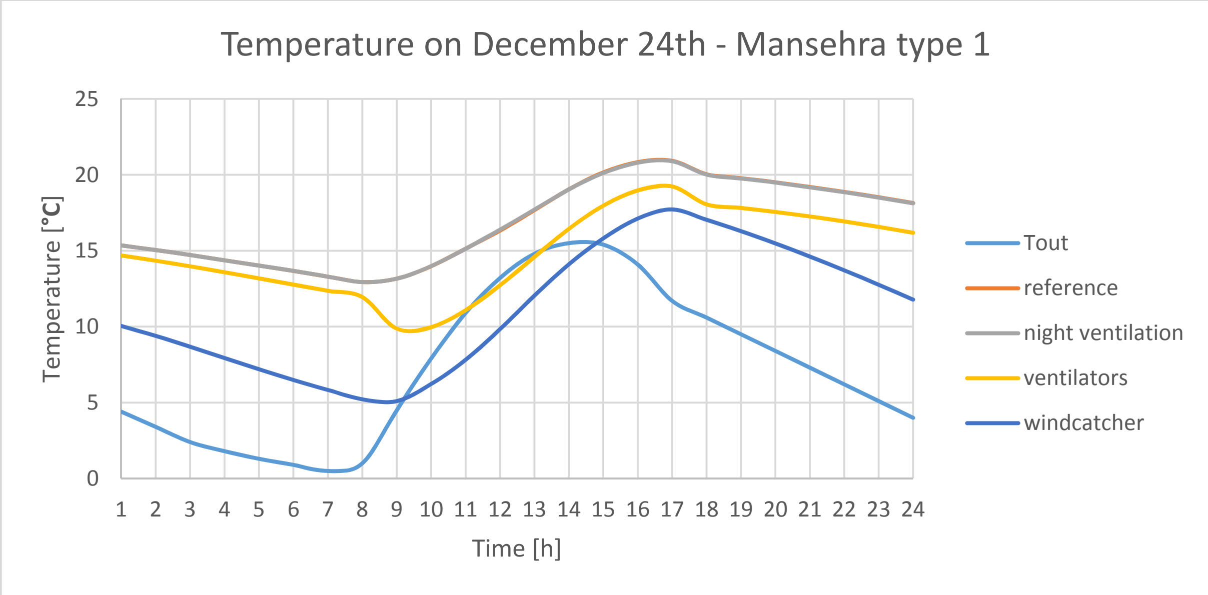


Figure 4.56: Hourly temperature variations on a cold day in Mansehra type 1 school with different ventilation strategies.

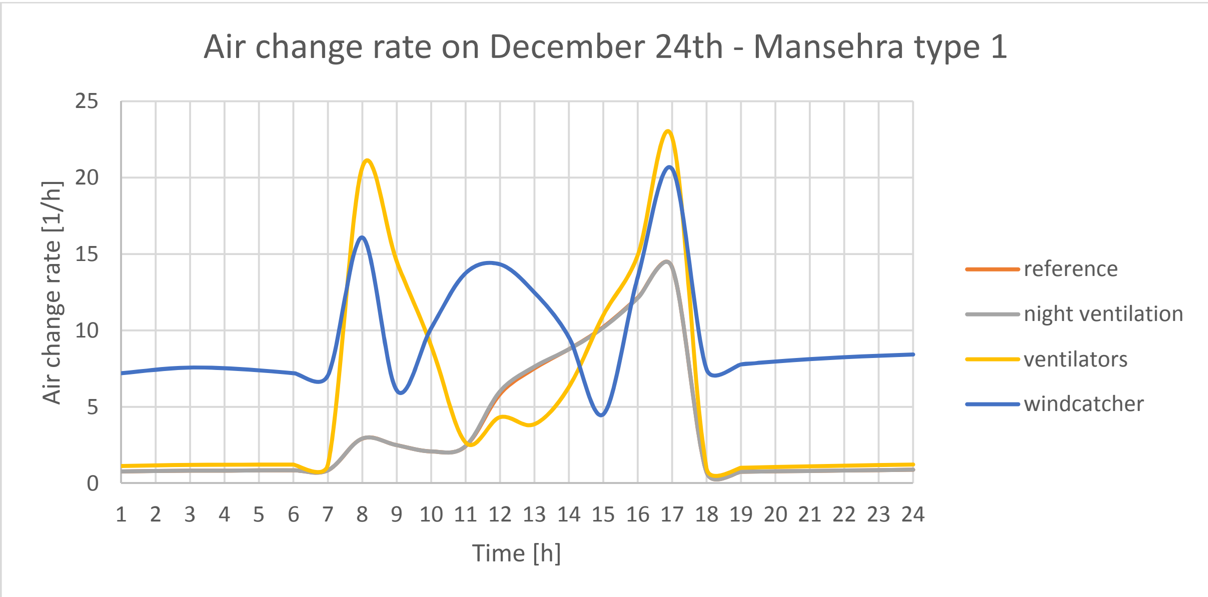


Figure 4.57: Hourly air change rate variations on a cold day in Mansehra type 1 school with different ventilation strategies.

The reference case keeps the building warmer, but the air change rate in the morning is very low because the windows are kept shut. The existing insulation is clearly beneficial, because the temperatures are warmer than in Islamabad, where the climate is warmer but there is no insulation. Increasing the amount of insulation could be a solution.

Figures 4.58 and 4.59 show the temperature and air change rate variations on the hottest day.

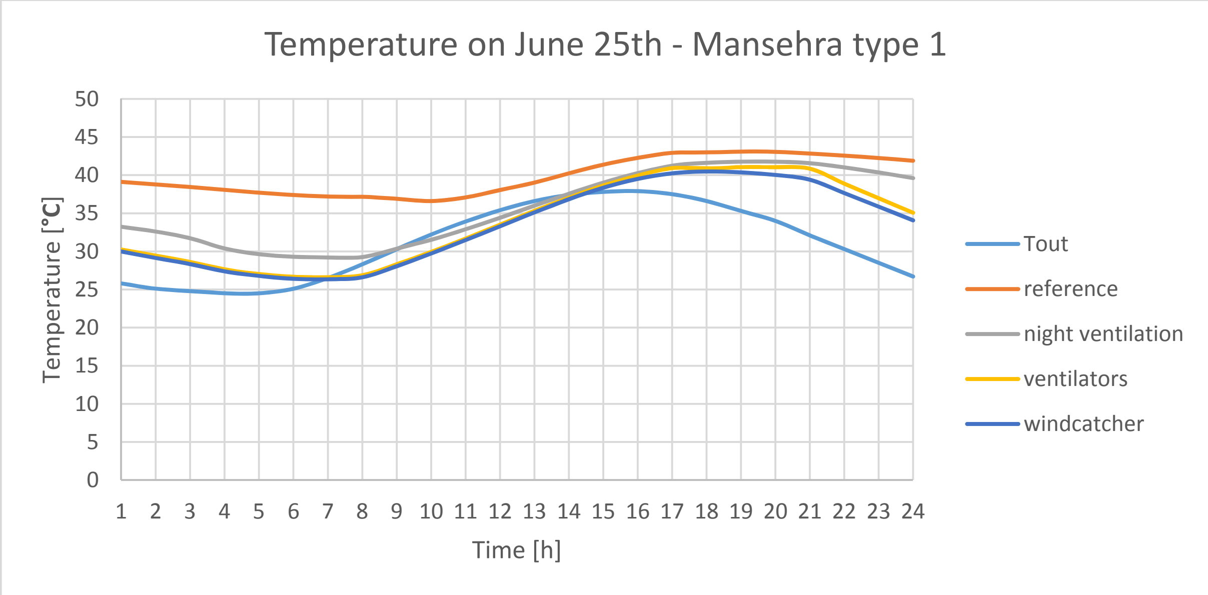


Figure 4.58: Hourly temperature variations on a hot day in Mansehra type 1 school with different ventilation strategies.

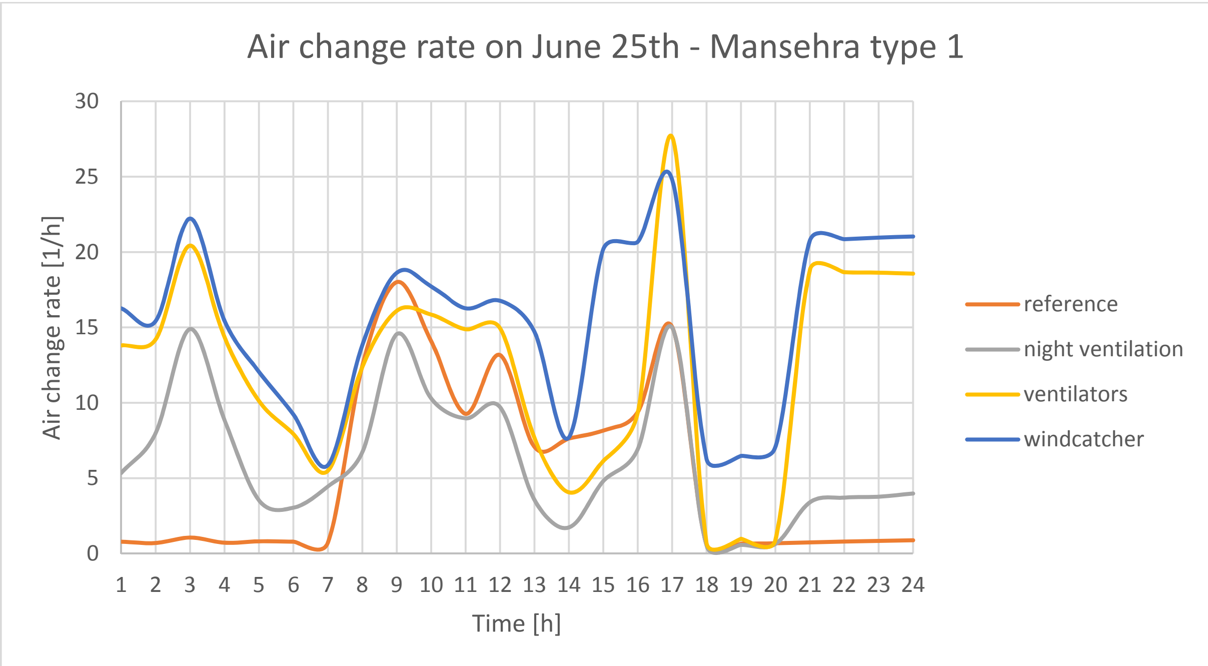
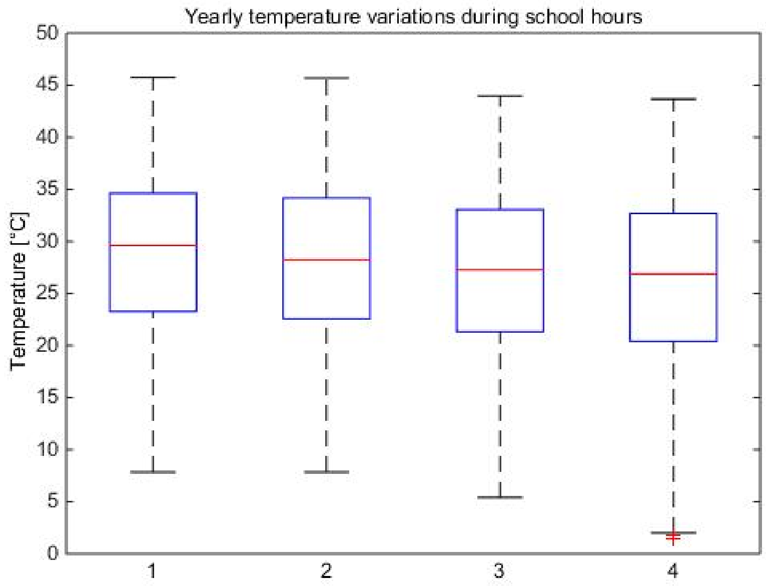


Figure 4.59: Hourly air change rate variations on a hot day in Mansehra type 1 school with different ventilation strategies.

The hottest day is similar to Lahore and Islamabad, although in this case night ventilation with regular windows is more effective than in the other two northern cities. Ventilators or windcatchers would be slightly better than just night ventilation.

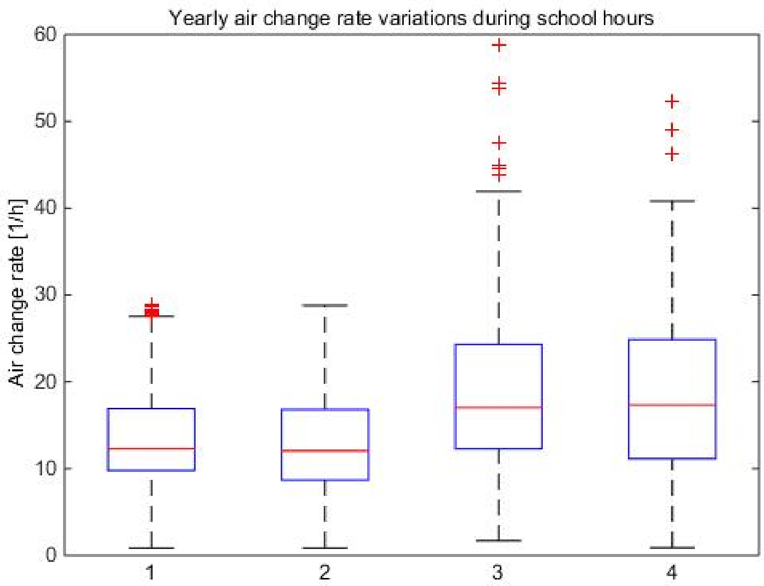
4.4.4.1 Mansehra type 2 school

Figures 4.60 and 4.61 below show the temperature and air change rate variations for the different cases in Mansehra type 2 school. This school has significantly less thermal inertia than the others.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.60: Temperature variations for one year during school hours in Mansehra type 2 school for cases with different ventilation strategies.



1 – Reference, windows opened during school hours according to need
2 – Windows seasonally open during the night, and also open during school hours according to need
3 – Ventilators open the during the day, normal windows according to need during school hours, and both seasonally also at night
4 – Windcatcher with openings south, north, east and west always open, normal windows according to need during school hours and also seasonally at night

Figure 4.61: Air change rate variations for one year during school hours in Mansehra type 2 school for cases with different ventilation strategies.

Comparing Figure 4.60 with Figure 4.54 for the type 1 school, shows that the temperature difference achieved with alternative ventilation strategies is less significant in the type 2 school. Without thermal inertia night ventilation is ineffective. Windcatcher and ventilators would be more effective than night ventilation in lowering temperatures, but the difference is small.

Figures 4.62 and 4.63 show the temperature and air change rate variations on the coldest day.

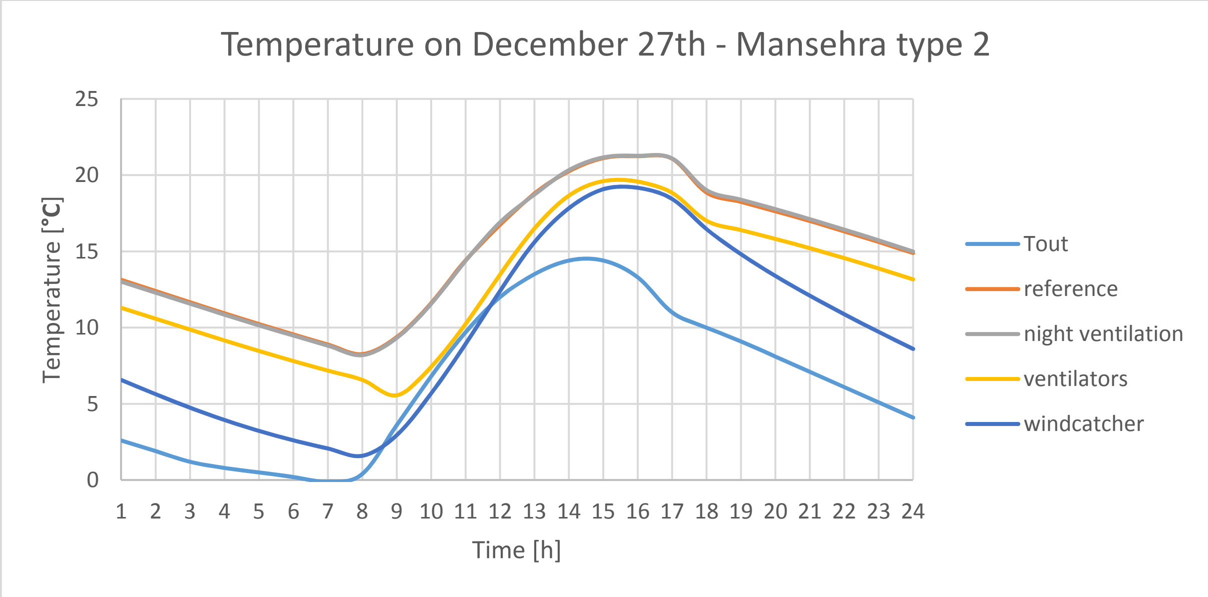


Figure 4.62: Hourly temperature variations on a cold day in Mansehra type 2 school with different ventilation strategies.

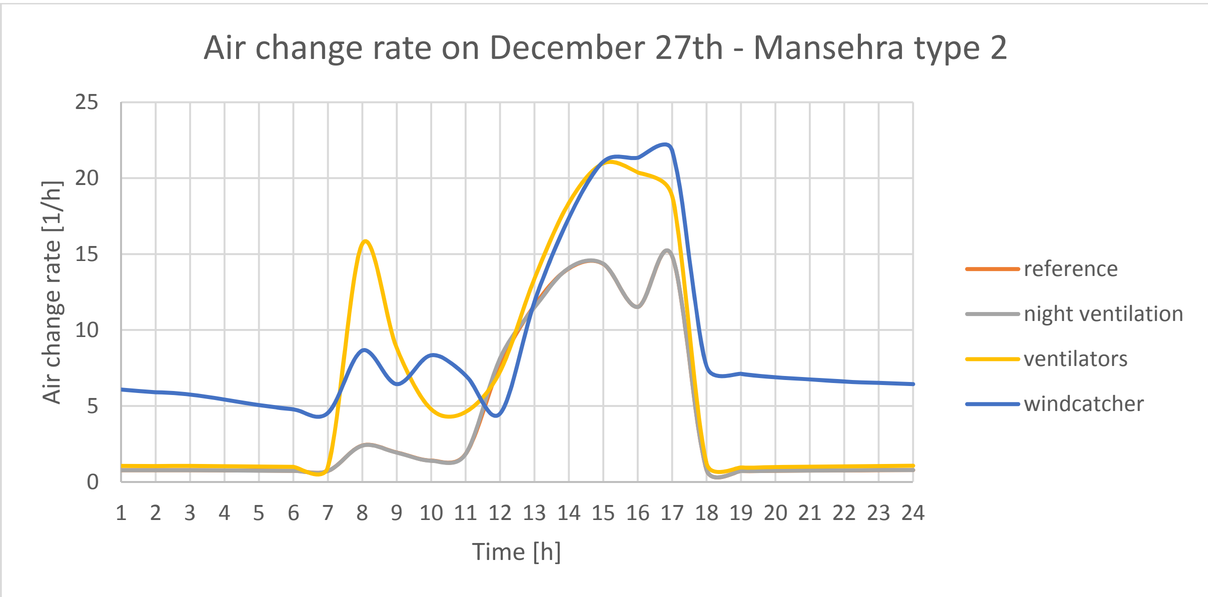


Figure 4.63: Hourly air change rate variations on a cold day in Mansehra type 2 school with different ventilation strategies.

The shape of the temperature graph in Figure 4.62 clearly follows the outdoor temperature more than in type 1 school, and the daily indoor temperature swing is about 5°C more. This shows that thermal mass is beneficial even during the cold season because it can better store the heat from the previous day. The type 2 school does heat up faster in the morning than the type 1 school, but this benefit is lost in the fact that the initial morning temperature is much lower (8°C vs. 13°C).

Figures 4.64 and 4.65 show the temperature and air change rate variations on the hottest day.

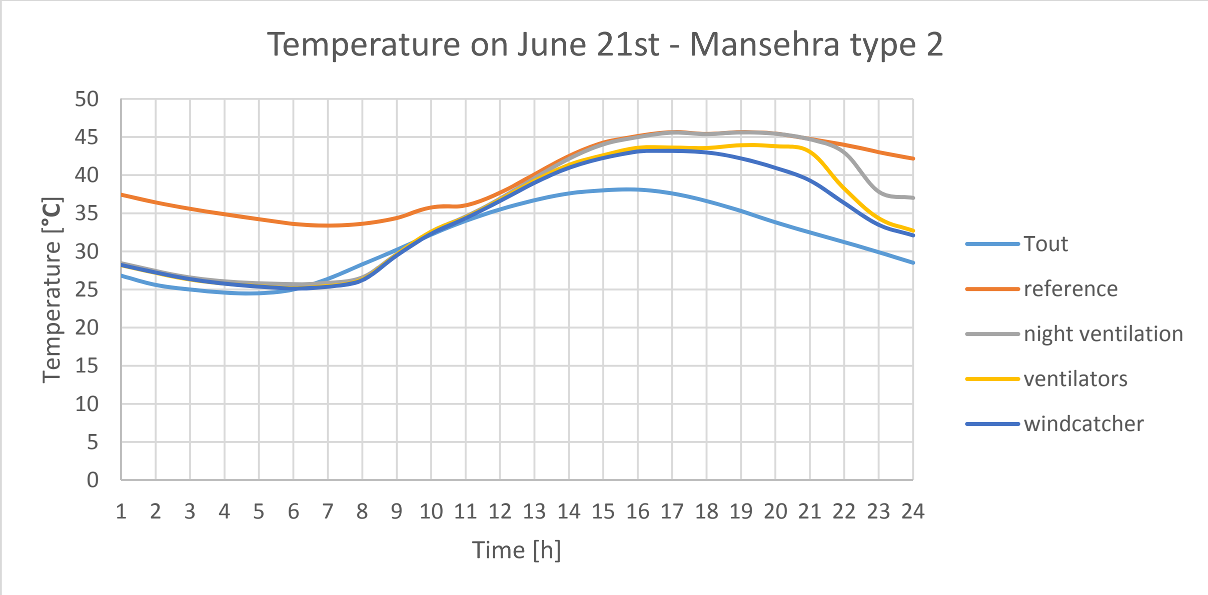


Figure 4.64: Hourly temperature variations on a hot day in Mansehra type 2 school with different ventilation strategies.

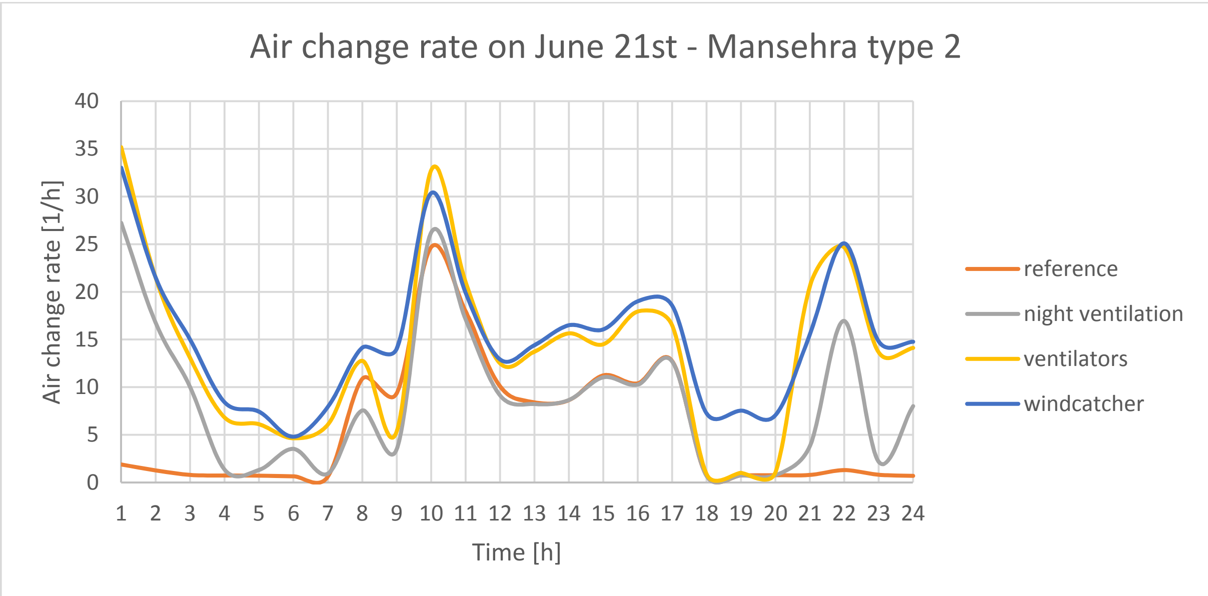


Figure 4.65: Hourly air change rate variations on a hot day in Mansehra type 2 school with different ventilation strategies.

Except for early mornings, night ventilation doesn't have much benefit in this school. This can be explained with the lack of thermal inertia as stated before. Windcatchers or ventilators could help slightly but the daytime indoor temperatures are still above the outdoor temperatures.

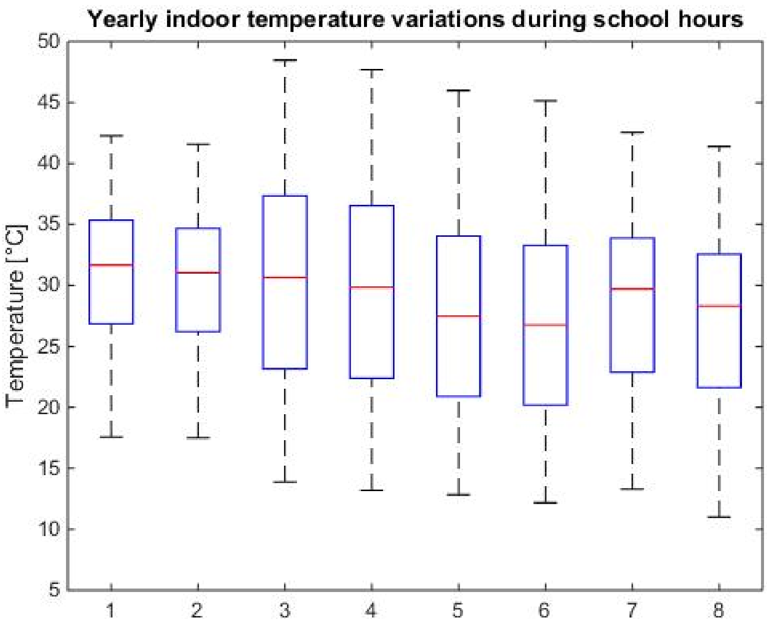
4.5 Revised and combined cases

This section presents studies where different cases are combined together to see their combined effect. The cases that are studied are ones that were identified to be the most beneficial based on the previous studies.

Based on the initial studies, the reference cases are slightly modified. Internal gains are reduced to 75% of the original, and air leakages are also added so that the air change rate is always at least 1.5 1/h.

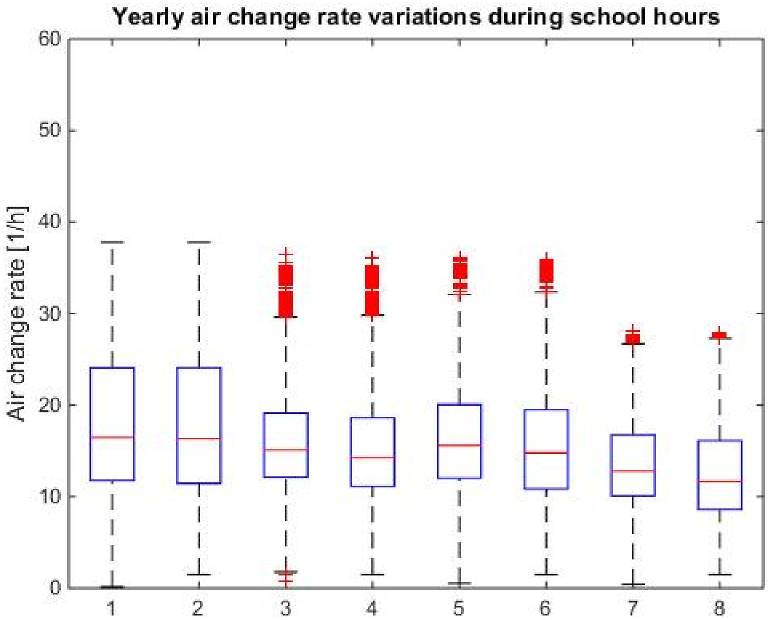
In the initial studies night ventilation was started at 21:00, meaning that windows were closed between 18:00 (when school ended) and 21:00. But the results above show that during the hottest days, at the end of the school day the indoor temperature is higher than the outdoor temperature. Because of this the night ventilation schedule is revised so that it now starts at 18:00. On school days during the warm and hot season the windows are thus in principle always open.

Figures 4.66 and 4.67 below show the indoor temperature and air change rate for the old and new reference cases. Only the type 1 school is studied for Mansehra because it has been identified as better due to its thermal inertia.



1 – Karachi old reference
2 – Karachi revised reference
3 – Lahore old reference
4 – Lahore revised reference
5 – Islamabad old reference
6 – Islamabad revised reference
7 – Mansehra type 1 old reference
8 – Mansehra type 1 revised reference

Figure 4.66: Temperature variations for one year during school hours in the old and new reference cases.



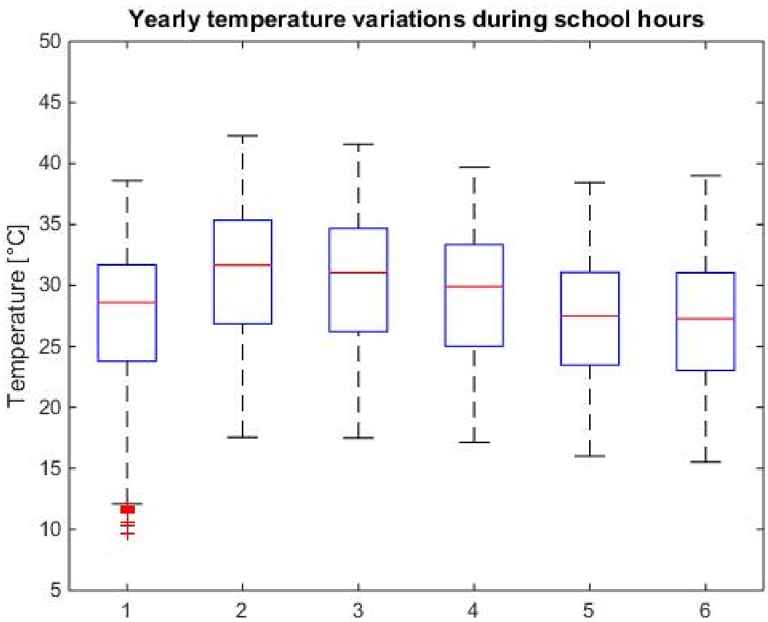
1 – Karachi old reference
2 – Karachi revised reference
3 – Lahore old reference
4 – Lahore revised reference
5 – Islamabad old reference
6 – Islamabad revised reference
7 – Mansehra type 1 old reference
8 – Mansehra type 1 revised reference

Figure 4.67: Air change rate variations for one year during school hours in the old and new reference cases.

The following sections present the combined cases studied with the new reference case. In Karachi, Lahore and Islamabad, absorption of solar radiation is first reduced with a lighter surface color, then seasonal night ventilation is added, and then ventilators are also added. In Mansehra, thermal inertia is first added to the roof, then night ventilation is added and lastly also ventilators.

4.5.1 Karachi

Figure 4.68 shows the indoor temperature variations in Karachi.

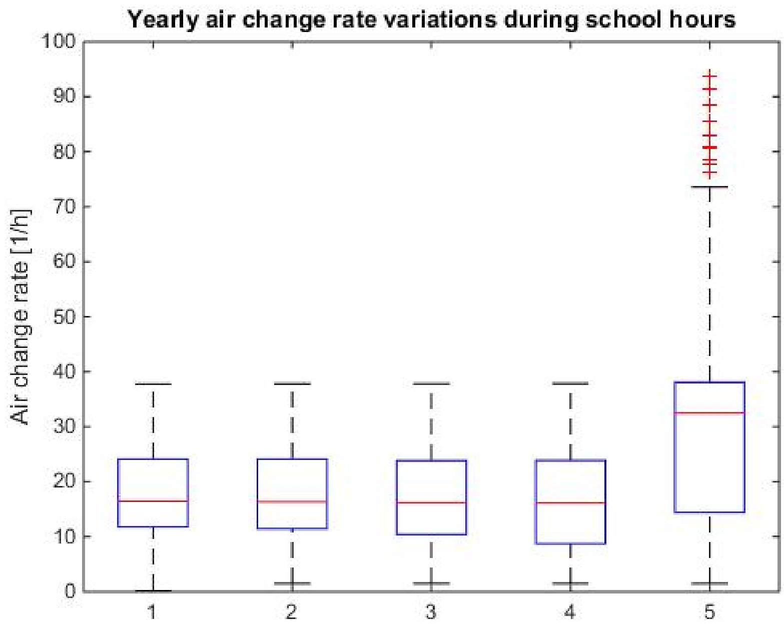


1 – Outdoor temperature
2 – Old reference
3 – Revised reference
4 – Reduced absorption for solar radiation (white paint or similar)
5 – Case 4 + seasonal night ventilation with windows, windows also open according to need during school hours
6 – Case 5 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.68: Temperature variations for one year during school hours in Karachi for combined cases.

For the combined case, ventilators are not as beneficial anymore. Having the ventilators open at all times actually raises the peak temperature slightly when compared with the case without ventilators. This can be explained with the fact that heat gains through the building envelope have been reduced with white paint, and because of this heat gains from the outdoor air become more significant. The average and peak temperatures could be reduced by approximately 4-5°C going from case 3 to 5.

Figure 4.69 shows air change rate variations. The cases are fairly similar except when ventilators are added.



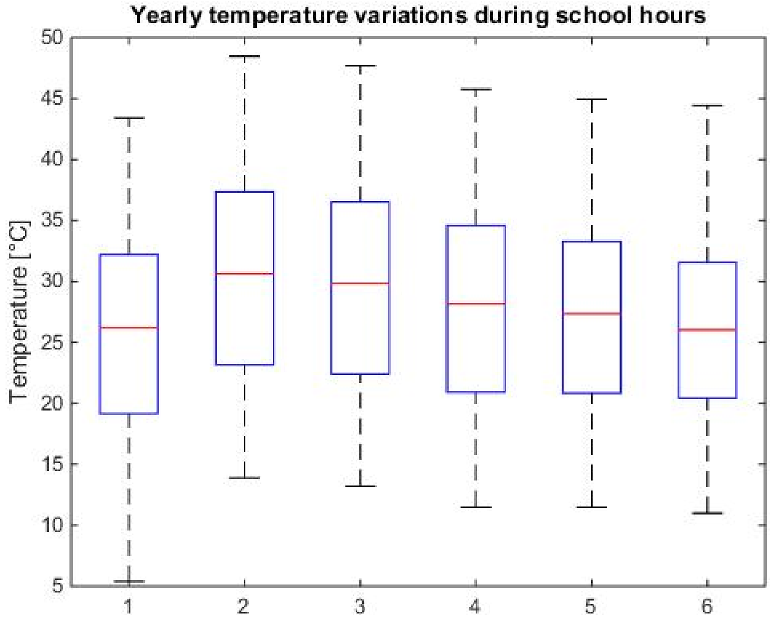
1 – Old reference
2 – Revised reference
3 – Reduced absorption for solar radiation (white paint or similar)
4 – Case 3 + seasonal night ventilation with windows, windows also open according to need during school hours
5 – Case 4 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.69: Air change rate variations for one year during school hours in Karachi for combined cases.

Ventilators are always open during the day, even when the wind speed is very high, and because of this the air change rate becomes very high at times, but this is unnecessary. Now that minimum air leakages are present, ventilators are not as beneficial in raising the minimum air change rates either. The courtyard is more effective in raising the minimum air change rates, as seen in Section 4.3.6.

4.5.2 Lahore

Figure 4.70 shows the indoor temperature variations in Lahore for the combined cases.

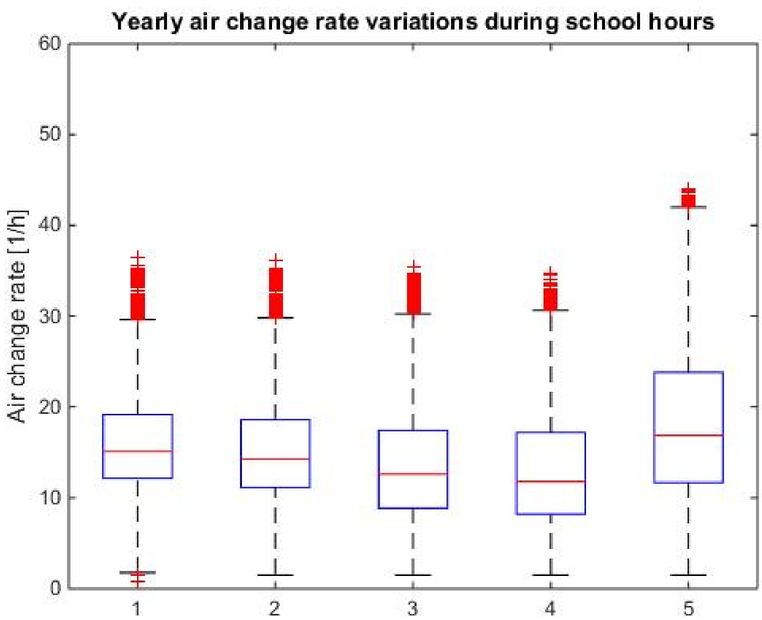


1 – Outdoor temperature
2 – Old reference
3 – Revised reference
4 – Reduced absorption for solar radiation (white paint or similar)
5 – Case 4 + seasonal night ventilation with windows, windows also open according to need during school hours
6 – Case 5 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.70: Temperature variations for one year during school hours in Lahore for combined cases.

In Lahore, ventilators are more beneificial than in Karachi, even in the combined cases. The average and peak temperatures could be reduced by approximately 4°C going from case 3 to 6, and the variation in temperature would also be reduced. However, the coldest temperature is also lowered which suggest that the cold season needs to be looked at in more detail.

Figure 4.71 shows the air change rate variations for the combined cases. Before ventilators are added in case 6, the air change rate actually drops slightly. Since ventilation in Lahore relies a lot on stack effect, the drop in air change rate could be explained with the fact that the temperature difference between indoors and outdoor is lower, and this temperature difference is a driving force for stack effect.

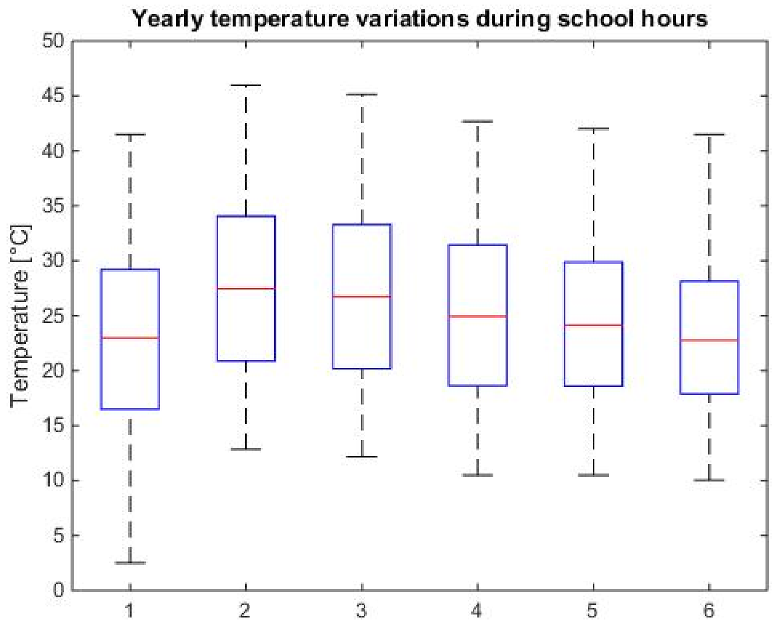


1 – Old reference
2 – Revised reference
3 – Reduced absorption for solar radiation (white paint or similar)
4 – Case 3 + seasonal night ventilation with windows, windows also open according to need during school hours
5 – Case 4 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.71: Air change rate variations for one year during school hours in Lahore for combined cases.

4.5.3 Islamabad

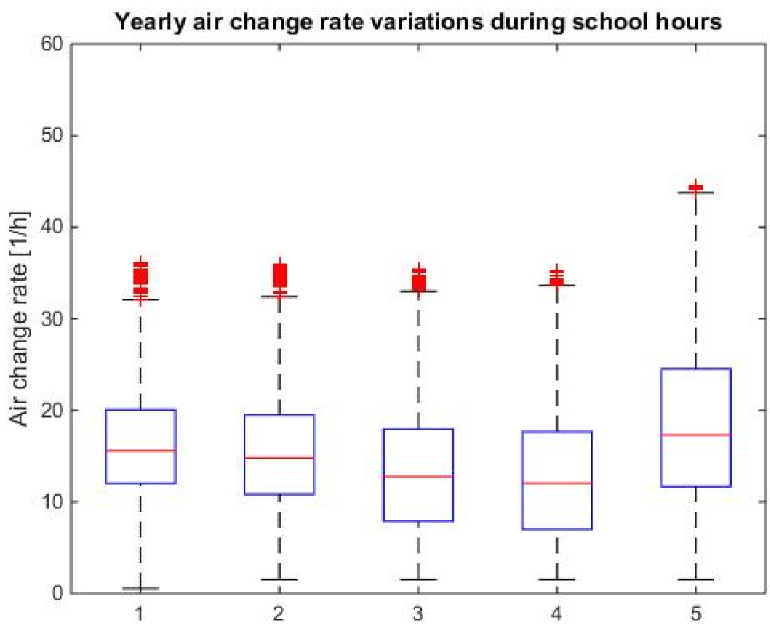
Figure 4.72 shows the indoor temperature variations in Islamabad for the combined cases.



1 – Outdoor temperature
2 – Old reference
3 – Revised reference
4 – Reduced absorption for solar radiation (white paint or similar)
5 – Case 4 + seasonal night ventilation with windows, windows also open according to need during school hours
6 – Case 5 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.72: Temperature variations for one year during school hours in Islamabad for combined cases.

The results are very similar to Lahore and the average and peak temperatures could be reduced by approximately 5°C going from case 3 to 6. Figure 4.73 shows the air change rate variations and they are also similar to Lahore.

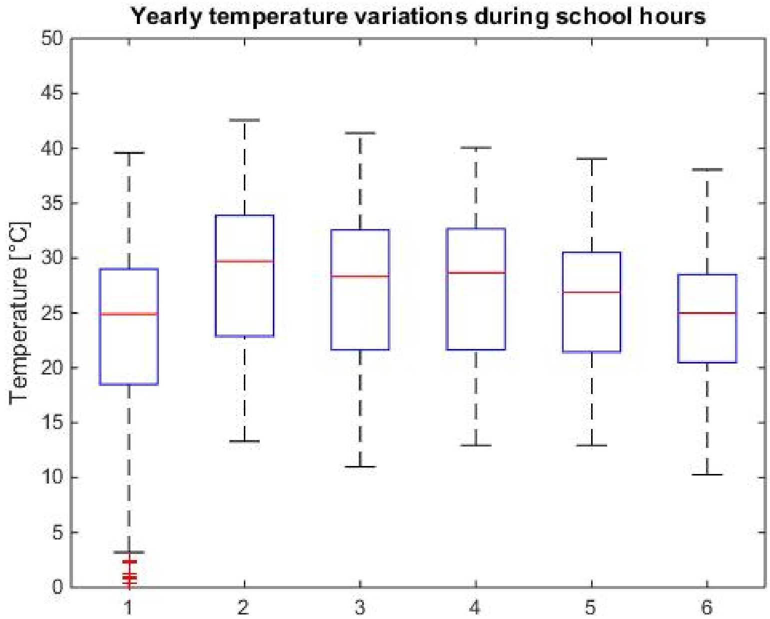


1 – Old reference
2 – Revised reference
3 – Reduced absorption for solar radiation (white paint or similar)
4 – Case 3 + seasonal night ventilation with windows, windows also open according to need during school hours
5 – Case 4 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.73: Air change rate variations for one year during school hours in Islamabad for combined cases.

4.5.4 Mansehra

Figure 4.74 shows the indoor temperature variations in Mansehra for the combined cases.

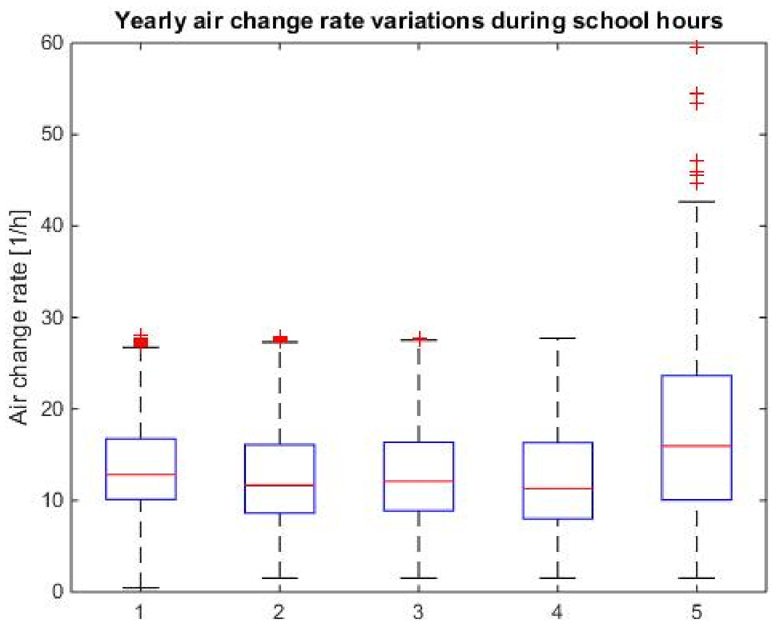


1 – Outdoor temperature
2 – Old reference (type 1 school)
3 – Revised reference (type 1 school)
4 – Wall 6 + Roof 6 (added thermal inertia to the roof)
5 – Case 4 + seasonal night ventilation with windows, windows also open according to need during school hours
6 – Case 5 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.74: Temperature variations for one year during school hours in Mansehra type 1 school for combined cases.

Average temperatures could be lowered by about 4°C going from case 3 to 6. Adding thermal inertia to the roof would raise the minimum temperature by about 2°C, but ventilators would cancel this benefit.

Figure 4.75 shows that the air change rate is similar in all cases, but ventilators would increase ventilation as in Islamabad and Lahore.



1 – Old reference (school type 1)
2 – Revised reference (school type 1)
3 – Wall 6 + Roof 6 (added thermal inertia to the roof)
4 – Case 3 + seasonal night ventilation with windows, windows also open according to need during school hours
5 – Case 4 + seasonal night ventilation also with ventilators, ventilators always open during school hours

Figure 4.75: Air change rate variations for one year during school hours in Mansehra school type 1 for combined cases.

5 Moisture safety assessment

This chapter studies the moisture problems in Lahore that were identified during the field study as described in Section 3.1.5. The moisture problem is only present in and around Lahore but there it affects in principle every school. Since the climate is not that different from Islamabad, the reason for the problem should be in how the schools are constructed. Lahore is the only region where schools are constructed with bricks exposed to the rain so this could be part of the reason. Similar problems are also found in other buildings in Lahore. The problem is studied with the commercial software WUFI

5.1 Precipitation

The problem can be caused by the detail where the brick wall meets the concrete ceiling. Bricks are very porous and they can absorb and transport moisture much easier than concrete. The moisture enters the brick when it rains and it rises in the wall due to capillary action. When the moisture hits the concrete, the moisture transfer is slowed down considerably and moisture starts to accumulate. The moisture from the bricks also moves inwards through the wall and when it hits the plaster on the interior wall, the same thing happens.

It is thus possible that the bricks are the cause of the problem, even though the original reason for using bricks was that they require less maintenance because the façade doesn’t need to be painted. Concrete blocks might be a better solution even if they will require an outer plastering. Alternatively the bricks should be protected from rain.

5.1.1 Model and assumptions

The problem has been investigated by studying the connection between the brick wall and the concrete roof. Figure 5.1 below shows how the studied detail looks. The wall is plastered on the inside and the roof has a roof membrane on top of the concrete.

A climate file generated by Meteonorm has been used. An eastern wall has been studied because according to WUFI’s analysis of the climate data, the eastern wall received the most driving rain. The results from the Simulink calculations have been used to determine the hourly indoor temperature and air change rate during the year, and from this data and the known outdoor relative humidity, the indoor relative humidity has been calculated, as described in Section 2.4.2. A minimum air change rate of 1.5 was used in the Simulink calculation.

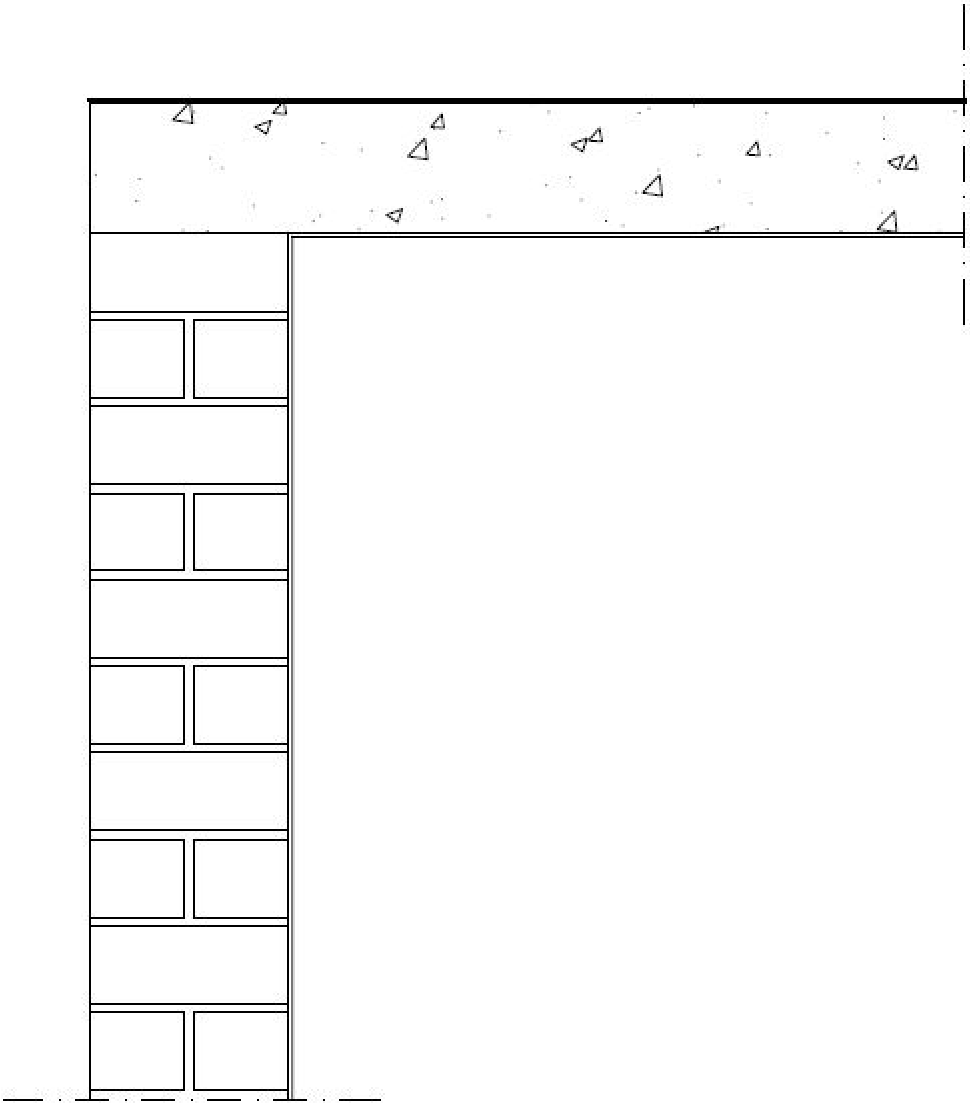


Figure 5.1: Detail of wall-roof connection studied with WUFI.

Solid extruded brick has been used in the simulation. In order to be able to run the simulation without mathematical errors, the moisture buffering value of the brick was increased by raising the moisture content at high relative humidities. The original and modified moisture storage functions are shown in Figure 5.2.

Original moisture storage function

Modified moisture storage function

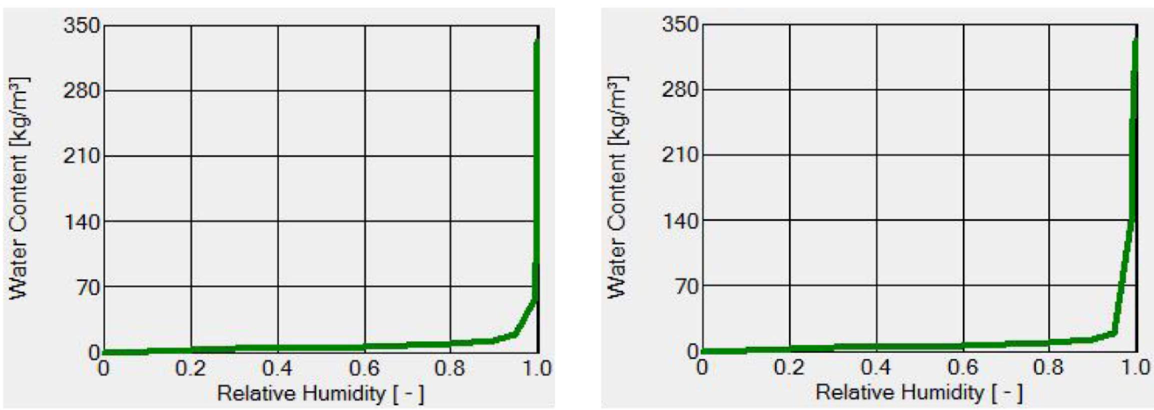


Figure 5.2: Original and modified moisture storage function of brick used in simulation.

5.1.2 Results

The simulation has been run during different times of the year. Even though it mostly rains during the rainy season between June and September, it rains occasionally during other times of the year as well. Figures 5.3 and 5.4 show how the water content and the relative humidity, respectively, vary in different parts of the wall during one week in June when there is heavy rainfall. The spots studied are in the top part of the wall. The spot on the interior surface is located in the plaster while the other two are located in the bricks. Brick can hold much more moisture than plaster, and because of this the correlation between water content and relative humidity is not the same for both materials.

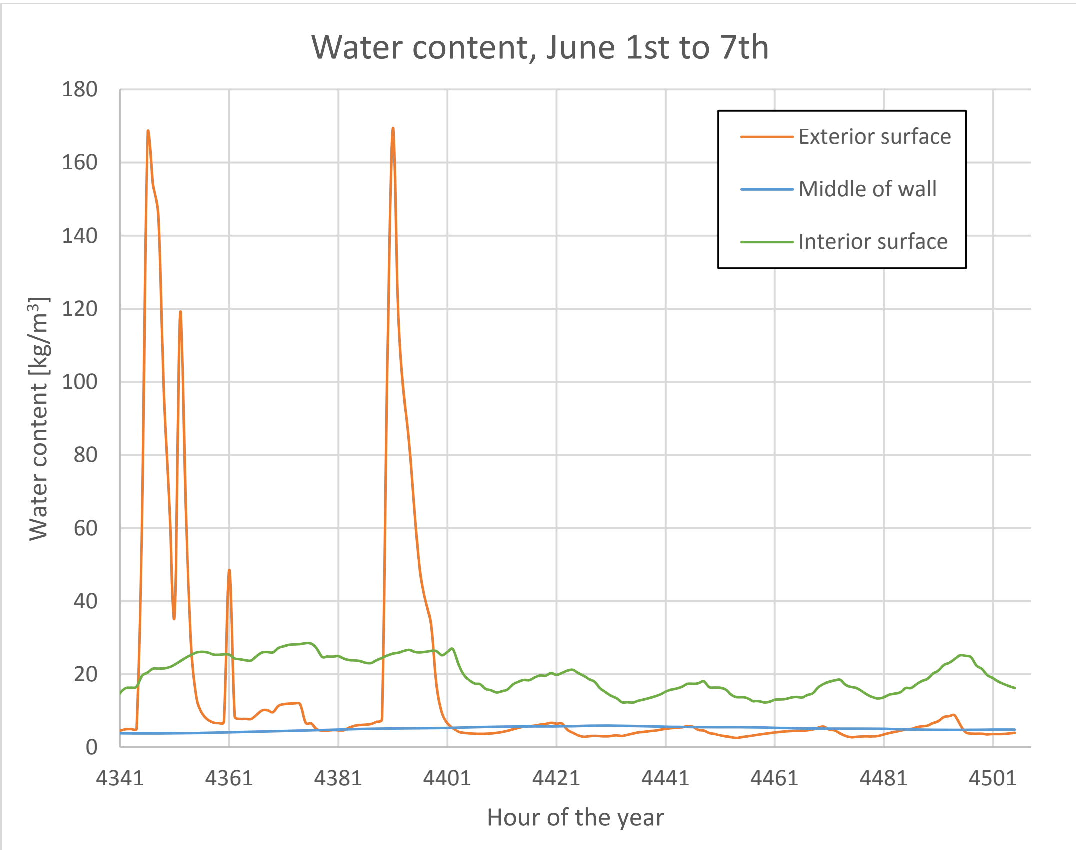


Figure 5.3: Variation of water content in the wall during one rainy week.

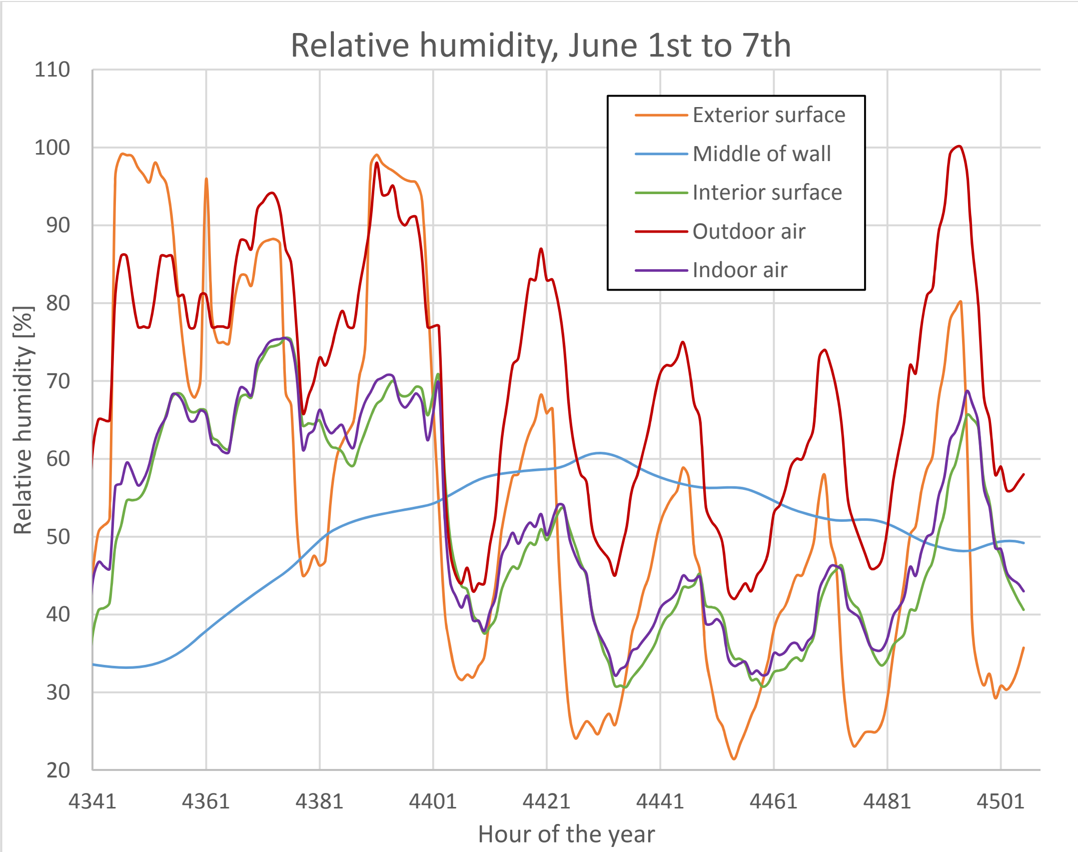


Figure 5.4: Variation of relative humidity in the wall, outside and indoors during one rainy weak.

Figure 5.3 shows that the water content on the exterior surface reaches a clear peak when it rains, but the variation on the interior surface doesn't correlate. The moisture content in the middle of the wall varies very little, and there is very little moisture transport through the wall. From Figure 5.4 it can be seen that the relative humidity on the interior surface follows the relative humidity of the indoor air.

Based on these results, it doesn't look like rain would be the cause of the problem. However, different types of bricks transport moisture in different ways, and with a different type of brick the results could also be different. Figure 5.5 shows the liquid transport coefficient for the brick that was used and for one alternative brick that would transport more moisture at higher water contents. For these two bricks the liquid transport coefficient for suction and redistribution were the same. Other bricks from different WUFI databases were also tested, but because of mathematical errors it was not possible to run the simulation with alternative bricks.

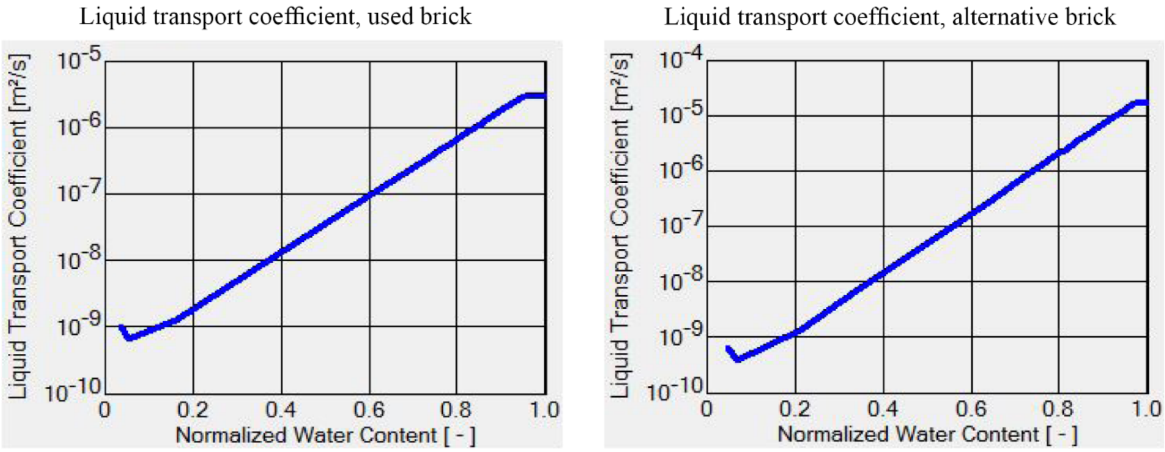


Figure 5.5: Liquid transport coefficient for the brick used and one alternative brick that could have given different results if the simulation hadn't stopped because of mathematical errors.

More studies should be done to study the problem in more detail with different materials before it can be determined whether precipitation is the cause of the problem.

5.2 Indoor moisture

The field study was done during the colder time of the year, and surface temperature measurement showed that the wall surfaces were significantly colder on the interior than on the exterior side during the day. Because of the cold, windows were also mostly closed which means there was little ventilation. This combination of cold surfaces and little ventilation could mean that the indoor moisture produced by the students during the day could be the cause of the problem.

5.2.1 Model and assumptions

The model and assumptions are the same as described in Section 5.1.1 for the precipitation study. Different air change rates have been tested in order to see the effect of ventilation. In some cases a constant air change rate has been used. In other cases case a minimum air change rate is set to account for air leakages, while most of the time the air change rate varies as in the reference case in the Simulink simulation.

5.2.2 Results

The studies have been done in December-January when the weather is cold and humid. Figure 5.6 shows how the relative humidity of the indoor air varies during one week in January in the different cases with varying air change rates. From this it can be seen that the relative humidity can become very high, even 100%, during the school day if there is not enough ventilation. However, outside school hours less ventilation keeps the relative humidity lower because the building stays warmer.

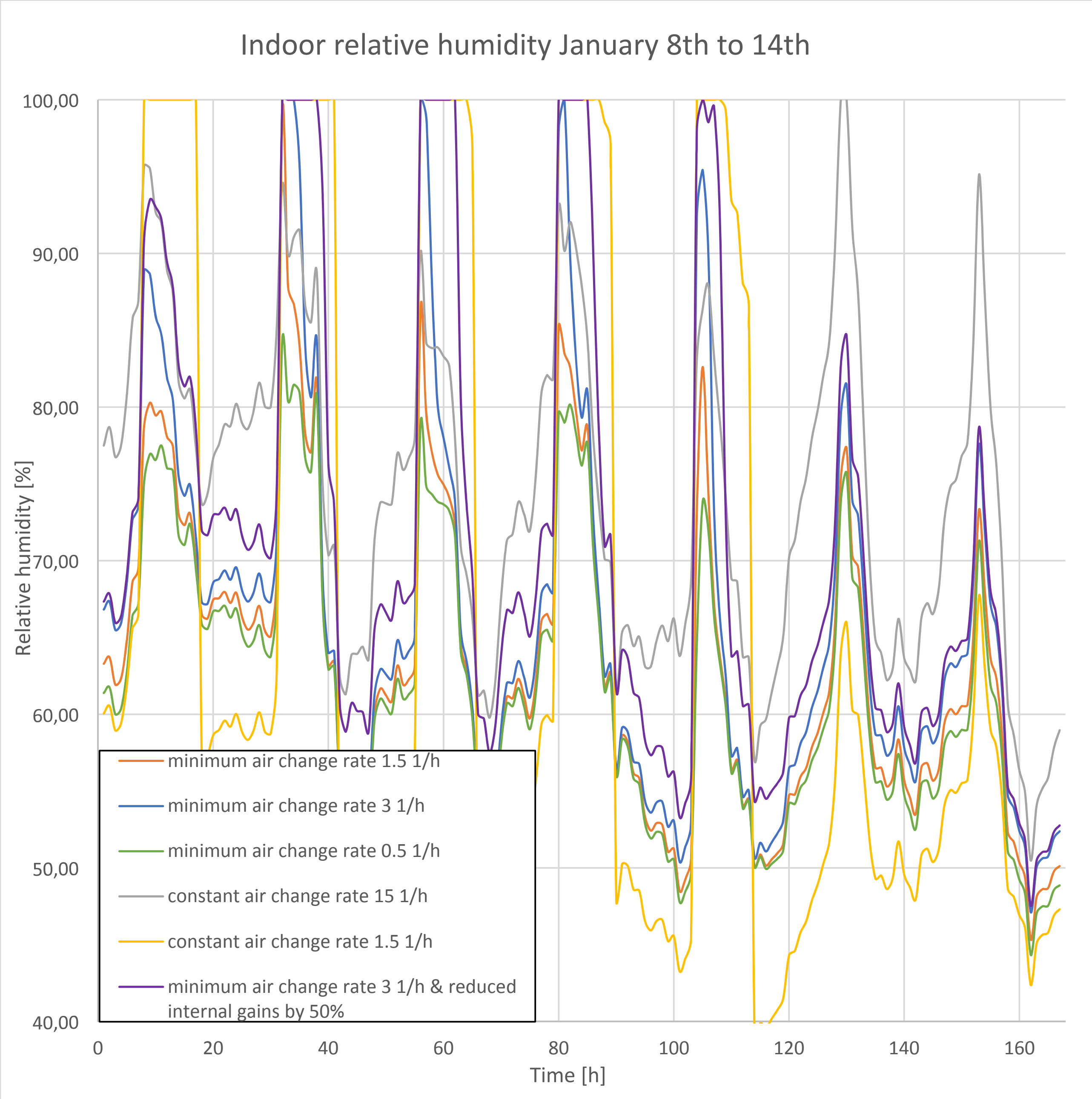


Figure 5.6: Variation of indoor relative humidity with different ventilation rates during one cold and humid week.

Ventilation removes humidity from the air but it also makes the surfaces and the air colder. Air leakages during the night should be avoided in order to keep the building warmer and this can be done with better windows. More ventilation is needed during the day to remove humidity, even though this can cause discomfort due to cold weather, especially in the mornings. Alternatively, moisture buffering materials could be used, and these would absorb moisture during the day and release it during the night. However, ventilation is also needed to provide fresh air for health reasons, and it would be better if the issue with the cold can be solved by utilizing the heat from the sun more effectively in the winter.

Figure 5.7 shows how the relative humidity on the interior surface of an exterior wall varies. The trend is similar to that of the indoor air but the peaks are not quite as high.

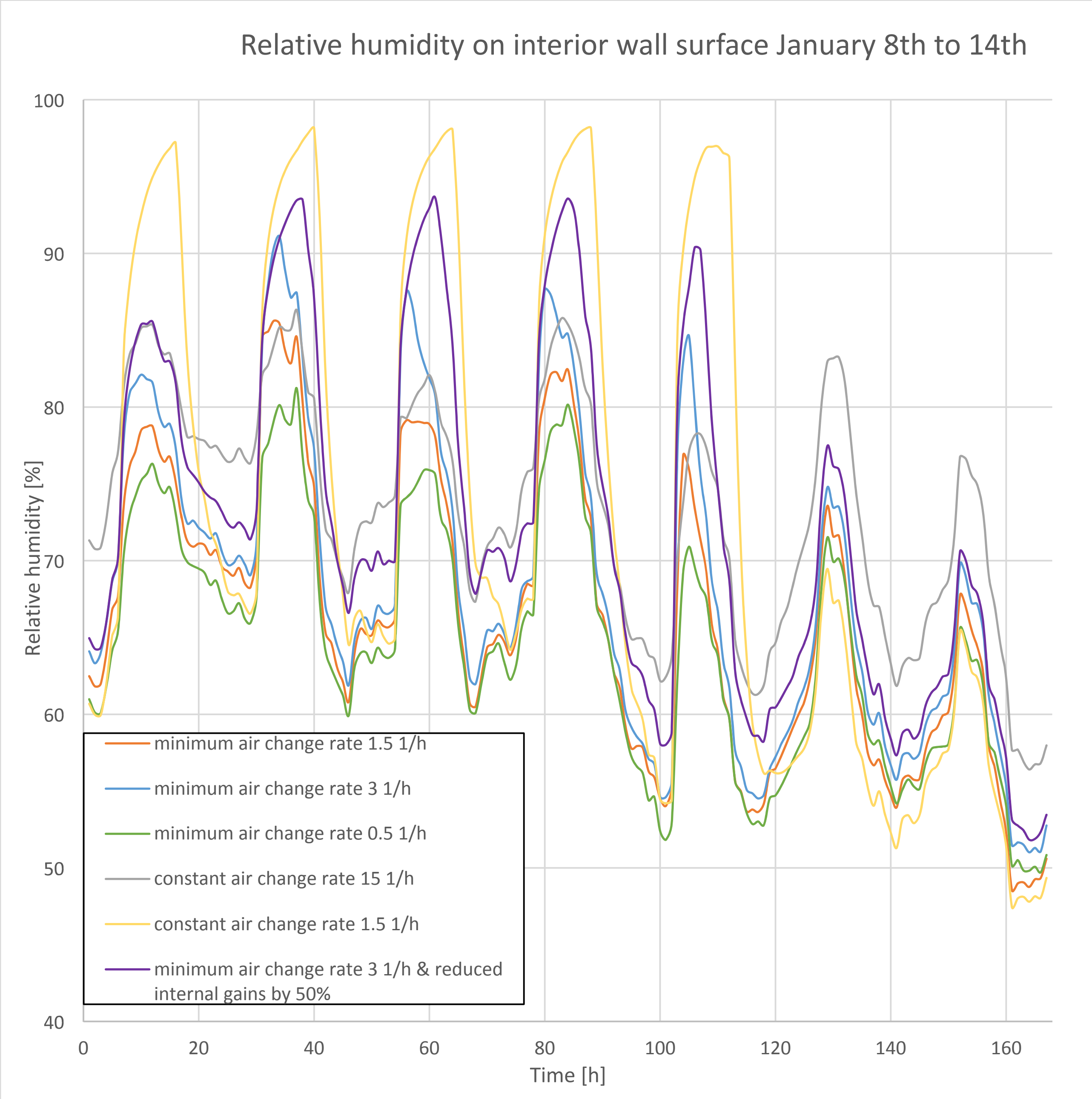


Figure 5.7: Variation of relative humidity on indoor wall surface with different ventilation rates during one cold and humid week.

Even though there are clear peaks during the day in Figure 5.7, the relative humidity drops quickly after school hours. The relative humidity also doesn't reach 100% which means that the surface temperature is above the dew point temperature of the air. However, Figure 5.8 shows how the surface temperature varies according to the simulations, and even when internal gains are reduced by 50%, the surface temperatures (15-17°C) are considerably higher than the temperatures that were measured during the field study (9-12°C). With lower surface temperatures the relative humidity would also be higher and could be enough to cause condensation.

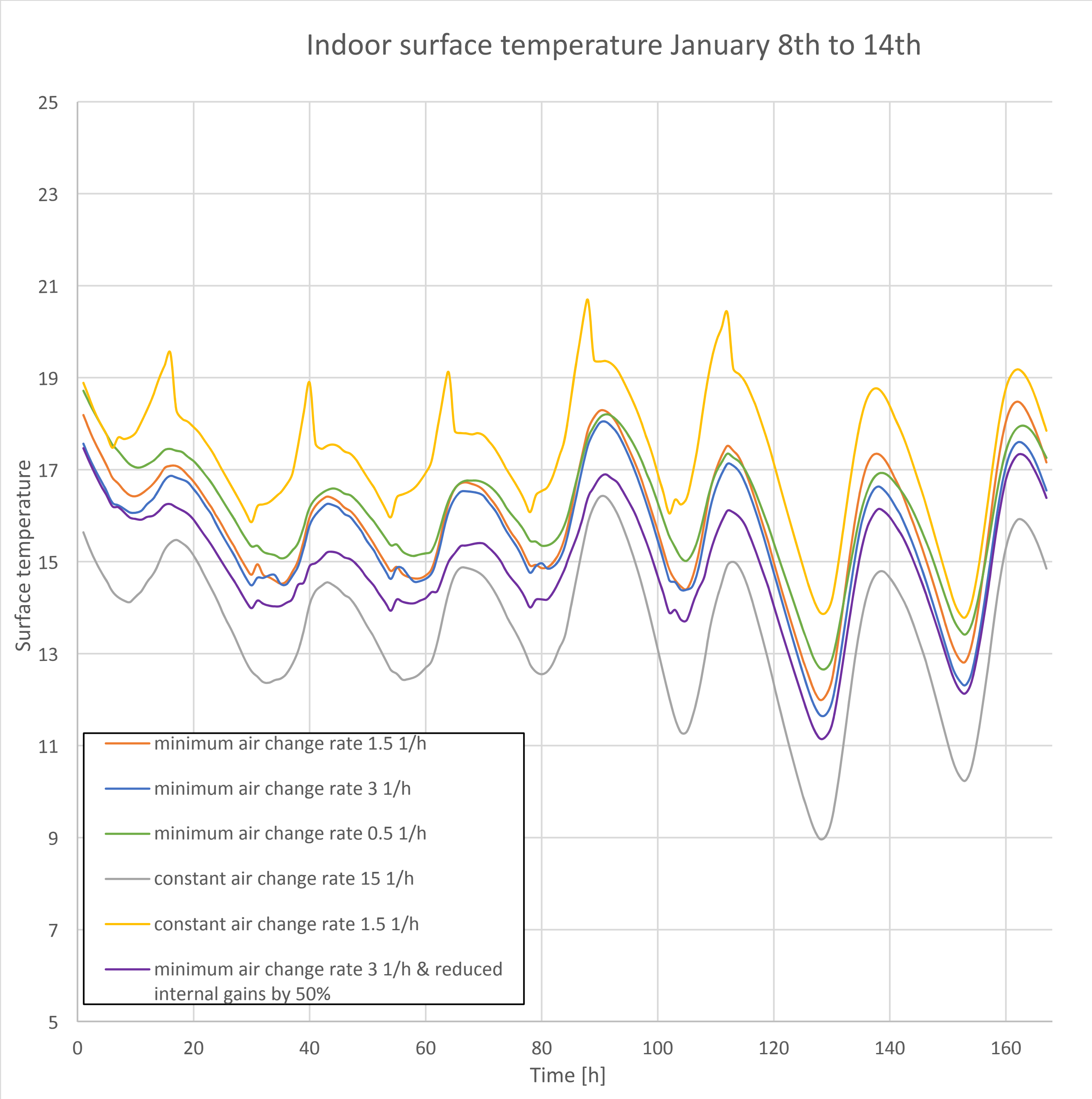


Figure 5.8: Variation of temperature on indoor wall surface with different ventilation rates during one cold and humid week.

Cold surfaces combined with high indoor air humidity could thus be a reason for the problem, but more studies would be needed with more accurate surface temperatures. However, the problem is present all year and yet it is only cold during a few months. Also, if indoor moisture is the source of the problem, it wouldn't explain why the problem is present throughout the year and why the problem isn't present in Islamabad.

5.3 Moisture from the ground

The local TCF engineer and some other TCF employees believe that the moisture problems are caused by moisture seeping from the ground. According to them, the water table in Lahore is very high.

5.3.1 Model and assumptions

Figure 5.9 below shows how the detail between the brick wall and the ground looks like. The wall has two damp proof courses (DPCs) that consist on concrete, bitumen and a layer of plastic. Between these two DPCs there is a vertical DPC on the interior which consists of bitumen. The floor construction consists of concrete, a moisture barrier and mosaic tiling.

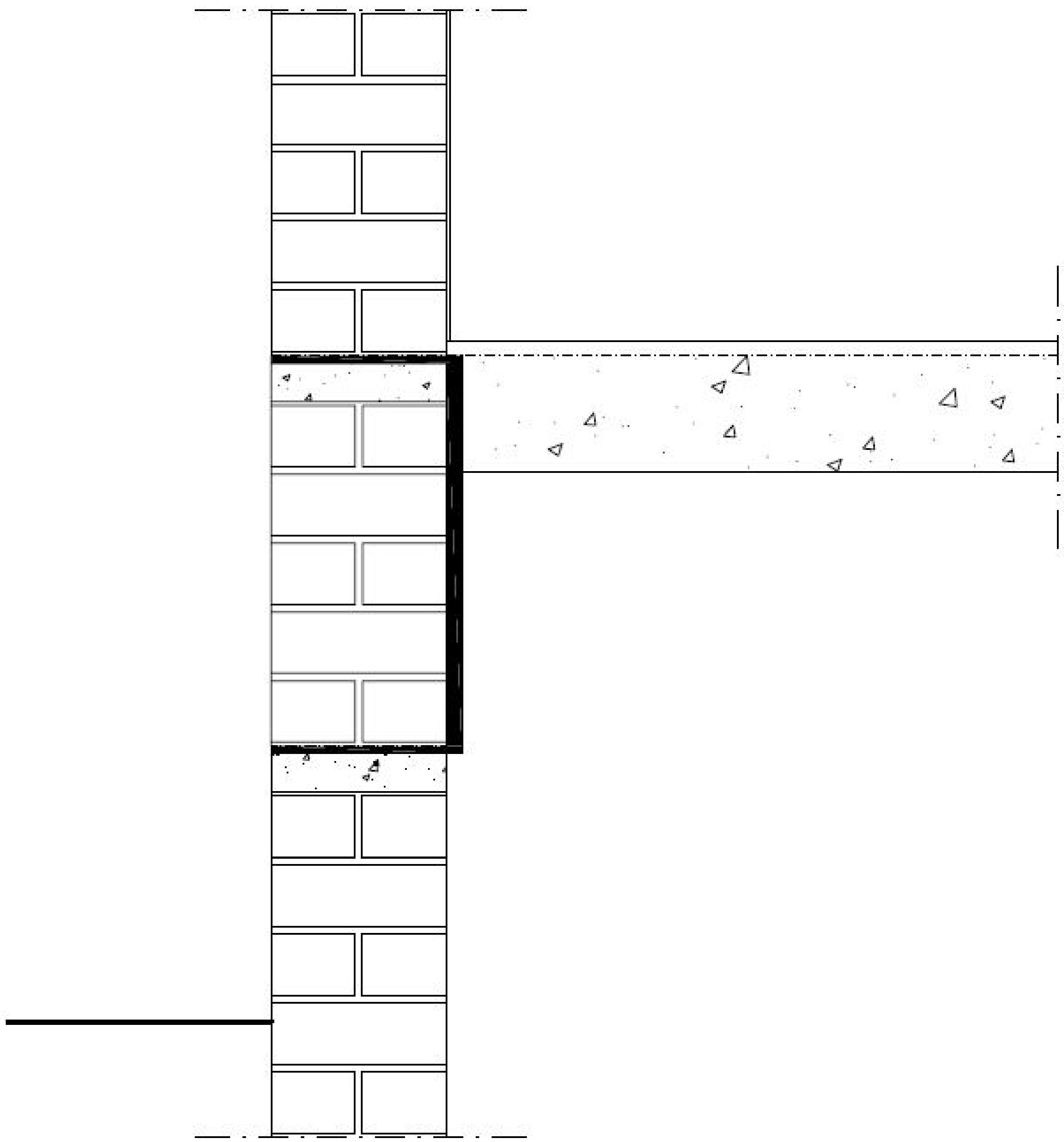


Figure 5.9: Detail between ground and wall used to study effect of ground moisture.

The same brick has been used as in the other simulations. The indoor relative humidity is set to vary between 45% and 85% and the indoor temperature between 16°C and 36°C during the year. These variations follow approximately the average variations in outdoor temperature, but the values are slightly higher indoors. The relative humidity of the ground varies between 95% and 99%.

5.3.2 Results

Figure 5.10 below shows the resulting relative humidity variations on the interior wall surface in a spot close to the ground.

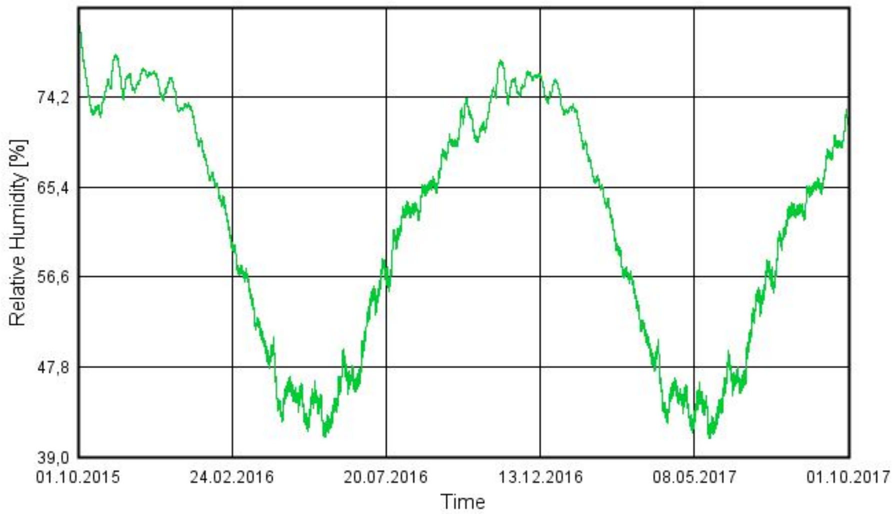


Figure 5.10: Variation of relative humidity on interior wall surface close to the ground during two years.

Based on these results, it doesn't look like moisture from the ground would be the cause of the problem, and the relative humidity of the wall follows the humidity of the indoor air. The two DPCs are thus sufficient to keep the moisture from the ground from entering the wall construction. However, if the DPCs are not carefully constructed, they could leak and then moisture from the ground could become a problem. If the moisture came from the ground, making the foundation from concrete instead of brick should help since concrete doesn't absorb or transport moisture as easily as brick.

5.4 Other moisture sources

The model that was described in Section 5.1.1 was also used to test a possible leakage or construction damp. Leakage was tested by placing a moisture source in the connection between the wall and the roof and this moisture source was 1% of the driving rain. Construction damp was tested by running the simulation with a high initial relative humidity for the concrete, because the concrete slab is cast in situ. Neither of these two showed high enough values to cause the moisture problems. However, the exact detailing on the roof-wall connection is not completely known, and a more detailed analysis could show different results.

6 Conclusion

This thesis has studied the performance of TCF schools in four cities, and the existing schools in Karachi seem to perform best. The climate in Karachi varies less throughout the year, both in term of temperature and wind speed, and this makes it easier to design passive systems there than in Northern Pakistan. Night ventilation would be recommended since it would improve thermal comfort. If security is an issue, ventilator windows could provide a more secure way of achieving night ventilation, and ventilators could also help increase air flows during still weather. Favouring light colors for the facades would be a simple way to reduce some of the heat gains, especially on the roof.

In the north in Lahore, Islamabad and Mansehra the situation is different. Because wind speeds are lower, relying only on windows for ventilation is difficult, and adding alternative openings would be beneficial. More openings would both increase the air change rate and lower the indoor temperatures. Night ventilation during the hot months is also recommended.

Better windows, closer to those now found in Mansehra, would be recommended for all regions. This way air flow can be controlled better so that air leakages are minimized during the night in the winter months. These air leakages not only make the schools colder and more uncomfortable, they can also be the cause of moisture problems. To avoid moisture problems, it is also important that the windows are open during the day even in the winter so that the moisture produced by people doesn’t build up in the structure. If this is uncomfortable because of cold weather, moisture buffering materials could be considered.

This thesis has focused on passive cooling of the schools since cooling has been identified as a more pressing issue than heating in Pakistan. However, in Northern Pakistan winter months can be uncomfortably cold and because of this passive heating should also be developed. In Mansehra, the heavy structure that uses local techniques is preferable over the light gauge system, because the heavy structure utilizes both insulation and thermal inertia, both of which are beneficial in both summer and winter. Insulation could be considered in Lahore and Islamabad as well, but it would be an extra cost and the downside would be that insulated schools would lose heat less efficiently during the night in the summer. The architectural design should consider how the heat from the sun could be utilized more in the winter, especially in the mornings.

The moisture safety assessment of the schools in Lahore didn’t show any definitive results. Because the problem is present in all schools in the region, the problem should be caused by the construction detailing. Because the problem is present all year, and because it is present close to the ceiling, precipitation seems to be the most likely source, but this couldn’t be verified with the simulations that have been done. More detailed simulations would be needed to study the problem further.

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