Re-addressing the Window: Environmental Performance of Adaptive Fenestrations for Indian Climate

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RE-ADDRESSING **THE WINDOW**

Environmental Performance of Adaptive Fenestrations for Indian Climate

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ABSTRACT

The primary function of building fenestrations known to humankind is to provide daylight, fresh air and view. However, with the emergence of mechanical systems, the purpose of space heating and cooling, ventilation and lighting are widely fulfilled artificially. The comprehensive focus of this research is to investigate the role and evolution of windows to date, the factors that have influenced them, its effect on human psychology and their contribution in creating better living spaces. The Indian government's scheme of constructing 20 million homes by 2022 and about 15% rise in the use of air conditioning per year in the urban and rural parts of India can be directly associated with the persistent shortage in electricity supply which has led to power cuts of about 16 hours per day in mostly the rural areas of the country and especially during the summer months (National Building Organization, 2016), (The Hindu, 2013; Wolfram, 2012). Hence, it is of specific importance to undertake this research to understand how windows have evolved and what their role in the future might be, especially in relation to design and the attainment of comfort. This research will contribute by portraying 'window' as an adaptive tool since they have the potential to create diversity, flexibility and social interaction along with providing thermal and visual comfort for its users. This will be achieved by examining and readdressing passive design elements prevalent in the traditional Indian buildings, by documenting the current trend in window design and user preference, and by testing the documented windows through computational analysis to understand their impact on the thermal comfort in a modern residential unit setting. The final outcomes of this study that were achieved through fieldwork and performance analysis strongly demonstrated the significance of windows in improving the indoor thermal comfort. Moreover, the simulations ascertained that the contribution of windows was more substantial when they were a part of a holistic design intervention that took into consideration window design, building materials, building form and orientation, building techniques, climatic conditions, surrounding context and application of appropriate environmental controls.

Key words: Window systems, adaptive tool, building elements, natural ventilation, passive strategies

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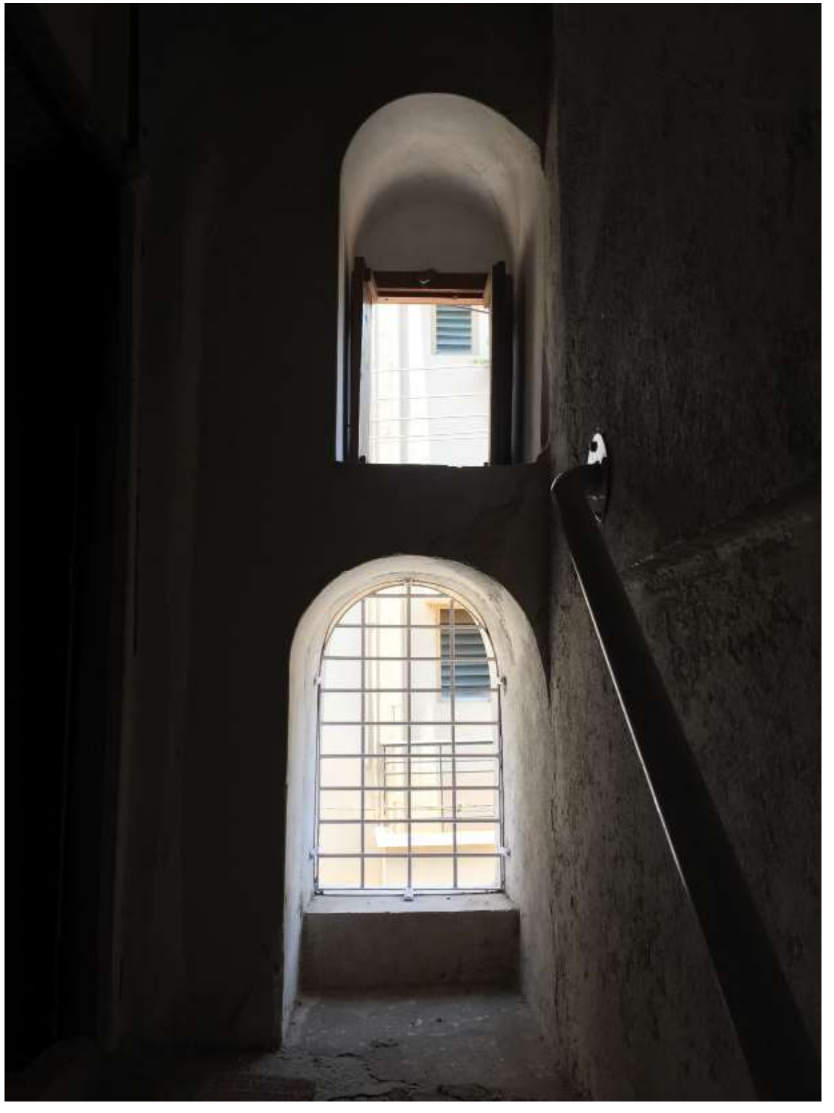

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AUTHOR'S DECLARATION

Total Number of Words: Approximately 49,956.

I declare that all the material contained in this thesis is my own work.

CHAPTER 1

PREFACE

McKinsey Global Institute has projected that India will see a rise in its urban population from 340 million in 2008 to 590 million by 2030, which is estimated to be 40% of the total population of India (Sankhe et al., 2010). Today, cities are responsible for 78% of the Green House Gas emissions due to highly modified land use and concentrated urban activities, which has led to Urban Heat Island (UHI) effect (Schiano-Phan et al., 2015). The maximum heat island intensity data reported by Padmanabhamurty for some Indian cities are; 9.5K in Mumbai, 10.0K in Pune, 4K in Kolkatta, 6.5K in Bhopal respectively (Santamouris et al., 2011). Hence, the demand for cooling in Indian cities is evident now more than ever due to the concentration of the high number of population in the urban centers of the country.

In 2015, although the global air conditioning market cooled down, the MEIA (Middle East, India and Africa) region showed a seven percent growth from 11.6 million units to 12.5 million units, the major contributor to which was India (McMahon, 2017; BSRIA, 2015). The reasons for the demand in air conditioning systems in India were associated with rising business and consumer confidence after the formation of the new government, growing real estate sector and growing income levels. Thus, with the prevalent air conditioning purchases by the middle-income group, India has been experiencing a shortage in electricity supply which has led to power cuts of about 16 hours per day in mostly the rural areas of the country and especially during the summer months (The Hindu, 2013; Wolfram, 2012).

To reduce the energy consumption by air conditioning units, new technologies are being developed. However, as cited by Cox (2010), producing energy efficient air conditioning systems will not solve the energy over-consumption problem because with the increased efficiency we might use even more energy since the temperatures are getting hotter and the demand is increasing at a very fast pace along with the growing population (Watson, 2010). With 10 to 15% rise in air conditioner sales in India per year (Mooney and Dennis, 2016), mechanical cooling has dramatically discouraged the use of passive cooling strategies. Hence, the emerging cities of a developing nation like India, are experiencing higher energy consumption issues which are responsible for changes in the weather patterns with an increase in the intensity and frequency of climate change (Revi, 2008; Intergovernmental Panel on Climate Change, 2014).

Looking at the future population growth, climatic projections and the rising energy demand, there is a need to reduce the reliance on mechanical cooling systems and introduce alternative solutions. Therefore, this research, lays an emphasis on the importance of occupant use of adaptive tools such as 'windows' to achieve comfort in Indian households. Also, the reason this research focuses on 'windows' as an appropriate alternative solution is that, apart from providing thermal comfort windows are also responsible for the social and visual linkage and hence, they form an important relationship between the outside community and life inside the buildings.

Research Objectives

Keeping in mind the demand and issues of mechanical cooling systems in India, the next big concern is the ambitious aim of constructing 20 million homes by 2022 for the economically weaker sections of the society and for the people belonging to the middle income group by the Government of India (Prime Minister's Office, 2015). One can imagine the drastic rise in the energy consumption on a household level. Hence, in order to address the growing issue of energy consumption, various interventions are put forth such as renewable energy, sustainable design, preference to local produce etc. Of which, the most discussed alternative solution to minimize the energy consumption is by improving the thermal performance of homes, which can be achieved by providing thermal mass, the choice of materials, reducing glazed areas, improving the natural ventilation of the spaces and suitable shading design (Nicol, Humphreys and Roaf, 2012).

Taking into consideration glazing area, the allowance of daylight and natural ventilation, a window has the potential to act as an architectural element as well as an environmental element. The form and alignment of opening a window determines the daylight and air movement that influences the temperature patterns of an indoor space. Windows are capable of creating thermal and visual diversity since they can be adaptable in multiple forms. For example, the degree of thermal comfort can be adjusted by the percentage of window opened or the use of blinds or curtains provides control over the daylight factor (Steemers and Steane, 2004). They provide us with flexibility and opportunities to adjust our indoor environment according to the outdoor climatic conditions and also according to our comfort requirement. By connecting us with the changing outdoor environment, they keep us informed about the time of the day, the weather conditions and about the activities taking place outdoors. Windows have become a part of our daily lives, the way we operate windows during different times of the day and in different seasons to achieve environmental comfort has become our everyday tradition and is also been largely researched by experts such as Elizabeth Shove, Kirsten Gram-Hanssen and others. (Shove, 2003) (Gram-Hanssen, 2010).

Hence, the objectives of this research are:

- *To determine the importance of windows in regulating indoor thermal comfort in present times.*
- *To document the traditional and contemporary window designs belonging to the hot-humid and hot-dry climatic regions of India and their performance with respect to climate.*
- *To understand the potential of windows as an adaptive comfort regulating tool out of all the other architectural elements.*
- *To put forth the importance of fenestration design and to lay an emphasis on why it needs to be modified.*
- *To highlight the importance of windows operability in attaining thermal comfort, hence challenging the current window design practices.*
- *To establish the significance of having a holistic design approach, that takes into consideration all the architectural elements.*

Research Questions

Bearing in mind the objectives of this study, the following research questions are framed:

- The reason to document the traditional window design is to know how they are capable of creating thermal comfort in present times.
- 'Windows' are considered as one of the important architectural elements since they have the potential to create the facade of a building and at the same time have the ability to regulate the indoor environment. With the changing climatic conditions and prior knowledge of the increase in the annual average temperatures, and in spite of the mechanical systems available to us for cooling, ventilation and lighting, do we still need windows?
- Do we need windows that provide the occupant with various permutations and combinations that can be applied to create an indoor environment as per their comfort requirements, i.e. do we need 'adaptive windows' or should we blindly continue to replicate the western practices of providing glass windows for our tropical climate?
- How effective is the integration of adaptive window design interventions in creating a comfortable indoor environment with minimum use of mechanical systems for cooling and why adaptive strategies even for window design are important?
- Through this research is there a scope to create an awareness of the importance of window design while designing spaces?

Contribution to Knowledge

Standardization with respect to materials, technology and building codes have manipulated the notion of comfort for the users. We are developing a 'mono-culture of comfort' since the management of the indoor climate is being significantly replaced from traditional and natural practices to the advanced mechanical systems (Gram-Hans sen, 2010). As a result, these systems and the universal set standards for a 'healthy indoor environment', are changing the way we live in our homes. Since the invention of the mechanical systems, we have been relying on them to attain comfort due to which we are losing our ability to adapt to the changing environment. Hence, it is extremely important that the designers treat this as an important issue and make it their responsibility to readdress the concept of comfort through design by taking in to consideration the user requirements, climatic opportunities, material availability and affordability.

Addressing the above concerns, a report published by Global Building Performance Network (GBPN) in 2014, had proposed few policy recommendations to achieve savings in the total residential energy consumption after analysis of the survey data and by considering major trends in the housing sector. One of the policy recommendations was to increase the residential building envelope efficiency by encouraging the use of alternative cooling techniques at least when the weather was favorable. It is believed that one of the ways to increase the building efficiency is by improving and redesigning the building envelope components such as windows, shading devices, daylight and natural ventilation strategies.

Although there is an awareness of the problem and also suggestions of what can be done, there seems to be lack of information on how the given suggestions can be implemented. Also, there is very little data available regarding the performance of different types of window de-sign in a typical Indian household, nor there are any suggestions with respect to the performance of different adaptive strategies and de -sign elements that can be added to the current fenestration design trend. Thus, there is a need to promote the potential of windows and their capabilities by the provision of adaptive strategies with respect to varying social and cultural expectations of comfort.

It is anticipated that this research will highlight 'window' as an adaptive tool since they have the potential to create diversity, flexibility, social interaction along with thermal and visual comfort for its users. It is to provide information on the performance of different types of window design in a typical Indian household, with suggestions on the performance of different adaptive strategies and design elements that can be added to the current fenestration system. This study aims to lay an emphasis on window as a comfort regulating adaptive tool, that provides the users with the flexibility to control their indoor environment and synchronize the same with the outdoor conditions.

Methodology

The objectives of this research are broadly achieved through three methods. The first is through the literature available related to this study that provides the supporting data for the aims considered for this research. Apart from statistical data, this segment defines the concept and history associated with windows. It also indulges into the documentation of different examples of climatically responsive windows available today from different periods and from different parts of the world. Furthermore, looking into the different environmental features and concepts associated with windows along with the various research studies conducted by researchers in relation to window and adaptive comfort, strengthens the proposition of this study. Also, before the commencement of the field-work, the base of the fieldwork is set through the literature available for the chosen sites of study such as climatic analysis, history of the building and so on.

The fieldwork is the second method applied, to achieve the objectives of this study. The elaborate section of this research documents the information associated with the built form, materials and technologies used to build these typologies in the form of drawings and photographs, along with the occupancy patterns of the users. It is through fieldwork that the environmental study is conducted which comprises of documentation of spot measurements and continuous measurements. Additionally, the on-site data collection method also involved collecting occupant feedback through BUS (Building Use Studies) survey and an additional questionnaire designed specifically for this research.

The third important part of this study is computational analysis. A method that is used to verify and scientifically prove the hypothesis of this research. The analysis helps in drawing a comparison between various architectural elements such as windows, walls, floor and ceilings. It tests various permutations and combinations, in the form of different cases, to ascertain their effect on the indoor thermal environment.

Project Limitations:

Although the above methodology was followed, there were certain limitations that were observed during the entire research period. The performance analysis was carried out only for the hot-humid climate. Hence, it is evident that the performance of the design interventions considered for this climate will certainly differ for a different climatic scenario.

The BUS survey and the customised survey on windows was carried out mainly in one high-rise building only. To understand the performance of different typologies and the user satisfaction of their living spaces, the survey could have formed the part of the study of *chawl* as well as *wada* plus additional residential high-rise buildings.

The number of case studies could have been more and from different parts of India belonging to different climatic regions. The diversity of vernacular architecture in India is large and hence there is a lot of scope to learn from them and apply the learnings in the research or production field. However, it was not in the scope of an MPhil research.

The performance analysis outcomes are with respect to the internal conditions of only one particular user, however, typical conditions will be different for different occupants along with their distinct use of an adaptive window.

It was also noted that various adaptive combinations could be adopted by the inhabitant to achieve the desired comfort setting. While it is possible to test all the likely combinations, it was not possible to document them all in the given time frame.

Although the objective of the research was to lay emphasis on the application of affordable adaptive window instead of the conventional sliding windows along with extensive use of mechanical cooling, the most challenging part is altering the mind-set of the users and manufacturers into adapting such window systems, especially when the users are increasingly getting accustomed to a more convenient option of mechanical cooling. The challenge at the manufacturing level consists of the willingness of the production companies to fabricate such windows at an affordable rate. With a strong market of sliding windows and glass cladding in India, the readiness of the manufacturers to risk the introduction of customised windows seems doubtful. In addition to this, to convince the inhabitants, who are the consumers, of the long term benefits of adaptive windows and urging them to minimise the use of mechanical systems is the biggest challenge in present times, where mechanical cooling seems to, very conveniently, protect the occupants from the rising temperature, sound, and air pollution. Apart from these setbacks, it also becomes the responsibility of designers to propagate and practice the use of adaptive technologies and try to minimise energy consumption through their designs.

Structure of the Work

1. Preface: This introductory chapter gives an outline regarding the aim of the research and the need to conduct this study. Whereas the statistical data regarding energy consumption and the growing use of air conditioning units are discussed in the literature overview section. This data stresses further, on the urgency of the need to provide passive alternative solutions to the use of mechanical systems.

2. The Meaning of 'Windows': Before progressing into the examples of the window and the analysis of the fieldwork, it is essential to first understand the meaning of a 'window', their origin, their purpose. Hence, it is first important to know about the history of windows and the various environmental factors associated with them. This chapter explores the different definitions of windows, theoretical as well as technical, which further helps in defining the concept of this thesis i.e. 'adaptive windows'.

3. Examples of Windows: The fieldwork comprises the study of contemporary and traditional window designs located in Western India. Hence, before the onset of the fieldwork, it was essential to look at additional traditional window designs prevalent in other parts of India such as '*jaalis*' and '*jharokhas'*. Apart from traditional Indian windows, this chapter also reviews the modern adaptive window design by Geoffrey Bawa widely known as the 'Monsoon Window'. Furthermore, a modified version of 'Monsoon window' is presented, which is used in a modern residential high-rise building - the Moulmein Tower, Singapore. All these examples are studied based on drawings, photographs and the write-up available. The study of modern and traditional window design aided in evaluating the possibilities of applying those concepts in a typical household setting or to suggest if there is any room for modification to fit the same in an urban setting. The examples provide with ideas and information which have the potential to become part of design interventions in future work.

4. Indoor Environmental Comfort: This chapter revisits the theory of comfort. It helps in understanding the notion of comfort in brief and how it has been extensively analyzed by various experts over the period of time. It involves interpretation of adaptive comfort and its connection with the social and economic conditions of its user. The chapter discusses the need to address adaptive comfort and how it is perceived by researchers. Before the fieldwork, it was essential to define and understand adaptive windows. This was achieved by analyzing scientific and analytic studies conducted by researchers across the globe since their study was also similarly based on the role of adaptive controls available to the occupant. The last section of this chapter draws a conclusion from the collected research data and the analytical studies that form the guideline for the elaborate fieldwork.

5. Introduction of Case Studies: The three different types of windows studied as a part of the fieldwork are:

1. The Contemporary Window
2. The Window for hot-humid climate
3. The Window for hot-dry climate

The researched windows belong to three habitable spaces located in a densely populated hot-humid and hot-dry climatic regions of Maharashtra, Western India, belonging to the three different eras. The fieldwork helped in drawing major differences in the type of built-form, the materials and the technologies used in building these windows as well as these homes. The ways in which the habitable space and the space around was used also differed. These distinctions are presented by documenting the design, materials, function and technologies used in building these windows as well as homes, mainly in the form of photographs and drawings. With *chawls* and *wadas* belonging to the colonial period, this chapter also documents the rich history associated with them, through which a connection can be made with the social and cultural significance of these built-forms. Moreover, the qualitative interviews taken allows to understand the daily practice of the users in detail and also their perception of windows. It gives a clear picture of the quality of indoor spaces in these homes which is highly influenced by its built form, architectural elements like window and the material used. Thus, this section, as the name suggests, introduces the three types of windows which are scientifically analyzed further.

6. Fieldwork: In continuation with the previous chapter, this section documents the building layouts, user pattern and analyses the results from the spot measurements taken for the different environmental factors such as air temperature, humidity levels, illuminance levels and wind velocity levels inside the house as well as outside during the same time. Plus, the graphical representation of the continuous measurements taken over a while in the above mentioned habitable spaces and the analyses of the same. The collected data helps in concluding the functioning of these built spaces during the different times of the day. It allows to draw a comparison between the performance of the three households during the summer months.

The second half of this chapter discusses a methodological survey performed during the fieldwork. The procedure of conducting the survey was carried out through a practice adopted by BUS (Building Use Study). BUS methodology was developed and used for the government-funded PROBE (Post-occupancy Review of Building Engineering), that studies to investigate the building performance and quantify occupant satisfaction and also follows rigorous ethical guidelines and marketing protocols. In this case, this survey was performed to understand the daily practices of the occupants in detail. In addition to this, a questionnaire was created specially to understand the role windows played in the daily routine of the occupants of an Indian household.

Thus, the fieldwork analysis and the survey outcomes form the bases for further analytic work and show the possibility of future work that can be performed based on these findings.

7.Performance Analysis: Since the main focus of this research is on 'windows', the computational analysis was performed to put more emphasis on its importance. As mentioned earlier there are various architectural elements such as walls, floors, roofs and windows. All these elements are equally important and have the potential to provide indoor comfort. However, this analysis was performed to establish the adaptability that 'windows' provide. The fieldwork looks at three different typologies belonging to the different eras. The three built forms exhibit a different style of construction, different materials, different technical details and different designs. The simulations are performed to determine their impact on a typical contemporary apartment block which is one of the studied typologies of the fieldwork. The following cases are simulated:

1. Case 01: the existing contemporary apartment block where the windows, floor, walls and ceiling are considered as per existing apartment design. (Typology 1)

2. Case 02: The window of case 01 is replaced with the one used in *'chawl'* (typology 2)

3. Case 03: The wall thickness and material of case 02 are replaced with the one used in *'chawl'.* (typology 2)

4. Case 04: The floor and ceiling of case 03 are replaced with the one used in *'chawl'* (typology 2)

5. Case 05: The window of case 01 is replaced with the one used in *'wada'* (typology 3).

6. Case 06: The wall thickness and material of case 05 are replaced with the one used in *'wada'* (typology 3).

7. Case 07: The floor and ceiling of case 06 are replaced with the one used in *'wada'* (typology 3)

The above simulations help in determining the following:

1. The performance and impact of different types of windows for apartment design.

2. The influence of other elements on the indoor environment which in turn helps in understanding the extent of impact windows have on an apartment block.

In addition to the above simulations, two more cases were analysed to suggest the importance of holistic design that not only aimed at creating an adaptive window but also took into consideration thermal properties of other architectural elements to achieve maximum comfort along with the application of effective environmental features such as solar shading.

Thus, these simulations help in understanding help in understanding to what extent 'windows' are responsible for the indoor environmental changes and comfort and thus, also forms supporting information for the concluding chapter.

8. Conclusion & Next Steps: The last chapter summarises the literature study, fieldwork and analytical work and reflects on the lessons learnt from this study. The findings from this piece of work further aides in identifying the scope of work that can be done in the continuation of this research.

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LITERATURE OVERVIEW

In most regions around the world, heat waves, heavy precipitation, coastal flooding, increased frequency of hot days and hot nights have been increasingly observed (Done, 2012; Intergovernmental Panel on Climate Change, 2014; National Research Council, 2001). These changes have been linked to human influences with respect to growth in population, soaring CO_2 emissions and increased use of fossil fuels (Intergovernmental Panel on Climate Change, 2014; National Research Council, 2001). With 54% of the world population residing in the urban agglomerations (UNDESA, 2014), the cities are facing huge problems in terms of higher average temperature and large carbon emissions due to excessive concentration of buildings, infrastructure and transportation. Approximately 30-40% of the total energy is used by the building sector, of which maximum energy consumption is attributed to the residential sector (United Nations Environment Programme, 2007). Thus, the growing need for housing and the rising energy consumption patterns have become one of the crucial issues of the present times that need to be addressed.

The increasing energy consumption trend has been predominantly associated with the attainment of comfort in the housing sector by many researchers. Experts such as Lisa Heschong, Fergus Nicol, Michael Humphrey and Susan Roaf have widely discussed the concept of 'science of comfort' which was developed in the 20th century to mainly justify the HVAC calculations to obtain neutral environment for the occupants. According to Nicol and Roaf (2017), one of the reason for increasing difficulty in predicting the weather conditions, extensive use of fossil fuels and global warming is due to our dependency on mechanical systems. Their paper 'Rethinking thermal comfort', talks about the issues of the modern world where we have the provision to modify our indoor environment with the help of controllable mechanical heating and cooling to attain comfort (Nicol and Roaf, 2017).

Furthermore, with regards to energy consumption and the use of mechanical systems to achieve indoor comfort, Indian residential buildings consume around 73% of the total energy produced (Energy Conservation Building Case, 2007). This energy is largely used for lighting (30%), and ventilation controls (fans – 34%, AC – 7% and air coolers – 7%). Another survey by the International Energy Agency predicts a rapid rise in household electricity consumption in the Indian households via the purchase of appliances and air conditioning units by 2040, both at urban as well as at rural level (Fig.1.1). Additional predictions regarding the growth of air conditioning market in India by experts such as Phadke, Abhyankar, Chaturvedi and Sharma (2014) suggests the need to implement environmental controls to reduce the need for high energy solutions.

Looking at the above theories and statistics there is a great pressure to provide comfort, especially thermal, and this is particularly challenging because it is not just about achieving temperatures in comfort range, but also about providing comfort that is affordable and energy-efficient. Thus, as highlighted by Leaman and Bordass (1995), to reduce the need for energy it is important to reintroduce simple controls such as openable windows, blinds, shading devices etc. which can be easily controlled by building occupants.

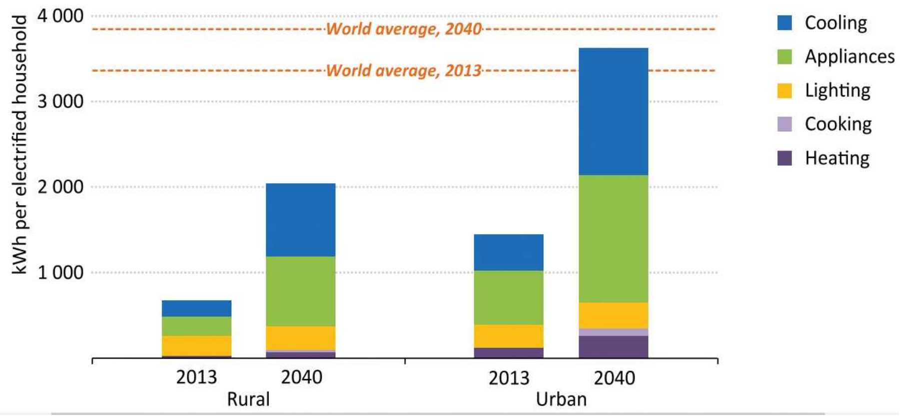

Fig.1.1. Projected annual energy consumption per rural and urban electrified household in India, 2013 and 2040 (International Energy Agency)

Additionally, regarding the latest adaptive comfort theories and strategies, environmental experts like Humphrey, de Dear and Brager, Auliciems and others have correlated the relationship between the behavioural adaptations such as changes in metabolic rate, clothing insulation and environmental parameters like wind velocity and the psychological satisfaction. Behavioural use of controls acts as a link between the occupants and the buildings. Also, de Dear et al. (1998), in their paper 'Developing an adaptive model of thermal comfort and preference' have suggested that the occupants of naturally ventilated buildings have greater thermal control than air-conditioned buildings and hence, it leads to greater tolerance of temperature excursions and relaxation of expectations. Adding on to this hypothesis was a similar explanation given by Bordass et al. stating that people accept variations from a predictable source such as naturally ventilated building (Bordass et al., 1994). Therefore, it becomes important to consider occupant interaction with the building control systems while designing buildings because variations in occupant behaviour significantly affects the energy consumption of the buildings. There is a lot of research available on the use of controls from throughout the world, by way of case studies conducted in office and residential buildings by Fergus Nicol, Richard de Dear, Gail Brager, Charlie Huizenga, Hui Zhang, Edward Arens etc. However, there are very few studies on occupant behaviour in terms of the use of environmental controls in residential buildings, especially in India. One of the few studies within an Indian context is a survey by Indraganti in 2010 that recorded the use of environmental controls such as windows, curtains, doors and user comfort responses that were carried out in five medium-sized residential apartments in Hyderabad. The research challenged the Indian standards of comfort (23-26°C) since the analysis suggested that with the neutral temperature at 29.3°C, the comfort band was between 26-32.3°C, hence questioning the data and methodology considered to determine comfort standards for Indian dwellings. This study found that the lack of adaptive opportunities resulted in a majority feeling uncomfortable during the summer months and recommended urgent need in the provision of 'operability and openability' of windows, and their careful placement and orientation for better adaptive use of environmental controls.

Hence, considering the above, this research will be an investigation into finding the relations between the use of adaptive controls and the thermal sensation of the occupants in residential buildings in the hot-humid and hot-dry climate of western Indian cities like Mumbai and Kolhapur. This research will also explore the traditional adaptive strategies that were adopted in Indian homes before the pre-air conditioned era to achieve environmental comfort and analyze the affordability and efficiency of the window typology in these homes that aided in improving the indoor quality of the spaces, improve occupant satisfaction, health and well-being and hence reduce the overall energy consumption of the Indian households. Therefore, the first essential step is to understand the true meaning of windows and the terms associated with it. The next chapter discusses the origin of windows, the technical and scientific definition of windows, plus, various factors that correlate with fenestrations.

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CHAPTER 2

THE MEANING OF 'WINDOW'

The noun 'window' is derived from Old Norse 'vindauga' which means 'wind eyes' (Philips, 2012), which further means that they allow 'wind' in to the enclosed living spaces and are also the 'eyes' of the building that provide the view outside as well as allow light in to the building.

The noun 'fenestration' is derived from Old French 'fenestre'. This French word was further derived from the Greek verb 'phaino' which means to give light, to come to light, to bring to light (Treguer, 2016).

Architectural Definition of 'Window'

A window is defined as an opening in a wall of a building that allows light and air into the indoor environment (Philips, 2012). They are considered as the most important and expressive feature of a building that widely contribute to the physical and mental well-being of the occupants. Windows allow the user to look outside and also have the potential to allow to look inside the building. They play an extremely vital role in connecting open and enclosed spaces.

History of ‘Window’

Windows have been termed as the ‘eyes of the building’. They are the most prominent feature of a building that gives character to a built form. The evolution of windows is directly related to the evolution of architecture, the use of materials and building construction technologies. The need for light and ventilation has been an important requirement of an occupant. Letting in light allows its occupants to perform their tasks better and help in navigation within their habitat. Whereas, view and ventilation provided by them allow in understanding the time of the day as well as in providing health and well-being to its occupants.

Before the discovery of glass, windows were just holes in the façade or the roof of the building that allowed little bit of light in and exhausted smoke and smells out of the house and were left open to the external climate (Hansmann, 2015). These holes were small since the buildings had no structural system and as they were open, the restricted size did not allow extra light or air into the house since the occupants had no control over it, other than completely shutting it down. They were covered with animal skins or furs to protect the indoor environment from the harsh outdoor weather conditions (Weston, 2011).

However, by the pre 16th century, windows were constructed out of wood or stone (Wychavon District Council, 2007). This type of window construction is found even today in many parts of the world including India where stone mullions or timber frames are used to construct them.

Fig.2.1. Unglazed shutter window (Pinterest)

The unglazed shutters, that were predominantly used, could be kept open or could be shut as per the user requirement. Giving a choice to the user to regulate their indoor environment in medieval times shows that the windows were adaptive since then (Fig.2.1).

Apart from solid wooden shutters, the window openings were also covered with mica or thin slabs of marble or flattened animal horn, while in the far east countries like China and Japan, paper windows were used (Parhammer, 2017) (Fig.2.2). The paper used for the window covering was called *shoji* (Khan, 2014). This material allowed diffused penetration of light into the house while protecting it from heat, cold and rain outside. The use of *shoji* is prevalent even today for various purpose such as in making artefacts, sliding door, room partitions and so on. Before the invention of glass, domestic unglazed windows were developed by the Islamic builders of Syria and Egypt that consisted of a framework in wood which was filled with intricate wooden grillwork, projected outside and were laid on brackets (Augustyn et.al., 1998).

During this time in India, the form of window that gained importance

Fig.2.2. Shoji panel wall (Homesteady)

were the *jharokhas* (Fig.2.3.) (Zulfiqar, 2018). The cantilevered enclosed balcony carved in stone and supported on corbels was especially used by the *Maharajas* (kings) as well as the Mughal emperors to address to their subjects (Saquib, 2012). They were also greatly used by the royal women to view public activities without being seen by the people. It was during the 19th century that *jharokhas* made their way into houses of the ordinary people from palaces and *havelis* (mansions) (Zulfiqar, 2018). Along with *jharokhas, jaalis* were also one of the most important form of a window that was used extensively. *Jaalis* were the ornamented perforated screens that were carved in wood or stone and acted as a shading device (Kamath and Daketi, 2016). They allowed enough light to penetrate the living spaces and at the same time also provided privacy to the occupants. Hence, it can be said that the emergence of glass was very gradual in Indian architecture.

Fig.2.3. Window of a House, Lahore (Architexturez South Asia)

I.

II.

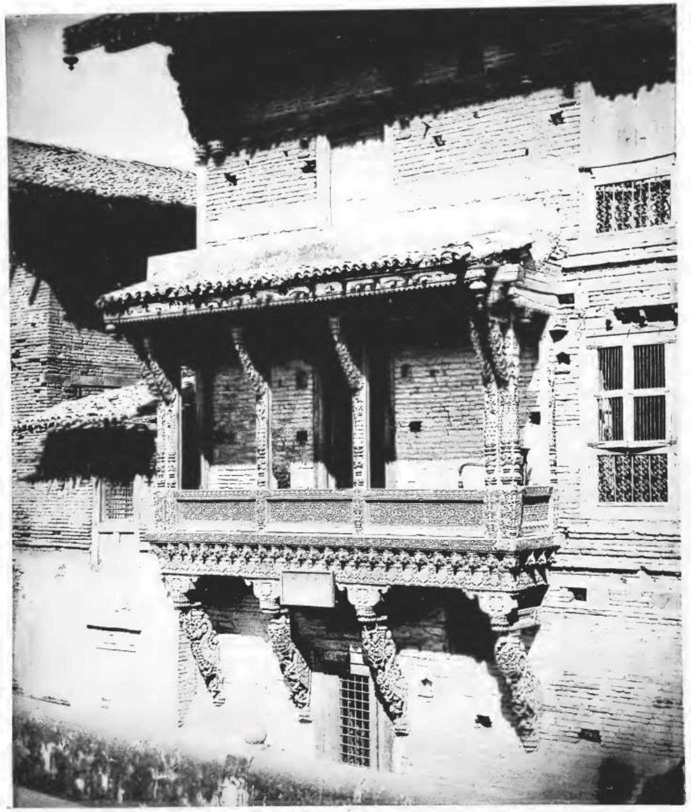
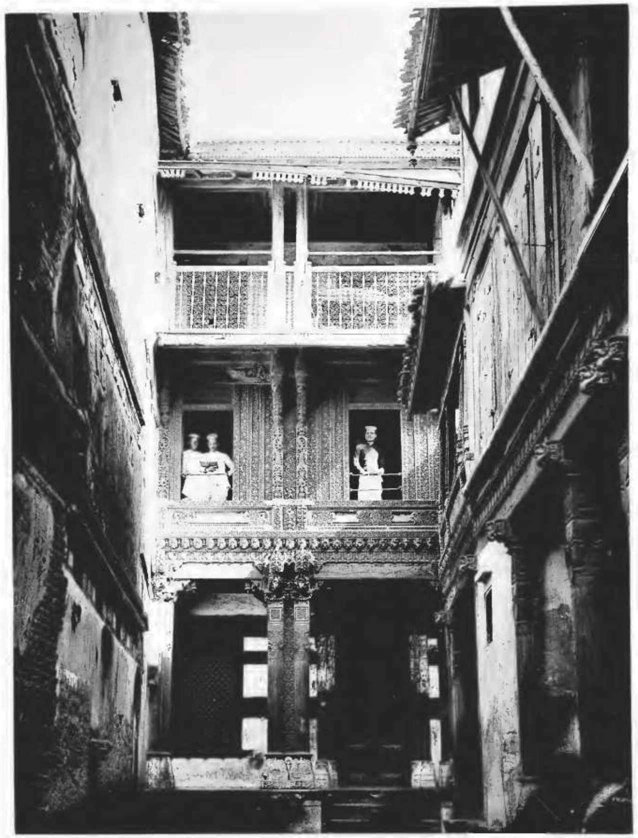


Fig.2.4. House at Ahmedabad, 16th century (Architexturez South Asia)

Fig.2.5. House at Ahmedabad, 17th century (Architexturez South Asia)

III.



VI.

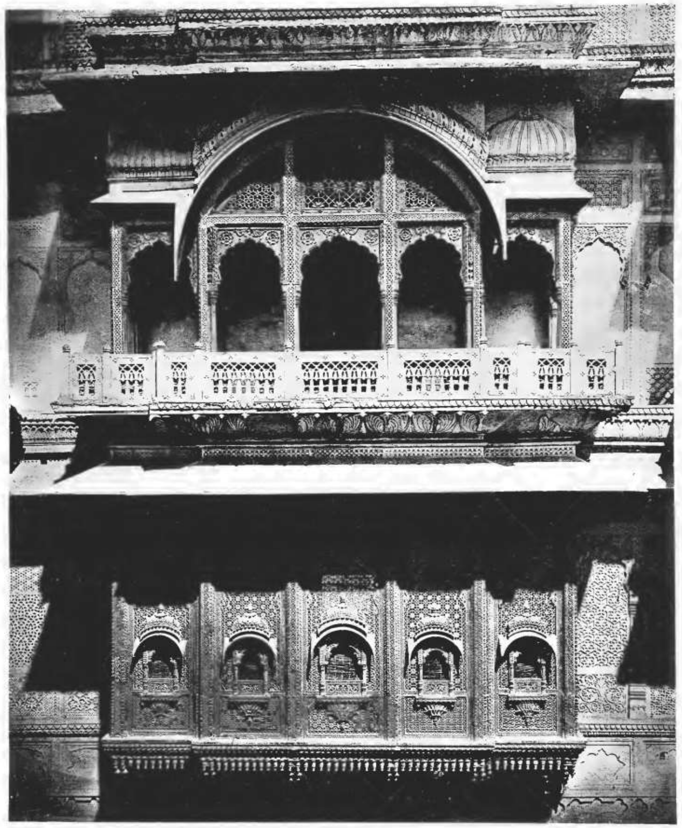


Fig.2.6. House at Ahmedabad, 18th century (Architexturez South Asia)

Fig.2.7. Front of a House, Ajemer (Architexturez South Asia)

According to an article by Encyclopedia Britannica on the History of Window Architecture, glass was first discovered in Roman – ruled Egypt and it was not just used for creating crockery and decorative items but was also used to form small glass panes that lead to the emergence of glass windows. They were exceptional and were mainly reserved for the highest status buildings. These windows were constructed of small glass panes known as glass quarrels or quarries and were divided by bronze or lead strips known as *cames* (Pickles, 2014). Wooden window frames in oak or stone mullions were usually used to fix these windows. Such type of glass window in a bronze frame has been found in Pompeii, Roman baths, in early Christian and Byzantine churches and so on. Glass panes enclosed with pierced marble frames were used for the construction of Hagia Sophia (begun 532) at Constantinople (Mlyniec, 2017). This technique was also used by the Islamic mosque buildings, were cement was substituted with marble which gave richness in pattern design.

The 17th century showcased a strong influence on the shape of the window (Wychavon District Council, 2007). During this time the window mullions and transoms became narrow and were produced in timber. The windows became taller since they were divided into four by a transom and mullion. During this time, sash windows originated in London (Louw, 1983). These windows were later found in the regions ruled by the United Kingdom, such as India, America and the Caribbean.

Sash windows were developed at the time when the streets in London were narrow and opening a shuttered window touched the opposite window. The windows could slide vertically thus allowing 25% to 50% openable area. Sash windows have been widely used since then and were also held responsible for the great fire in London in 1666 (Wrightson, 2000). As the windows with timber frame were fitted in the front face of the buildings, they were responsible for the rapid spread of the fire. Since, then as per regulations, sash windows were to be recessed back by 4” from the face of the building (Wrightson, 1999). Further, in 1696, ‘window tax’ came into existence in Britain (Glantz, 2008). The tax was implemented so that the higher class with bigger homes and more windows would pay more tax while the poor would have to make small payments (Bilal, 2019). Thus, to skip the tax altogether windows were blocked completely and people lived without natural light and air. Thus, only the rich could afford to put windows and others with constrained means were made to live in dark rooms with no air movement at all.

While the 18th century further saw the alterations in sash windows. The frames made from Baltic Pine were thinner since the thickness of the glass also reduced (Wychavon District Council, 2007). In 1770, plate glass was introduced that allowed a further increase in the size of the glass pane and the number of glazing bars also reduced. The thinner and larger windows were costlier.

By the 19th century glass was manufactured in masses and the production became mechanised which meant that glass windows were becoming more and more affordable (Sharman, 2017). This period also saw experimentation in the window grid-style arrangements such as the use of coloured glass, curved glazing bars and so on. The window size gradually kept growing from century to century. Since glass became more affordable, it was during this time that the ‘window tax’ was withdrawn from England and people from all sectors finally had the freedom to have windows in their homes (Glantz, 2008; Oates and

Schwab, 2015).

By the early 20th century the method of producing glass reached to an extremely good quality. The introduction of the float process in the 1950s in Britain allowed the production of very large glass panes remains largely the same even today (Mlyniec, 2017). With a number of choices available with respect to the type of window, the type of glass, the type of frame; the main criteria for selecting a window type today is based on the suitability and performance of a window for particular climate, the energy efficiency it would provide, safety and largely on aesthetics. Since glass allows solar heat transfer, it is one of the major causes for temperature fluctuations indoors. Therefore, at present glazing is being researched and developed to improve the energy efficiency of the indoor spaces. The need for efficient glazing systems has led to the introduction of double glazing and triple glazing. Similarly, today we have several different glass options such as float glass, decorative glass, low-e glass, insulating glass units,

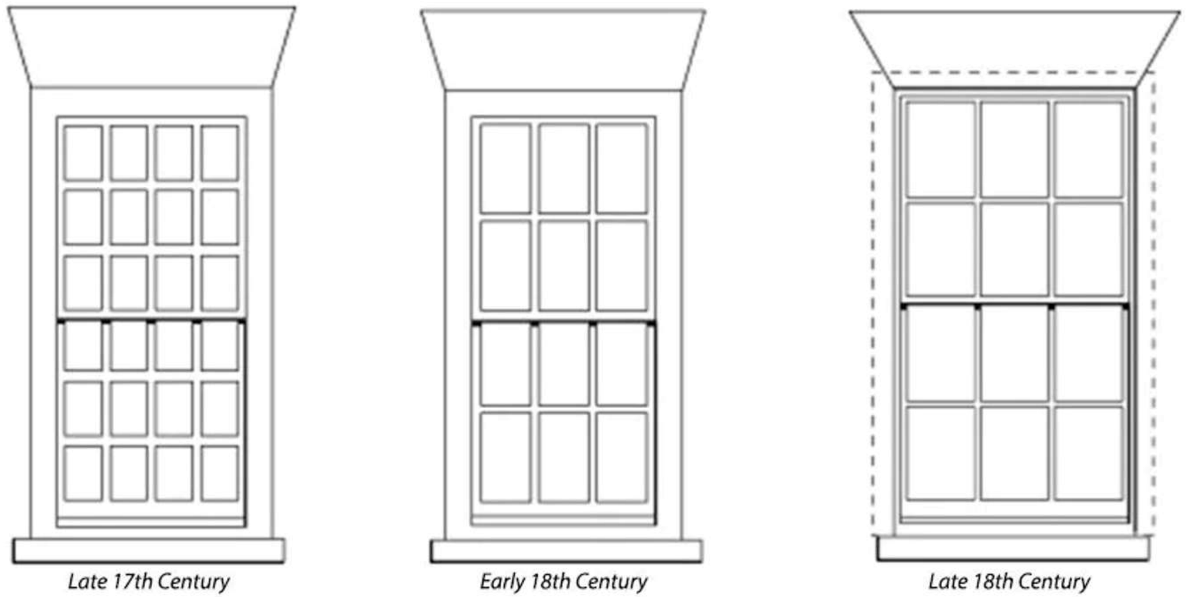


Fig.2.8. The Evolution of Sash Windows (Selectaglaze)

heat-strengthened glass, laminated glass, safety glass, toughened glass and so on. Although glass is comparatively not as expensive now, the affordability of glass reduces as the u-value of glass reduces, which means that the more the glass can minimize the direct solar heat transfer the more expensive it gets.

While glass is evolving even today in terms of its properties and efficiencies, the most common types of windows available in present times with respect to how they operate are shown below in Fig.2.9.

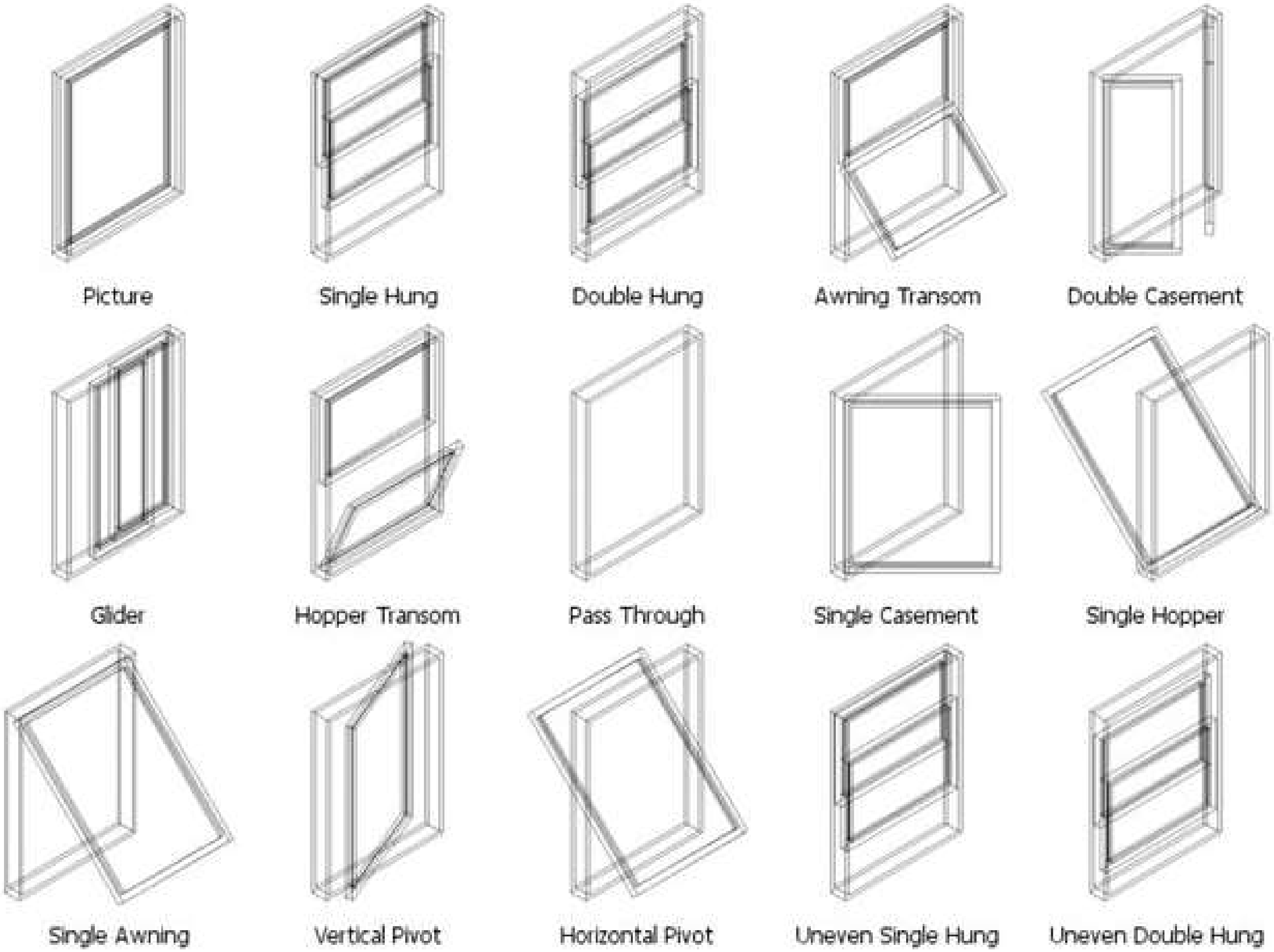


Fig.2.9. Types of Windows (Architizer)

THE ROLE OF A 'WINDOW'

The first part of this chapter discusses the meaning of 'window' and how windows came into existence and evolved further in terms of glazing, frame, the design of the window and so on. Windows contribute to environmental comfort, which means they have the ability to create thermal, visual and acoustic comfort. However, it is also essential to understand the role of windows in the present day scenario were windows are particularly designed and installed to overcome a number of issues that come along.

Furthermore, it needs to be noted that along with various functions of a window, the social, technical and environmental factors associated with an opening are addressed not just by window alone but a number of different layers that are associated with it to form a complete window system.

Therefore, it becomes important to understand the different design and environmental factors related to windows and also simultaneously look at the various layers associated with it, plus their role in addressing many issues that the occupants experience.

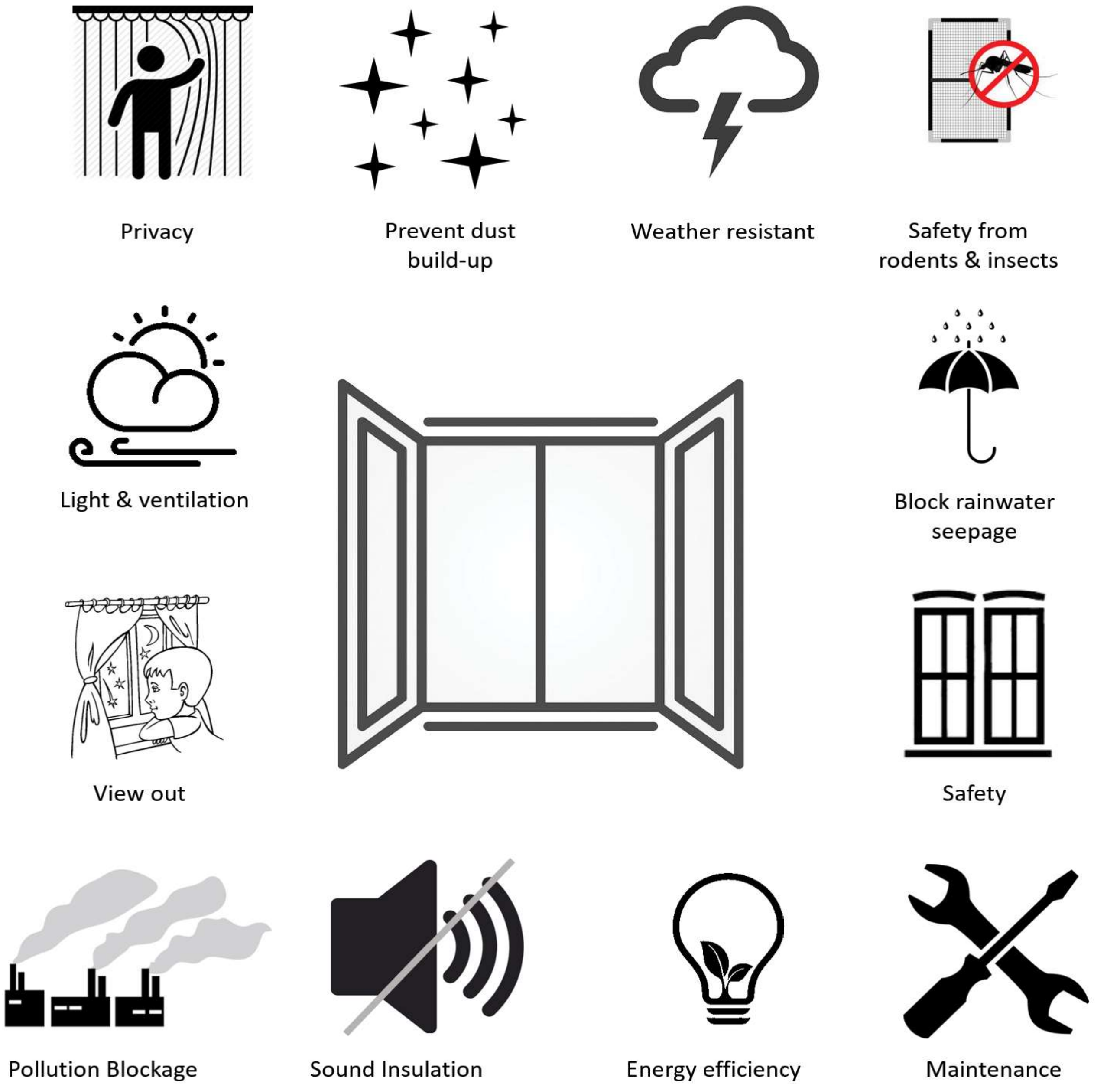


Fig.2.10. The purpose of a window

Thermal Comfort

The environmental factors that affect human comfort are temperature (°C), air movement (m/s) and humidity (%). The other factors that affect comfort are metabolic rate (watts) and clothing (clo). However, in order to remain at constant temperature, the body must maintain a balance between the metabolic heat produced and heat loss.

$$M = R + Cv + Cd - E$$

M = Metabolic rate R = Radiation Cv = Convection

Cd = Conduction E= Evaporation heat loss

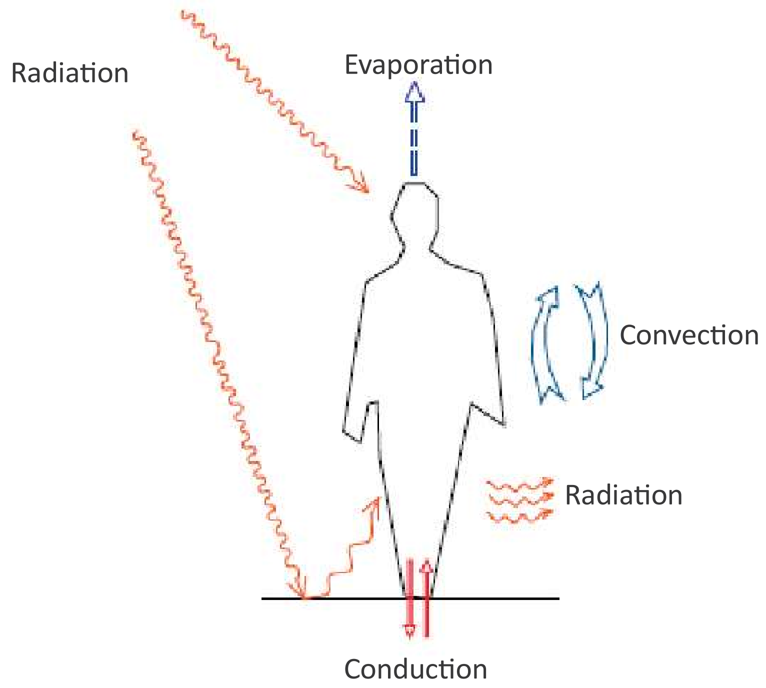


Fig.2.11. Metabolic Heat Loss from Body (Berisha, 2016)

If windows are considered for providing thermal comfort, they play a significant role in influencing the heat balance between the environment and a person. The primary factors that affect indoor comfort conditions due to windows are as follows (Huizenga et al., 2006):

- Window geometry – the size of the window
- Occupant location – the distance at which the occupant is based from the window
- Room geometry – the volume of the room
- Glazing system – single, double, triple, low-e, tinted etc.
- Frame type – wooden, plastic, aluminium
- Exterior conditions – air temperature, wind, solar radiation
- Interior conditions – air temperature, relative humidity, velocity, surface temperature).

A significant amount of solar radiation is absorbed and transmitted by windows. Due to the absorption of radiation, the internal surface of the heat absorbing glass can significantly raise the temperature of the glass which then contributes to the rise of the Mean Radiant Temperature (MRT). Whereas, a person sitting next to a window that receives direct solar radiation has the potential to cause extreme discomfort to the person. Thus, a glazed window plays a predominant role in the attainment of comfort since thermal comfort is closely associated with solar transmittance (Lyons et al. 1999). For example, when a 3mm clear single glass (Tsol=0.83) is replaced with 3mm Low-E double glass (Tsol=0.53), the amount of discomfort created by the glazed window reduces to half.

The three ways in which window influences thermal comfort are as follows (Huizenga et al., 2006) (Fig.2.12.):

- Transmitted solar radiation
- Long-wave radiation
- Induced air motion that gets created due to the difference between the adjacent air temperature and the glass surface temperature.

Today, in many parts of the world, the single glazed window is being rapidly replaced by multiple glass panes separated by air cavity or additionally by filling up the cavity by slow-moving, less conductive gases such as krypton or argon that reduces the conductance of the cavity even further which in turn improves the thermal performance of the windows.

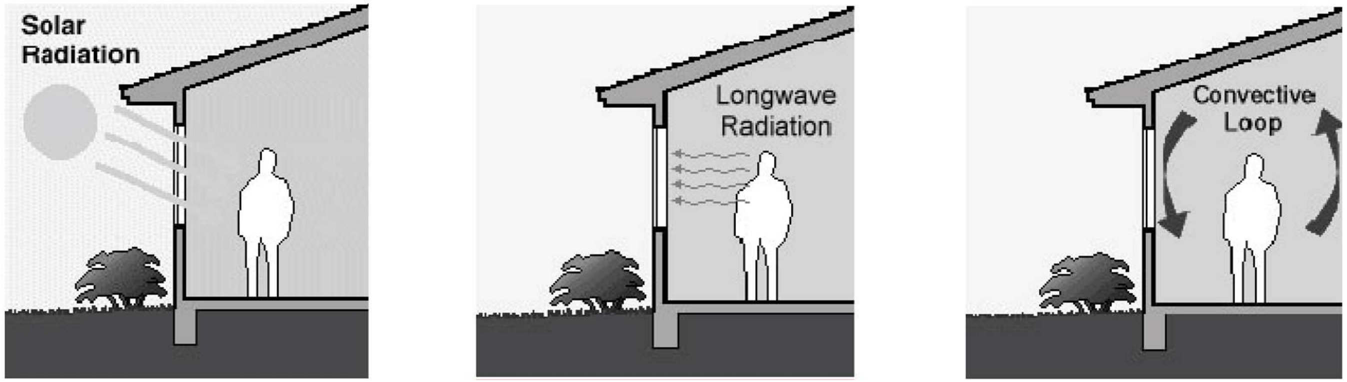


Fig.2.12. The influence of window over thermal comfort (Window Performance for Human Thermal Comfort)

Apart from this, to reduce the surface emissivity of glass, low-E glass with a low-emissivity coating such as a semiconductor film or a thin metal oxide film are used that help in reducing the long-wave infrared radiation which is absorbed and emitted by the window glass. Thus, while they allow the passage of light, they also reduce the heat loss/gain (Fig.2.13).

To assess the thermal performance of a window the thermal conductivity of a window is calculated. U-value (W/m^2K) or thermal

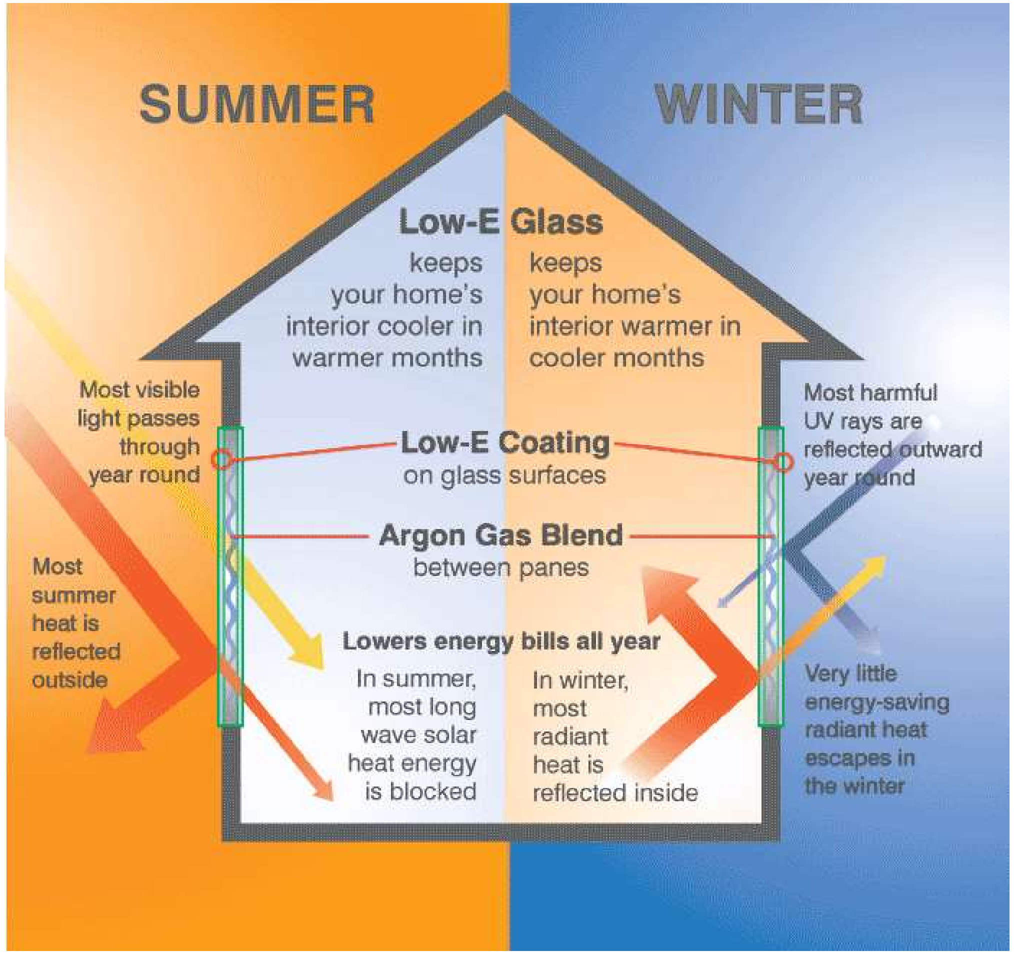


Fig.2.13. The effect of coating on a built space in summers and winters. (Source: Thermalwindows.com)

transmittance coefficient is used to compare the performance of different glazing types that consists of different characteristics such as gas infill, coating, cavity, number of glass used (single, double, triple) and so on. Similarly, G-value or Solar Heat Gain Coefficient (SHGC) is taken in consideration to compare the amount of solar heat allowed through a window. Table 2.1. draws a comparison between different types of glazing and their respective thermal performances and in turn gives a brief idea on the role of windows, especially glazing in attaining indoor thermal comfort.

	Glazing	Frame	U-Value (W/m^2K)	Solar Heat Gain Coefficient (SHGC)
1	Single, Clear	Metal	1.29	0.73
2	Double, Clear	Metal	0.83	0.65
3	Double, Tint	Metal	0.83	0.54
4	Double, Low-e, High SHGC, Argon	Metal	0.65	0.58
5	Double, Low-e, Medium SHGC, Argon	Metal	0.64	0.38
6	Double, Low-e, Low SHGC, Argon	Metal	0.63	0.26
7	Double, Clear	Metal, thermal break	0.60	0.62
8	Double, Tint	Metal, thermal break	0.60	0.51
9	Double, Low-e, High SHGC, Argon	Metal, thermal break	0.42	0.55
10	Double, Low-e, High SHGC, Argon	Metal, thermal break	0.42	0.35
11	Double, Low-e, High SHGC, Argon	Metal, thermal break	0.41	0.23
12	Single, Clear	Nonmetal	0.88	0.64
13	Double, Clear	Nonmetal	0.52	0.57
14	Double, Tint	Nonmetal	0.52	0.47
15	Double, Low-e, High SHGC, Argon, Improved	Improved non-metal	0.29	0.50
16	Double, Low-e, Medium SHGC, Argon, Improved	Improved non-metal	0.28	0.31
17	Double, Low-e, Low SHGC, Argon, Improved	Improved non-metal	0.27	0.20
18	Triple, Low-e, High SHGC, Argon, Improved	Improved non-metal	0.20	0.41
19	Triple, Low-e, Medium SHGC, Argon, Improved	Improved non-metal	0.19	0.28
20	Triple, Low-e, Low SHGC, Argon, Improved	Improved non-metal	0.19	0.18

Table.2.1. Heat transfer through different glazing options. (Snugg-Pro.com)

Heat gains and losses

The primary source of heat loss from a building are the windows, while they also have the potential to collect and distribute solar energy into the indoor spaces (Hyde, 2008). The important factor is the location of the windows since in the northern hemisphere passive solar heating occurs mainly in the south while in southern hemisphere passive solar heating takes place in the north part of the building, especially during winters. However, during summers when heating is not required, efficient shading systems are required along with the facility of being able to open the windows to allow heat loss from the building.

Various elements of a window that determine the heat gains or losses from a building are:

a. Window type
b. Glass type
c. Glass thickness
d. Solar heat gain coefficient
e. U-Value
f. Window size

Although windows are mainly responsible for the heat loss from a building, the façade of the building also has the potential to regulate the heat gains. Some of the ways are discussed below to give an idea of the role windows play in the heating of internal spaces:

• Direct Solar Gains (Fig.2.14): The window glazing allows solar energy to enter an indoor space. The size of the glazed surface, their orientation and location, the material used, the provision of external or internal shade as well as the depth of the internal space determines the extent of the effect of direct solar heating.

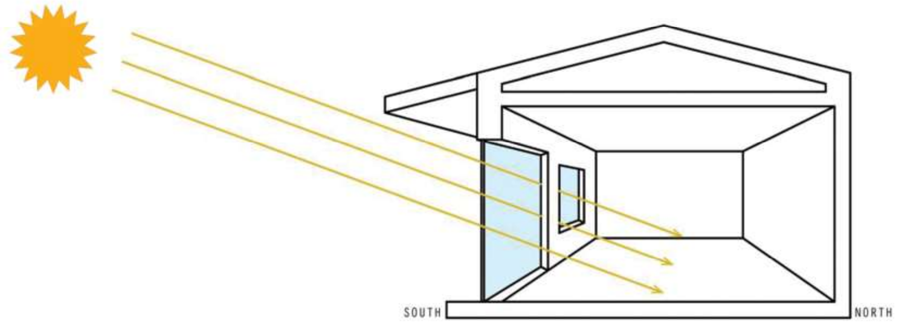


Fig.2.14. Direct Solar gains (greenhome.osu.edu.)

• Buffer Spaces: These are the intermediate spaces between the exterior and the interior space. The buffer zone acts as a space that is heated by solar radiation due to which the temperature in this space is higher than the external temperature because of the trapped heat. Thus, the high temperature of the buffer zone drastically reduces the transmission heat loss from the internal spaces. The buffer zone need not be a large area but can also be a second-skin façade or a double façade that restricts the heat loss and also help in ventilation, noise and wind protection (Fig.2.15). Thus, heat gains and losses through a window can be directly linked with the condition of thermal comfort indoors.

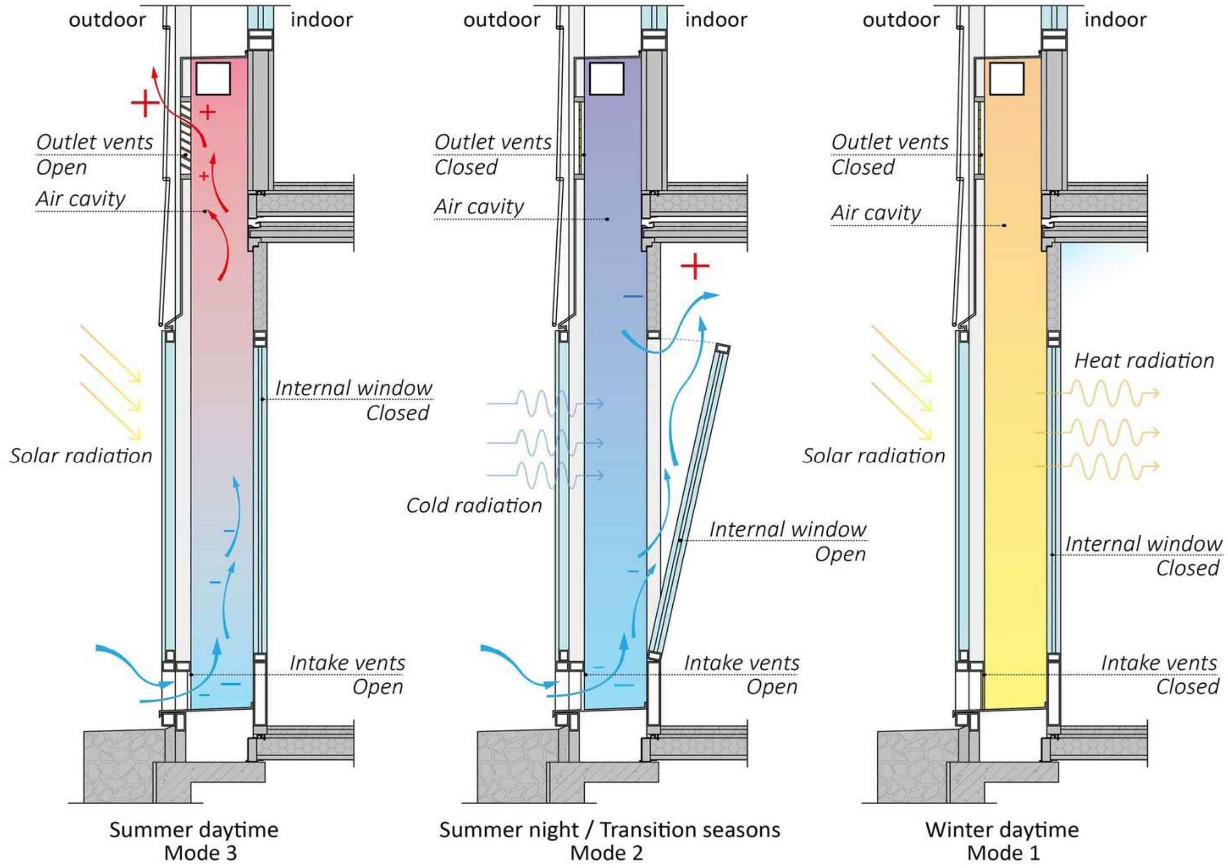


Fig.2.15. The functioning of buffer spaces. (Archdaily.com)

Daylight

Before the existence of artificial lighting, daylight served as an important factor in building design so that the occupants could make maximum use of the natural light in order to carry out their daily activities. Thus, buildings were designed with narrower plan and large windows (CIBSE, 2015). However, with the invention of artificial lighting, windows were no longer designed as per the occupant need and were driven mainly by aesthetics.

Today the energy consumption in residential sector for lighting is 10% of the total energy consumption whereas, 30% is consumed in high-rise commercial buildings (Konstantinou et.al., 2018). Thus, inorder to reduce the dependence on electric lighting, now-a-days, daylight is preferred for the purpose of illumination. Recent research points out the importance of natural light to regulate a person's internal clock, hence, laying an importance of adequate daily sunlight for human wellbeing (CIBSE, 2015). Also, exposure to sun throughout the year is essential to maintain adequate levels of vitamin D. Furthermore, the importance of natural light in the indoor spaces and a view out through a window has been shown as an important contributor in the health and wellbeing of humans in the built environment (Veitch et al., 2008). Additionally, lighting in a built space is essential for the following reasons:

1. So that the occupant can work and move about safely.
2. To create a pleasing visual appearance.
3. To be able to perform tasks correctly and at right pace.

Daylight improves visual perception and the greatest resource to allow daylight in to an indoor environment are the windows. A well-thought window design not only provides indoor comfort but also helps in reducing energy consumption by minimizing the use of artificial lighting (Acosta et.al., 2016). One of the fundamental purpose of a window is to provide light into a space for carrying out a function. Hence, it is important that the window meets the requirement of providing good quality of daylight in to the space that not only meets its functional demands but also creates a pleasant visual environment that enriches the user productivity. The three main reasons for enhancing the daylighting of buildings are:

1. energy consumption
2. space appearance
3. benefits to human wellbeing

Furthermore, a window has the ability to influence the distribution of light and its intensity to create an efficient and desirable indoor environment (Nasrollahi and Shokri, 2016). Therefore, it is important that a window not only provides protection against excessive heat gain but also thermal and visual discomfort to the user. An efficient lighting design ensures appropriate amount of daylight is made available to the occupants at appropriate time by effectively controlling the amount of sunlight entering through the openings. The required amount of daylight is based on the seasonal changes, building orientation, geographical and environmental conditions, the functional requirement of the space and of the occupants. Thus, the amount of daylight entering into a space is calculated by using (Hopkinson, 1966):

$$\mathbf{DF = SC + ERC + IRC}$$

where, DF = Daylight factor; SC = Sky Component; ERC = Externally reflected component and IRC = Internally reflected component

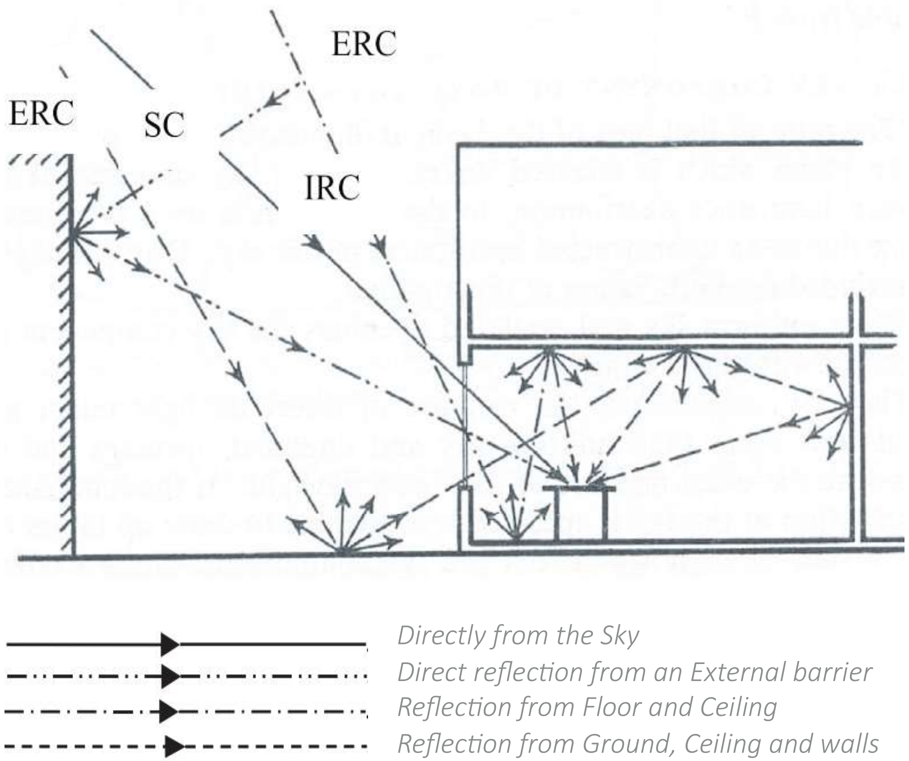


Fig.2.16. Different ways in which Daylight penetrates in to a built space (Nasrollahi and Shokri, 2016)

However, although an extensive use of natural light can lead to considerable savings in energy consumption, but at the same time it can also allow penetration of higher solar radiation in to the indoor space thus causing thermal discomfort or create glare and thus causing visual discomfort. Hence, as per the Workplace (Health, Safety and Welfare) Regulations 1992, an effective visual environment can be achieved when daylight is used in conjunction with artificial light. Therefore, it becomes essential to remember some aspects to improve the lighting energy efficiency such as:

1. Not over illuminating - using light only where and when necessary depending on the function of the space.
2. The lighting controls, how they work in conjunction with the available daylight.
3. Use of efficient electric fittings and lighting controls.
4. Regular maintenance

Thus, an efficient lighting design contributes in not only reducing energy consumption but also in preventing heat loss and minimizing cooling load, thus aiding in having zero energy buildings.

Glare

Glare may be caused due to a reflection from an outside source such as an opposite building, from direct sun or by reflection from items inside the building such as laptops or computers. Glare can be defined as one of the following three types (CIBSE, 2015):

1. Discomfort Glare: It causes visual discomfort without affecting the ability to see an object.
2. Disability Glare: When the level of discomfort reaches a critical threshold that impairs vision but is still tolerable.
3. Veiling Glare: When a surface (mirror-like) causes reflection and neither the surface position nor the viewers position can be moved, it causes veiling glare.

The placement and area of a window can have various repercussions such as the view outside, distribution of daylight indoors and glare. There are different ways in which windows may give rise to glare such as reflections on display screens or paper if the bright sky is close to the line of view or direct reflection due to the light from the sun. Although the glare effect by small windows are comparative less, with wall-size windows, the adaptive power of the eyes reduces the contrast with the surrounding area hence reducing the effect of glare. Thus, the tolerance level are the highest if the glazing area is approximately 40-55% of the wall area (Corrodi and Spechtenhauser, 2008).

An opaque or nearly opaque shading device such as dense weave fabric blinds, thick curtains or venetian blinds can control the amount of daylight that enters into a building and hence contributes in avoiding discomfort such as glare. However, excessive use of blinds may hamper the access to view, natural ventilation and daylight, hence some other suggested techniques to over come the issue of glare that forms a part of the entire window system are as follows:

i. Window design considerations such as deep bevelled reveal, use of slits rather than holes, diffusion, light from the sides and so on.

ii. Use of fixed sun shadings such as balconies, roof projections, overhangs, or permanently mounted slats.

iii. Provision of a good view which might compel the users to raise the blinds when glare is not an issue.

iv. Avoid over-glazed facades.

v. Use of smart glazing such as tinted glass which has low light transmittance level. (Light transmittance is defined as the ratio between the incident light and the light transmitted through a glass).

Solar shading

To avoid overheating of internal spaces and to avoid heat gain, especially during summers, external sunshade proves to be an effective addition to the existing window that interrupts the direct solar radiation hitting the window. Solar shading systems have the potential to regulate the daylight levels in an interior space. They can provide significant control over the indoor thermal conditions and at the same time, they are also capable of creating a view to the exterior environment (O'Brien et al., 2013; Kuhn et al., 2001). They can control solar gains, protect the building from direct solar radiation and have an effect on energy use (Al-Tamimi and Fadzil, 2011; Kirimtat et al., 2016). A good solar shading design can contribute extensively in reducing the energy consumption of a building through lighting, cooling and heating (Bellia et al., 2014) and hence can vary extensively with respect to their size, design, the way it is placed and the location where it should be placed in order to achieve the desired performance.

Manually movable shading devices such as curtains or blinds that are installed in the interiors are specifically used to resolve the issue of privacy in any building. These devices provide the occupants with the control to regulated their indoor environmental conditions as well as provide privacy as and when required (Nicol and Humphreys, 2002). They can contribute in regulating excessive light, in reducing solar heat gain and glare issues especially during summers (Al-Masrani et al., 2018).

To reduce heat gain in the internal spaces of a building, it is of prime importance to study sun path throughout the year before the design and placement of windows in a building. Hence, effective installation of the solar shading device can reduce the annual cooling load, especially for the tropical climate.

Various adjustable solar shading systems that are used today are roller shades, curtains, venetian blinds, vertical blinds, movable louvers and fins and so on (Fig.2.17.). The orientation of external shading system plays a very crucial role in achieving the desired results. For example, if they tend to successfully block the summer solar radiation, they should also be able to allow sun penetration in the internal spaces during winters plus the placement of external solar shading system must not or should least interfere with the view (Hausladen et al., 2008). Apart from the movable systems, the most extensively used fixed solar shading system is the *jaali* or external lattice work which also tends to cater to the same issue of privacy.

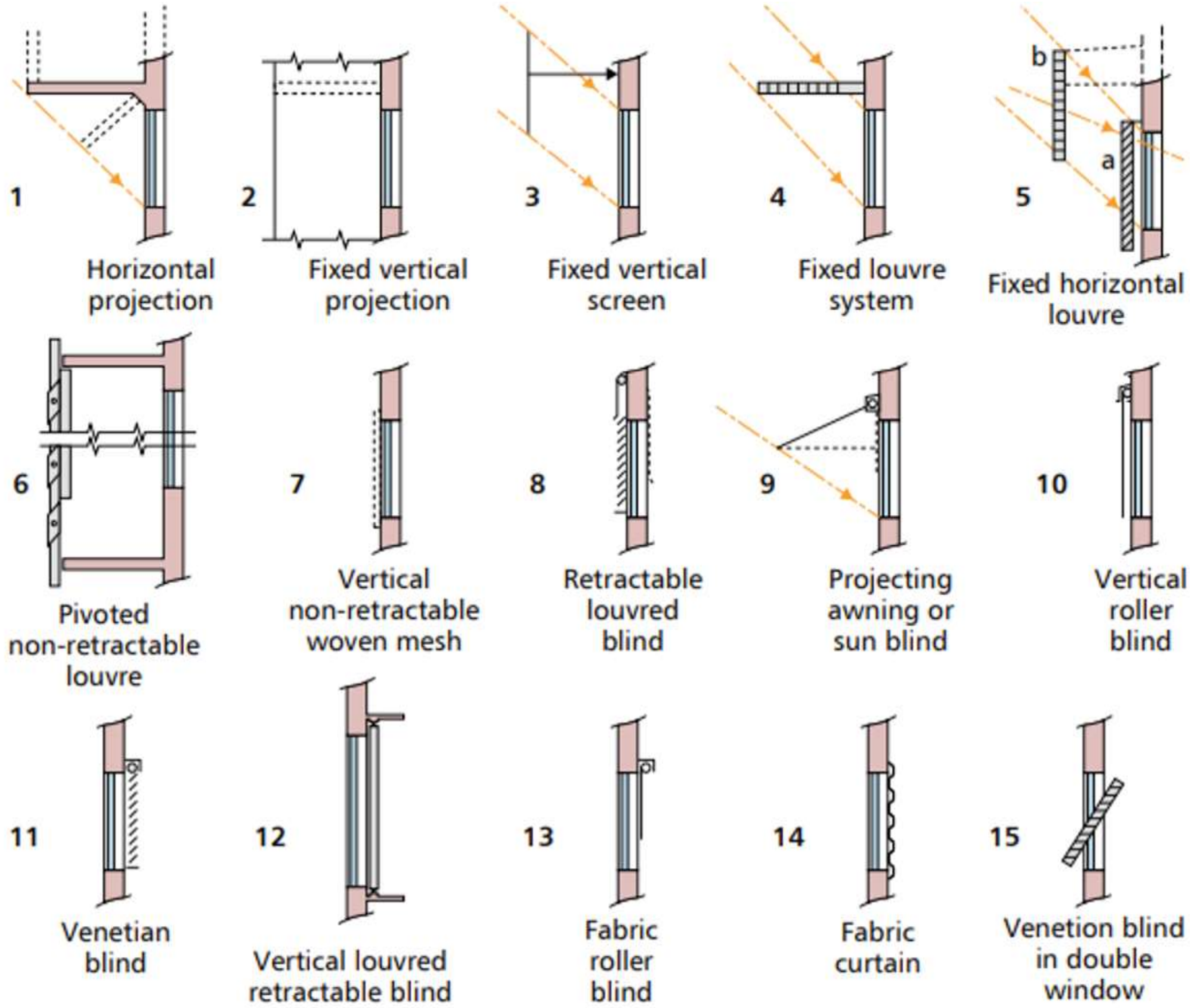


Fig.2.17. Types of Internal and External Shading Devices. (CIBSE, 2015)

Ventilation

An adequate amount of fresh air is essential for the inhabitants. It is essential to remove smoke from cooking or any other odour, it is also essential for the removal of moisture and pollutants from an enclosed space. Furthermore, one of the main purposes of ventilation is the dissipation of indoor heat produce and to bring in cool air from the outside. As recommended by BRE (Building Research Establishment) the minimum fresh air supply per hour per person should be 20-35m^3, which means on an average 0.5 to 1.0 air changes per hour for an entire house depending on the occupancy of the house, the activity taking place and the volume of the house (Yannas, 1994).

Ventilation strategies: Since natural ventilation depends on the climatic conditions, it is highly variable. Thus, it should be noted that the design for natural ventilation should be flexible so that it can respond to the changing climatic situations. Hence, the flow rate 'q', depends on the wind speed 'U' and direction 'ϕ' plus the temperature difference between the interior and the exterior 'ΔT' along with the opening area. All these factors must be taken in consideration while designing (Etheridge, 2011) (CIBSE, 2015). The two basic principles of natural ventilation (it is the flow of air without the use of fans) are as follows:

a. Wind-driven ventilation (Fig. 2.18.): This concept depends on the differences created through wind-induced pressure and air inlets in the building façade. Thus, the amount of air passing through the building increases with the increase in the size of the openings. Therefore, to obtain sufficient natural ventilation, adequate amount of openings need to be provided after analyzing the wind direction throughout the year.

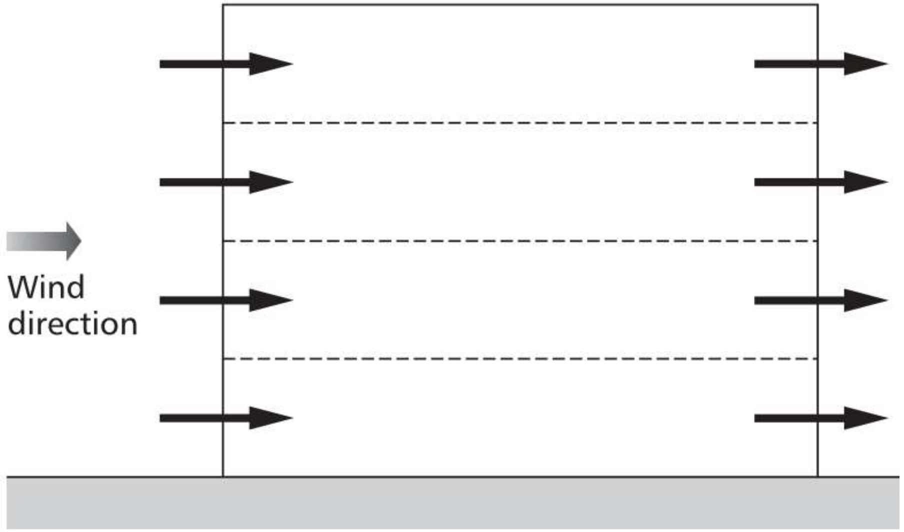


Fig.2.18. Wind driven ventilation (CIBSE, 2015)

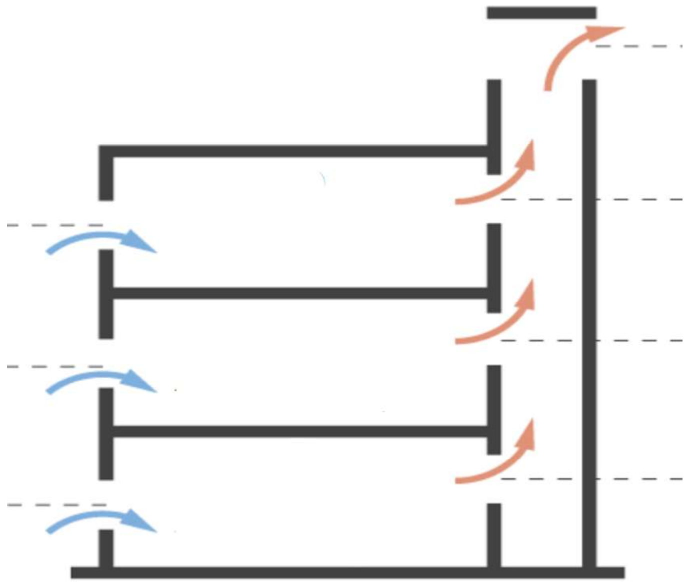


Fig.2.19. Stack driven Ventilation (Optivent, 2.0)

b. Stack or buoyancy-driven ventilation (Fig.2.19.) (Fig.2.20.): This type of ventilation is created due to the temperature gradients between the inside and the outside of a building (Konstantinou et.al., 2018). The air enters through the lower openings in the building and leaves through the higher-level openings when the internal temperature is higher than the external temperature. Similarly, when the internal temperature is lower than the external temperature, the flow of the air is reversed.

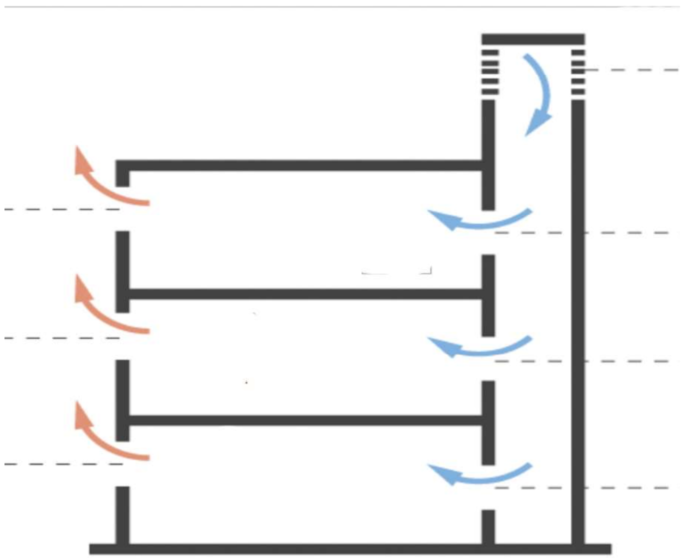


Fig.2.20. Buoyancy driven Ventilation (Optivent, 2.0)

Fig.2.19. and Fig.2.20. are derived from Optivent 2.0. It is a simple steady-state and a free tool to evaluate natural ventilation options. It's the tool that is used in early design stages to have a better grip on window design and to assess the effect that windows can have on performance. It helps in deriving preliminary sizing of vent opening areas and airflow path strategies, thus, supporting rapid design development (Vallejo et.al., 2015)

View Outside

A window provides its user with the means to be in contact with the outside world. It allows them to keep the track of time, it provides information on the changing climatic conditions and changing seasons, it also keeps the user updated of the on-goings in the immediate surroundings. Any view that connects with the outside, imparts physiological satisfaction and allows the human eyes to adapt to distance (Philips, 2004). There is extensive research that shows the impact of a view on the quick recovery of patients (Huisman et al., 2012) (Devlin and Arneill, 2003). However, the well-being of a person also depends on the kind of view that one sees. For example, a view towards open countryside or greenery would be more psychologically effective than a view out to a blank wall.

Hence, designers need to consider the site context before locating the windows and finalising the size and other window details.

Having said that, it is also important to understand the kind of view that is to be provided depending on the function of the internal spaces. For example, a window should be placed at a level in a hospital recovery room from where a patient can look outside while in a seated position. Whereas, in classrooms, the windows should be placed at a higher level so that it does not disturb the concentration of the students. The view outside is also directly related to the view inside, which means that while providing a view to the outside one must keep in mind how much of the inside will be visible to the outside world which then raises the issue of 'privacy' and 'social connection'.

Sound control

Although noise barriers such as trees are the most used mitigation measures to address the high noise levels, they can only partially resolve the issue (Lam et al., 2018). Therefore, the need arises to regulate noise at the receivers' end, such as through walls, doors, windows and roofs. Windows play a crucial role in providing indoor thermal and visual control plus it is also responsible to provide a view of the outside which is often linked with the mental well-being of the occupant. However, apart from the above roles, the window is also responsible for the transmission of sound. Nowadays, various technologies such as aerogel-based finishing, air insulation sheaths, water insulation sheaths, paints and so on are used to attain acoustical insulation (Granzotto et al., 2017). However, with respect to windows, the primary function of an openable glazed window is to provide ventilation and natural light. Hence, since they are not air-tight they do not provide acoustic protection. There is a lot of research done that proposes various passive noise control strategies that can be applied to glazed windows. One of the most widely used strategies is the use of staggered panels with louvers (Kang, 2006). These panels act as a secondary skin of the building façade and the louvres are lined with micro-perforated absorbers. Thus, the installation of these panels manages to control the sound levels and also allow natural ventilation and daylight to enter the usable spaces. Although the staggered panel window or "plenum" windows reduce the traffic noise they also reduce the amount of airflow into the indoor space (Fig.2.21.) (Tong and Tang, 2013).

Therefore, it is essential to address different types of noise at the design stage itself. The noise created by the building services can be controlled by the building services engineer, the noise from the activities that happen inside the building can be controlled by its inhabitants. However, the noise created by traffic cannot be controlled as such and the only way it can be reduced to an extent is through the design of the building.

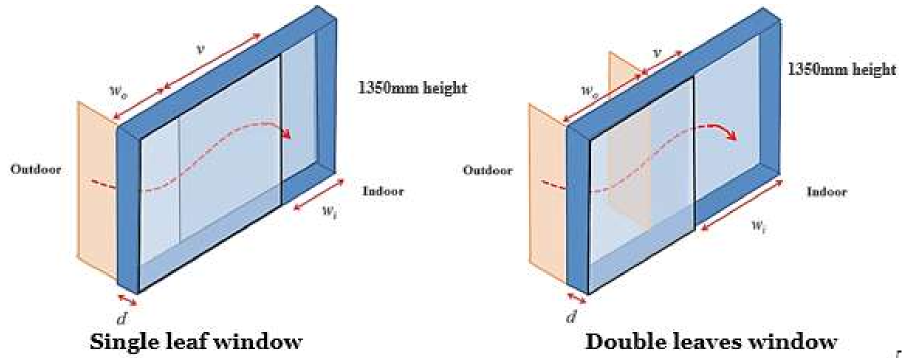


Fig.2.21. Plenum window schematics (Tong and Tang, 2017)

Reflections:

A brief discussion on the history of windows, their evolution, the definitions and the various factors that a window addresses, allows to conclude that windows indeed play an extremely crucial role in not only setting a comfortable indoor environment but also plays a significant role in social, cultural, psychological and physiological well-being of the occupants. This chapter highlights the importance of windows in creating good architecture and better indoor environments for the inhabitants. Therefore, the understandings from this chapter are taken forward in the form of 'examples of windows', where windows from three different periods are analysed for their architectural design and their role in providing environmental comfort that contributes to the well-being of its occupants.

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Fig. 2.19. Stack driven ventilation. Available from http://naturalcooling.co.uk/OV/optivent/optivent.php#close. [Accessed 06 July 2019].

Fig.2.20. Buoyancy driven ventilation. Available from http://naturalcooling.co.uk/OV/optivent/optivent.php#close. [Accessed 06 July 2019].

Fig.2.21. Plenum window schematics. Available from https://www.researchgate.net/publication/315974337_Acoustical_Benefits_of_Plenum_Window_as_Facade_Device_-_A_Parametric_Study. [Accessed 08 July 2019].

Table.2.1. Heat transfer through different glazing options. Available from https://snuggpro.com/help/article/windows-u-value-shgc. [Accessed 11 June 2020].

CHAPTER 3

EXAMPLES OF WINDOWS

Since this research contemplates the current window design trends, it essential to study some well-designed, climatically responsive windows from around the world. This chapter focuses on such windows to learn from them and understand the role these openings played to achieve indoor comfort, their spatial significance as well as their social and cultural relevance. The chosen case studies for this chapter are the different types of windows belonging to the different regions of the world as well as different eras, but all are climatically responsive. The documented examples belong to completely diverse periods, however, it is interesting to see that they do share some common threads in one form or the other. So, it needs to be investigated if with the evolution of windows over a period of time with respect to the materials available, changing architectural styles and evolving technologies and craftsmanship, have the main elements of windows changed? Has the main purpose of a well-thought-of and well-designed window changed (Fig.3.1), evolved or regressed? All these questions are addressed through the case studies discussed in this section.

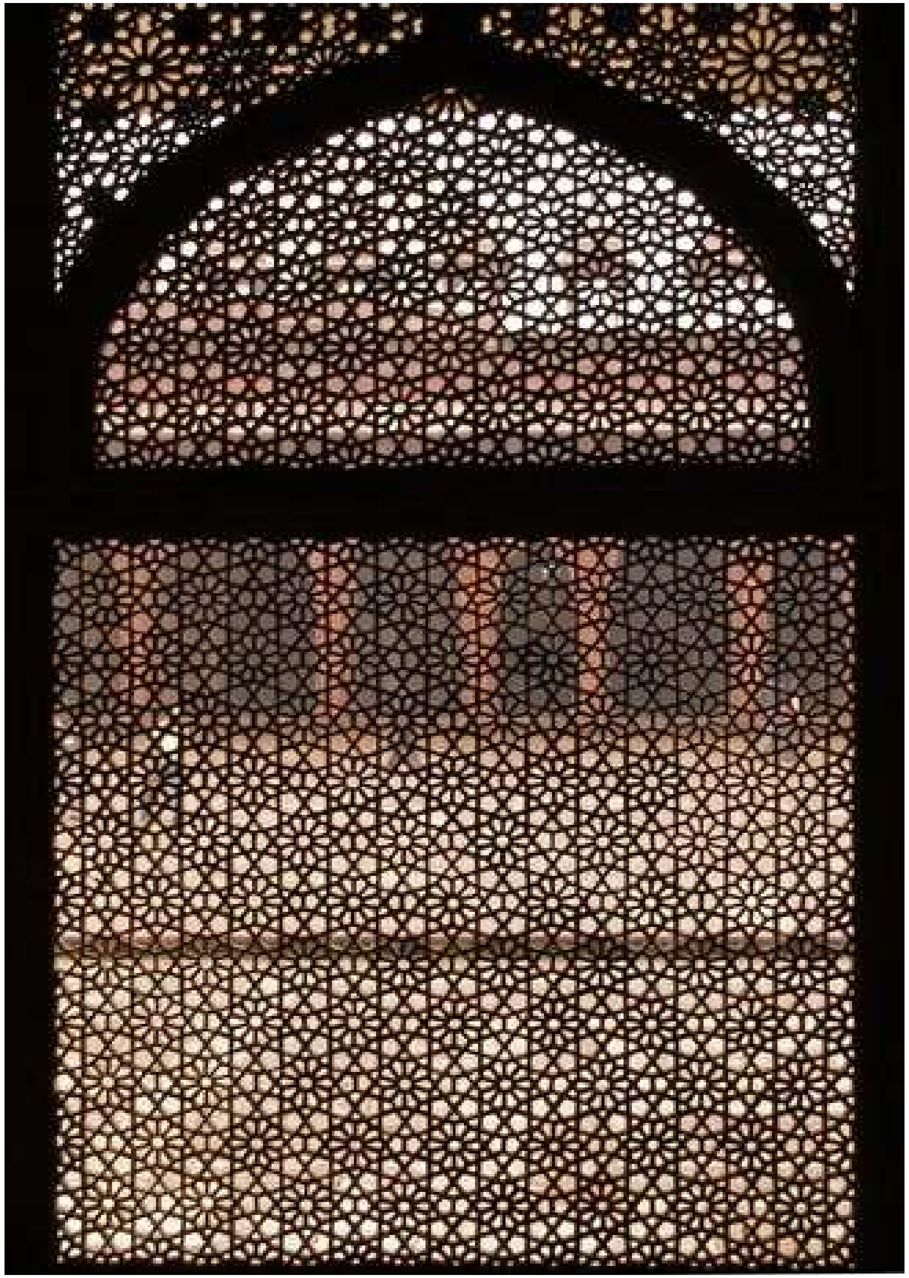


Fig.3.1. Carved marble screen at Fatehpur Sikri, Uttar Pradesh, India. (Pinterest)

1.(a). Jaali *- The traditional window*

Jali, Guss, veiled facades are the many names of the lattice perforated screens that are widely used in the hot-dry and hot-humid regions, especially in south-east Asia. *Jali* or *Jaali* is an Indian term used for the lattice screen that has punctures in a wall with geometric or ornamental pattern (Fig.3.1.). Apart from India, these lattice screens are found mostly in Iraq, Egypt, Morocco, Arabia, Persia, and so on. (Sarswat and Kamal, 2015). *Jaali* was mainly introduced to the Indian subcontinent by the Mughals during the 15th century (Kenzari and Elsheshtawy, 2003). The architecture in India during the Mughal rule was highly influenced by the Islamic, Persian and Hindu architecture and so the buildings built during this time saw a fusion of different architectural styles (Azmat and Hadi, 2018).

In India, *jaalis* were and still are mostly used as ventilators, partitions, as railings and also as windows. These multi-purpose screens act as shading devices, they regulate airflow and prevent powerful gusts, protects from direct solar radiation, allows diffused light throughout the interiors, secures privacy and at the same time regulates social interaction. Hence, the reason for placing *jaali* on a low sill or at times without sill was for the movement of air on floor level (Fig.3.2.). Traditionally these screens were constructed in materials such as marble stone, wood and sandstone. The wooden *jaalis* aided in absorbing excess humidity present in the air and when the humidity levels in the indoors were less, the *jaalis* aided in increasing the humidity levels through the infiltrations in them. (Sarswat and Kamal, 2015). Hence, maintaining comfortable humidity levels indoors.

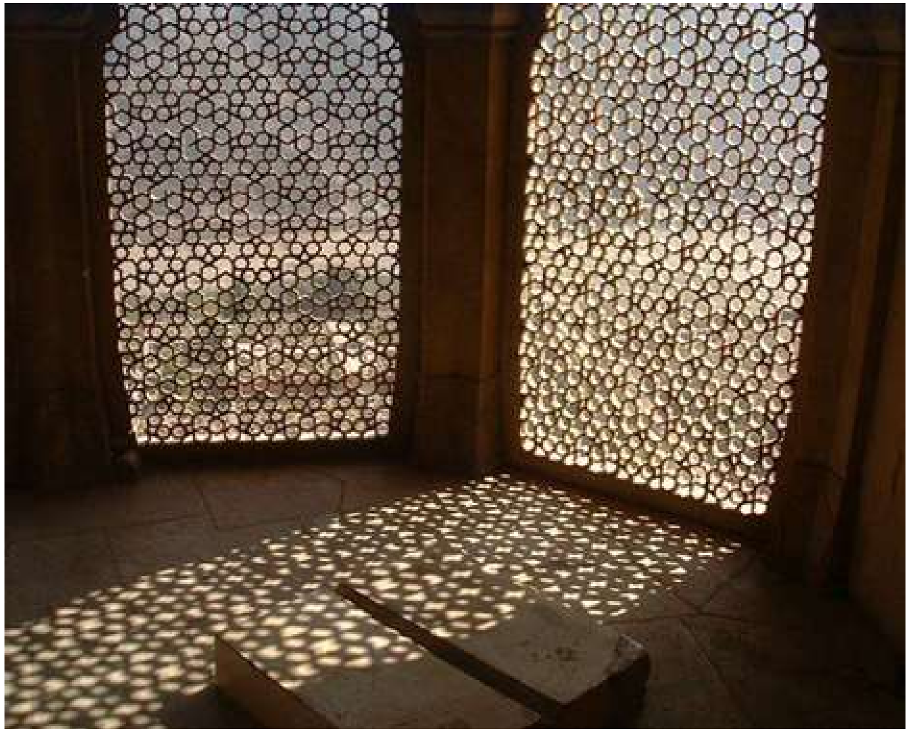


Fig.3.2. Jaali with no sill level for the movement of air. (Perforated Screen Designers)

Addressing *jaali* as an effective tool in achieving environmental comfort, Ar. Yatin Pandya further elaborates on '*Jaali'* as a versatile architectural element that is effective in hot-humid as well as hot-dry climate zones. It cuts direct sun and allows movement of air for cross -ventilation. *Jaali* breaks down a solid surface of a wall into several small apertures that are approximately of the same size as the thickness of the built material which means that each small hole is a cubical proportion of height equal to depth (Fig.3.3.). Hence, protecting the internal space from direct sun rays and glare as well. He further states that *jaalis* not only cut glare but also provides sufficient illuminance indoors. Plus, due to the difference in the illuminance levels indoors and outdoors, privacy is maintained because this difference prevents indoor visibility from outside. Thus, best suited for the Indian notions of privacy. Ar. Pandya also justifies *jaali* as a compressor i.e. when the hot air passes through small holes it gets compressed and hence releases cooler air as well as blows with higher velocity, which is a similar concept used in compressing air in mechanical ventilation.

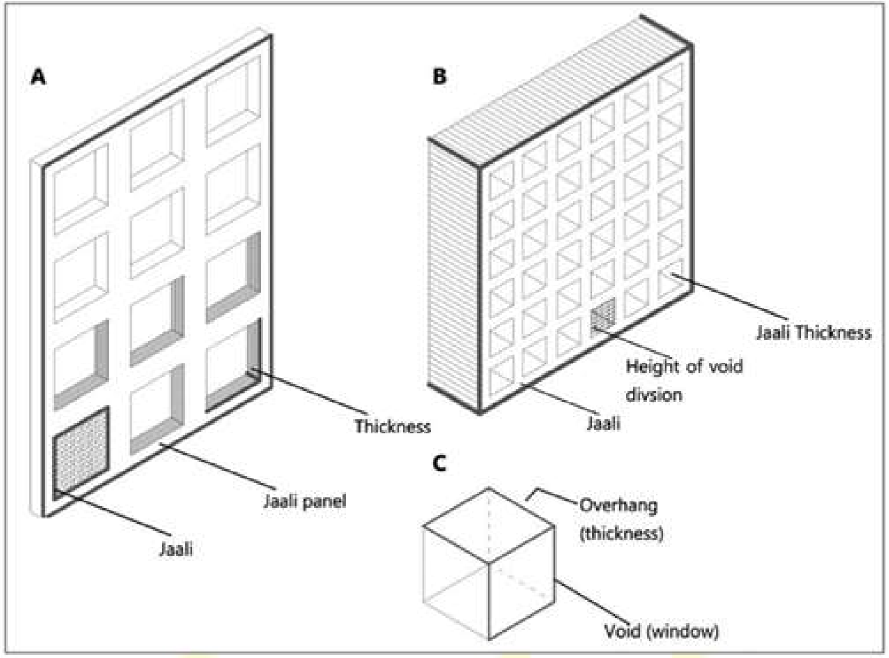


Fig.3.3. Sections of jaali showing the relation between the height of the void and the thickness of the jaali. (Gandhi, 2015)

Today, *Jaalis* have been replaced by transparent sliding windows in most parts of the country. Glass windows have given higher illuminance levels as well as higher indoor temperatures which have given rise to the use of fans and air conditioning units. The transparency that glass provides has given rise to the issue of privacy which has further given rise to the use of curtains, blinds and tinted glass. The openness of a sliding window has raised safety issues which has led to the introduction of metal grills. Hence, we have ended up increasing the layers associated with our windows that have possibly raised the total cost of the windows we use today. Though *jaalis* are not as adaptive but through appropriate design interventions, there is a great possibility that they can be user-controlled and if that can be achieved then it can drastically reduce the number of layers we have on our windows today and can also be efficient enough to reduce the cooling load.

With respect to the use of *jaalis* in recent times, many prominent architects such as Hasan Fathy, Laurie Baker, Frank Lloyd Wright have used *jaali* as a tool for ventilation or as the most prominent feature of their designs or as a façade (Fig.3.4.) (Fig.3.5.) (Fig.3.6.). According to Baker, *jaali* is one of the oldest methods that not only maintains privacy and security but also allows filtered light and ventilation in the built spaces (Baker, 1999).

Similar to *jaalis, jharokhas* are also one the oldest form of an entire window system that is described in detail, next.

Fig.3.4. New Baris Village, Egypt by Hasan Fathy. (Archidatum)

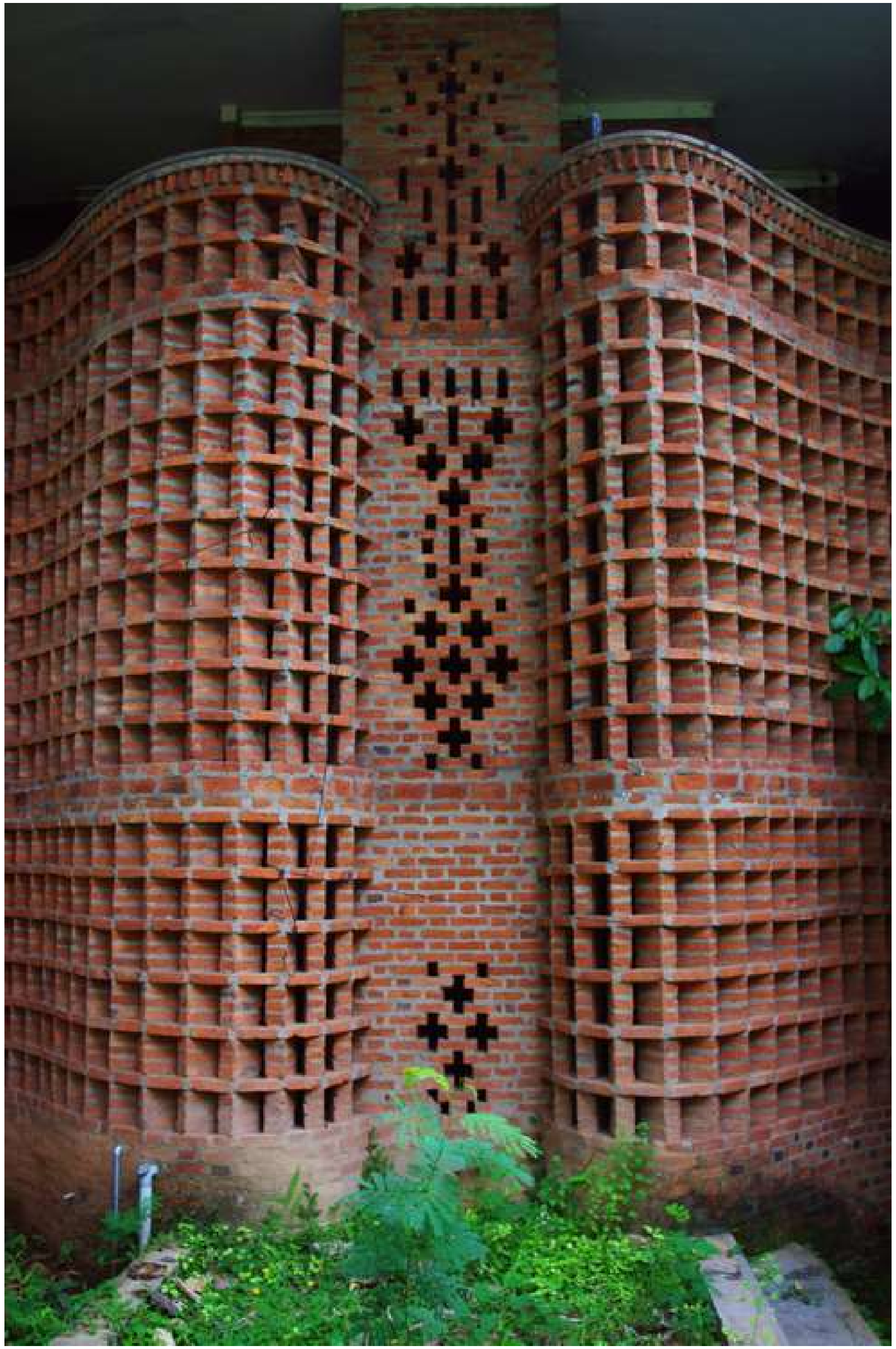


Fig.3.5. Women's Dormitory at the Centre for Development Studies, located in Ulloor, Trivandrum, by Laurie Baker. (Chothompson)

Fig.3.6. Men's Hostel at the Centre for Development Studies, located in Ulloor, Trivandrum, by Laurie Baker. (nayeemasif.wordpress.com)

Fig.3.7. Hawa Mahal or the 'The Palace of Winds' Jaipur, India. (Flikr.com)

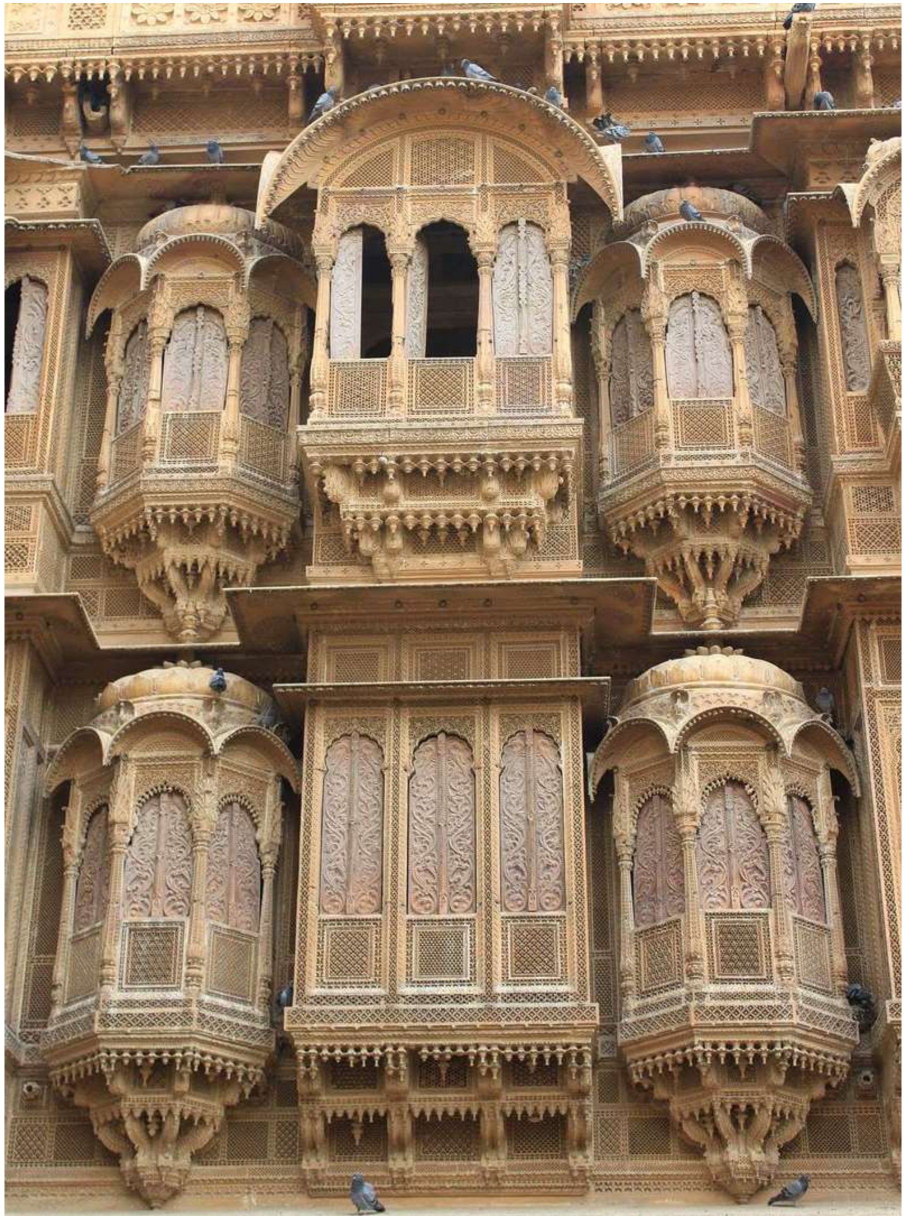


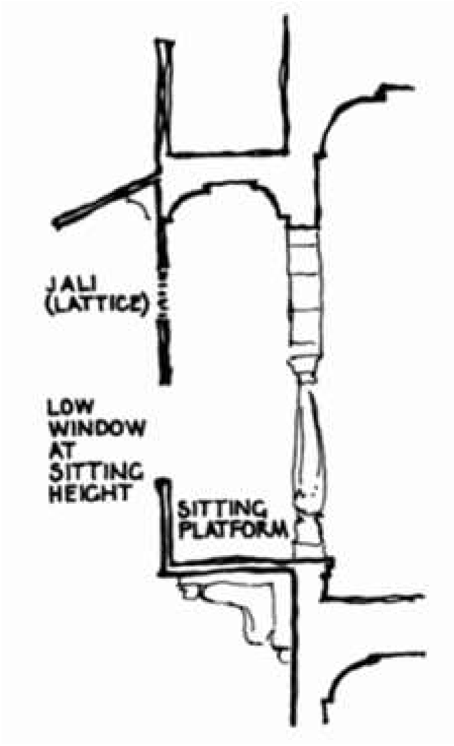
Fig.3.8. Ornately carved 'jharokhas', Patawon ki haveli, Jaiselmer. (twitter.com)

'Hawa Mahal' or 'the palace of winds' is so-called because it contains 953 windows known as *jharokhas* for ventilation and for keeping the indoors cool (Fig.3.7.).

Jharokha is a window with intricate lattice work, projecting from a wall, usually on the upper levels, overlooking the street below, courtyard, market or any other open space (Nath, 1986). It is like an enclosed cantilevered balcony, widely used in the western region of India such as Jaisalmer, Ahmedabad, Jaipur and also in the north Indian regions like Delhi, Agra, Lucknow and so on (Fig.3.8.). It represents a combination of Rajasthani and Mughal architecture (which further is a combination of Islamic, Persian and Indian architecture) (Ali, 2013). The wide use of these windows in Rajasthani architecture, Mughal architecture and later in Indo-Islamic residential buildings, was not only due to their aesthetics but also because they maintained privacy and because they were climate responsive. Apart from these functions, *jharokhas* were especially used by the *Maharajas* (kings) as well as the Mughal emperors to address to their subjects (Saquib, 2012).

Similar to the '*Mashrabiya*' from the middle-east, the *Jharokhas* block direct sunlight from entering the house and also directs cool air indoors through small apertures (Fig.3.9. (a) (b)). The *Jharokha* has three main features:

1. The base: It is the support structure formed of two or more brackets or has corbelling.
2. The main body: Has a platform, *jaali* and an opening at seating level through which a person can peep out.
3. The canopy: It is a projection on top also locally known as *'chajja'* that protects the indoor space from receiving direct sunlight.



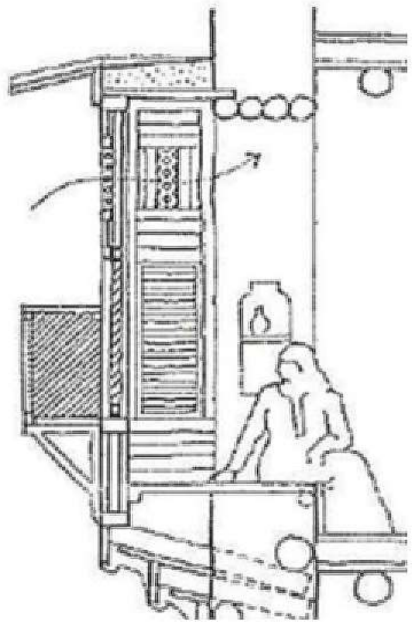


Fig.3.9. (a) *Fig.3.9. (b)*

(a)A typical section through a 'jharokha' (Tilloston, 1998)
(b) A typical section through 'mashrabiya' window (Alawad, 2017)

Like *jaalis, jharokhas* also provide privacy to the women in the house. Apart from being aesthetically appealing, the *jharokhas* are the climate moderators that allow ventilation and restrict direct sunlight from entering the main space such as the living area (Saquib, 2018). The projected overhang captures the heat and the small apertures in the *jaalis* channels cool air inside the house, acting as a transition space (Sarswat and Kamal, 2015). Hence the *jharokha* acts like a secondary layer and if this layer is absent then the building is exposed to direct sun, which makes the indoor environment hot.

Jharokhas also serve as a connection between the house and the street (Kaur, 2015). In a way that a person sitting in the house can view the street below without been seen. These projections on the street also provide shade to the passer-by, blocks direct sunlight hitting the streets which keeps the streets cooler and provides shelter

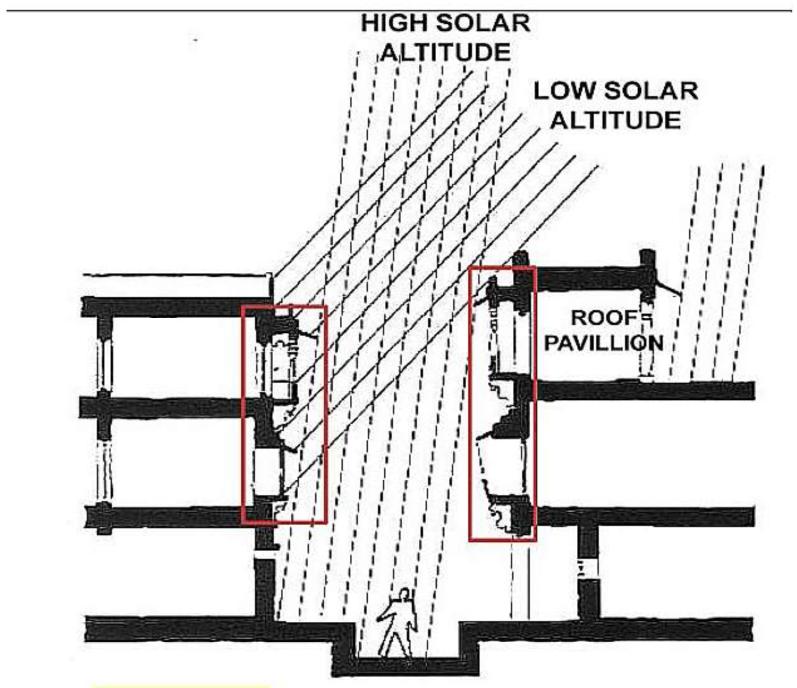


Fig.3.10. (a) Jharokhas in Jaisalmer over the narrow streets (Sarswat and Kamal, 2015)

to the passers during rainy season as well (Fig.3.10. (a) (b)). Hence, it can be said that the design, placement and structure of the *jharokhas* not only provides indoor thermal and visual comfort but also builds a pleasant micro-climate on a street level.

Thus, as rightly pointed out by researchers such as Batool and Zulfiqar that even in present-day conditions, traditional buildings can achieve thermal-visual comfort and can equally have social and cultural significance (Batool, 2014; Zulfiqar, 2018). The architectural elements such as *jharokhas, jaalis,* courtyards, verandahs, *chajjas,* fountains, plants provide natural comfort rather than the mechanical cooling systems and artificial lightings. Therefore, it can be said that even today, the traditional elements, especially the ones mentioned in this chapter, are energy efficient as compared to the current systems such as glazing, air-conditioning, artificial lighting and so on.

Fig.3.10. (b) Patwa-ki-haveli. Shaded streets. (Pinterest)

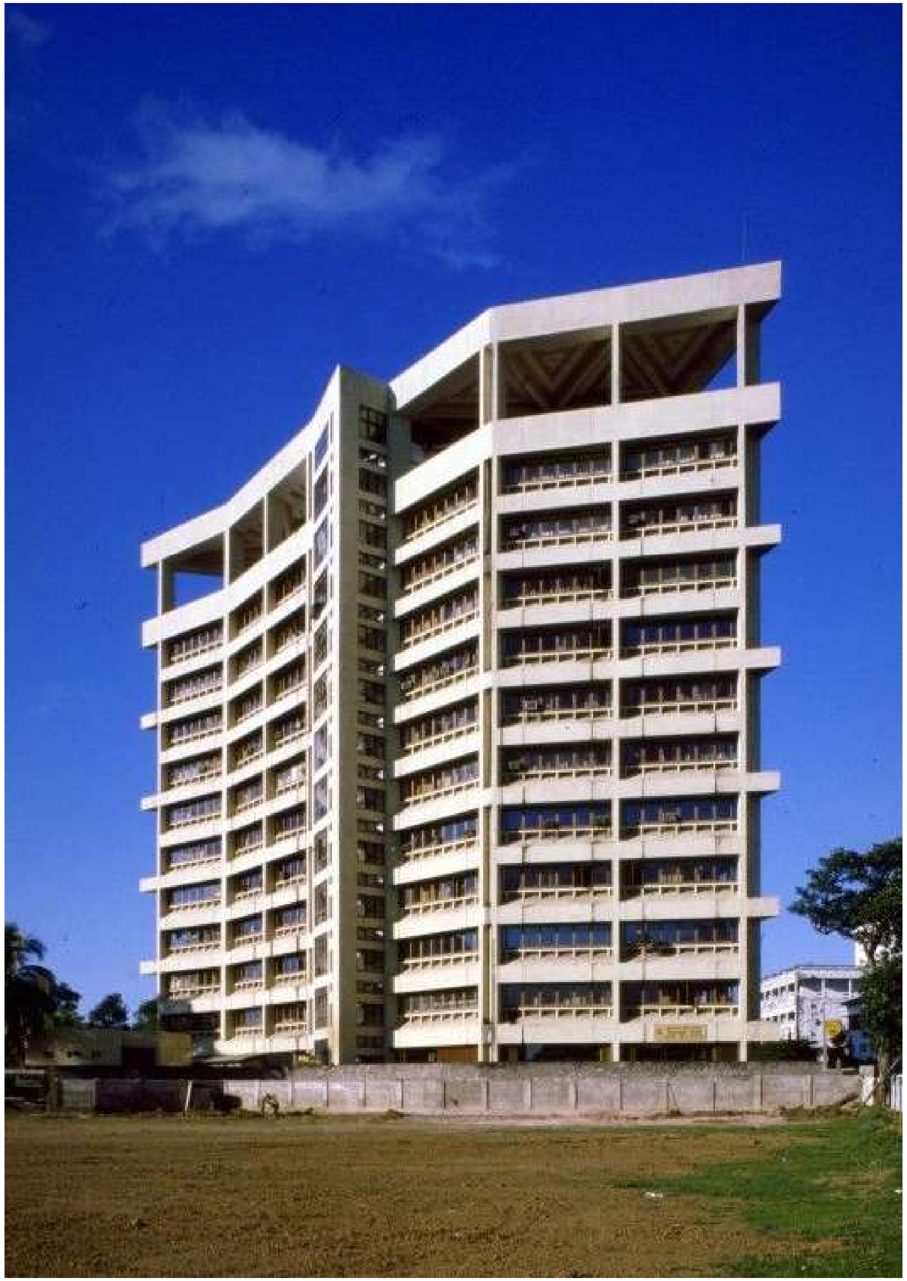


Fig.3.11. State Mortgage Bank (The Mahaveli Building), Colombo, Sri Lanka (1976-78). (Urban Condom)

2.(a). The 'Monsoon Window' - The Contemporary Window

Known as the architect who let light into Sri Lanka, Geoffrey Bawa, is well-known for his Tropical Modernist style of architecture. Inspired by the culture and traditions of Sri Lanka, Bawa followed a theme in most of his buildings to achieve their bio-climatic purpose (Sun et al., 2013). As per Sun et al., Bawa considered the role of 'breathing wall' as an important environmental element that filtered direct sunlight and strong wind currents. Thus, allowing indirect light and gentle air into the indoor space. Like the basic concept of the *'jaalis'* and the '*jharokhas',* the 'breathing wall' also maintained privacy, ensured safety and excluded unwanted noise from the outside. One such example where this concept was applied by Bawa is the 'State Mortgage Bank', Colombo (Fig.3.11.).

The twelve-storey office building was initially to house the State Mortgage bank. However, in 1977 after the election victory of J.R. Jayawardene, it became the secretariat of the Mahaveli Development Ministry. Although very different from the vernacular and picturesque style of architecture of Bawa, this building, even today serves as the greatest example of the bio-climatically responsive high-rise building in the world. (Keniger, 1996).

The main purpose of this commercial building was to provide a working atmosphere that was naturally lit and ventilated. (Robson and Daswatte, 1998). Hence, Bawa created an asymmetric layout that responded to the prevailing northeast and southwest winds to get the maximum amount of breeze which in turn minimized the solar gains from the west and the east façade of the building (Fig.3.12.). To maximize cross ventilation, the floor plan was not more 15m deep at any point, this also aided in achieving adequate natural light throughout the floor plan. The deep-spandrel panels functioned as louvres that were designed to receive maximum air and hence acted as the secondary façade and were specially designed to achieve maximum breeze even during the monsoon season.

The window consists of ventilation grills above the main window which is protected with a deep overhang with a downward fascia (Fig.3.13.). This overhang also protects from direct sunlight and rain entering the indoor space. The vertically pivoted window provides user operability, allows maximum light and air to reach the indoor space (Fig.3.13.). Apart from the ventilator on top and the main window, Bawa designed a horizontal ventilator at the sill level to maintain ventilation of the indoor space even during the monsoon season (Fig.3.14.). The top and the horizontal ventilators enabled night-time ventilation even when the main window was shut.

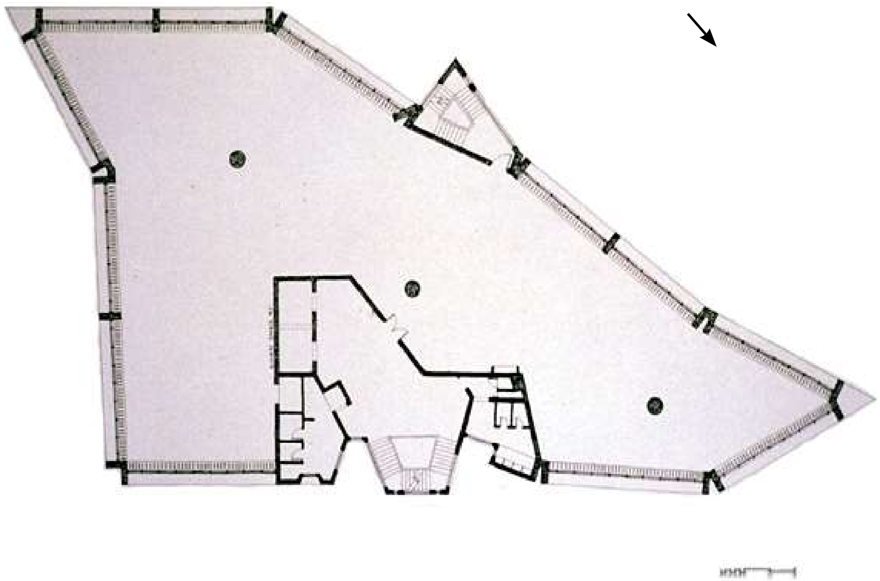


Fig.3.12. Drawing, plan of typical office floor (Archnet)

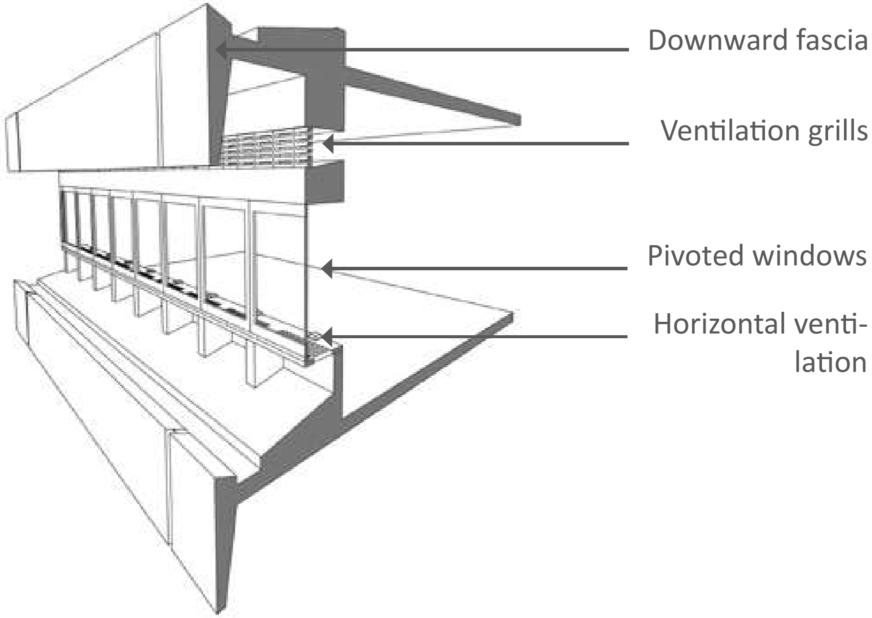


Fig.3.13. Detail of Façade. (Kambil, 2009).

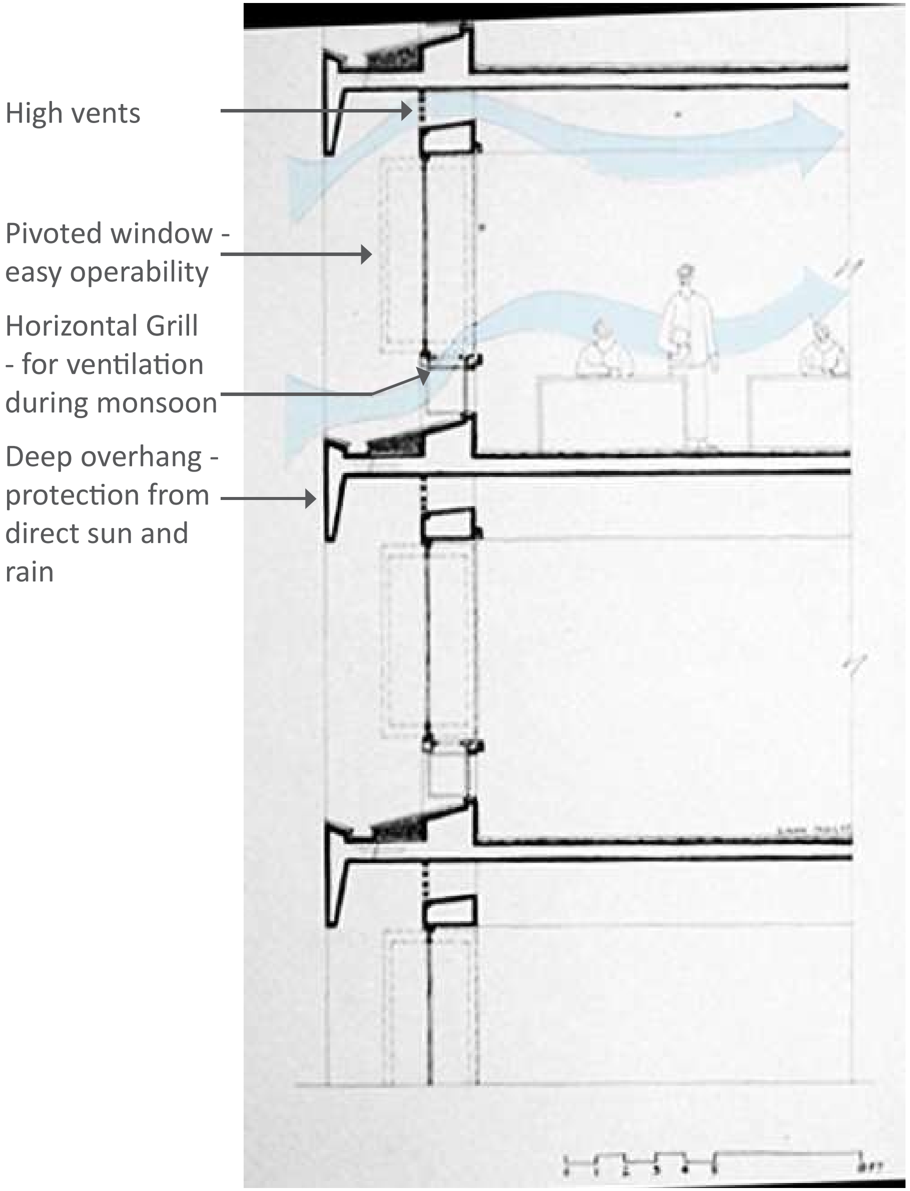


Fig.3.14. Drawing, section through breathing wall. (Archnet)

To understand the thermal and visual conditions of the spaces in this building and particularly to understand the environmental performance of the windows, they were further studied and computational analysis were performed by many researchers. One such research was carried out by Mingwei Sun et.al. (2013), where the thermal performance of the ‘monsoon window’ was assessed. This research concluded that the ‘breathing wall’ concept of Bawa responded successfully not only to the hot and humid climate of Sri Lanka but to all high-rise buildings. The facade had great potential to be applied in different regions of the world, especially with similar climatic conditions. This research observed that the window does provide with thermal and visual comfort to the user belonging to the hot and humid climate and also provides the user with options to choose from, to be comfortable. It was further concluded that the size and the material of the openings also played an important role in the thermal performance of the indoor space, hence these parameters should also be given importance while designing. Lastly, the façade of the building should be considered as an important element of the building since they have the potential to regulate the environmental performance of an indoor space.

Therefore, as mentioned earlier ‘monsoon window’ is regarded as one of the best-designed windows for hot-humid climatic conditions. Various elements of the window such as ventilator on top, the main pivoted window and the horizontal grill, provides various options for the user to choose from and to adjust their indoor environment according to the different climatic conditions during the different time of the day and throughout the year. It needs to be noted that no additional layers have been added to the existing window such as curtains or grills, but

the entire window is designed in such a way that it provides the user with multiple options to choose from. The window has the potential to improvise further and a potential to be used widely in hot-humid climatic conditions worldwide. One such modern-day example where 'the monsoon window' is developed further, technically as well as aesthetically is the 'Moulmein Rise' residential tower in Singapore, which becomes the next case study for this thesis.

Fig.3.15. View from South-east. (Archnet)

2.(b). Moulmein Rise, Singapore

One of the main constituents of urbanization is tall high-rise buildings. The mega-cities around the world such as Shanghai, Mumbai, Singapore, London, New York etc. are sprawling with high-density residential blocks on a very limited space available. However, there are very few such residential units that are high densities and at the same time sustainable. One such recent example is the Moulmein Rise, Singapore (Fig.3.16.). Designed by WOHA Architects, this 28-storey residential building consists of 48 typical apartments and 2 penthouse apartments (Hassel, 2007). Completed in 2003, this building acts as a trendsetter because the issues of environmental comfort and privacy, both are addressed in this building design with the help of various design elements.

Since the architects wanted to provide natural light and air in the indoor spaces and provide the users with an option of controlling their indoor environment, the 102m tall building was oriented in the north-south direction that maximized the thermal and visual comfort to its user. Each apartment is unique due to the use of different façade elements such as planters, monsoon window, horizontal sunshades and vertical perforated screens which were designed, keeping in mind factors such as orientation, wind movement, the direction of rain, the quality of indoor spaces etc. (Johnston, 2007).

Fig.3.16. Moulmein Rise, Singapore.
(Archnet)

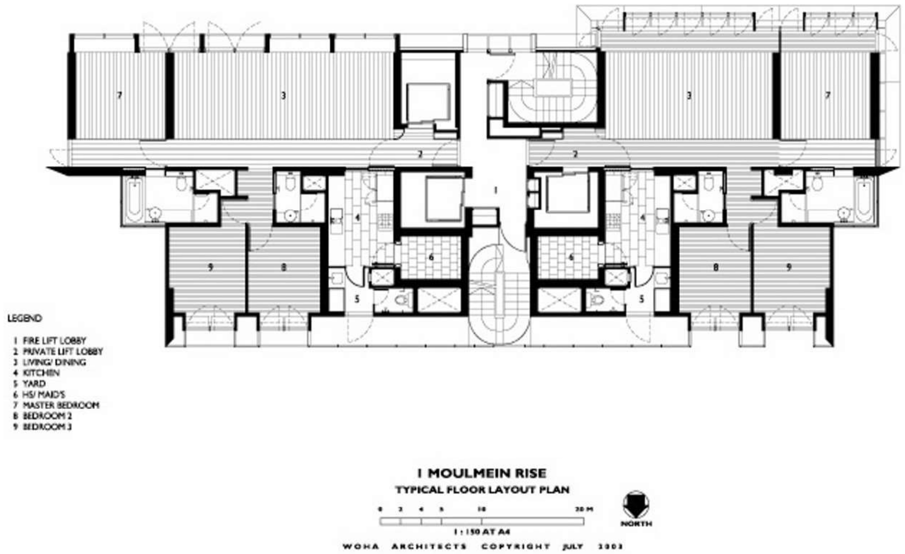
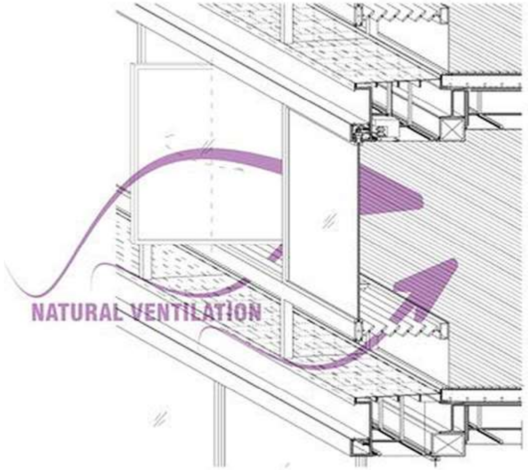


Fig.3.17. Typical Floor Plan (Ali, 2007).

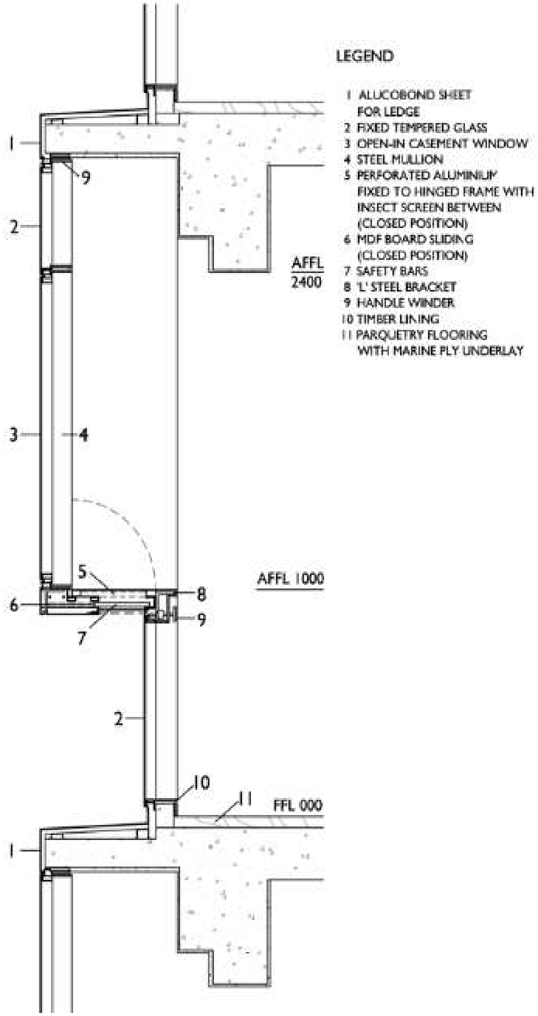
The need for different façade design: To reduce direct heat gains and to keep out driving rain, the windows have deeper overhang (about 0.6m) with vertical sunscreens on the south. To tackle the issue of unpredictable rain and to lower the consumption of mechanical cooling, the monsoon window, which is believed to be a traditional feature of the Malay, Indonesian and Vietnamese vernacular architecture, became the main façade element of this building. Taking inspiration from the State Mortgage Building, Colombo by Geoffrey Bawa, WOHA had tested this window form in their Victoria Park Road houses project and in Maple Avenue House (Hassel, 2007). The basic design for monsoon window developed by WOHA had horizontal steel grill between the main window and the timber louvres, set flush with the floor. This allowed cool air to come into the house when the windows were open and the louvres were shut. This was further developed for Moulmein Rise, where the grill opening was shifted on the bottom ledge of the bay window that projected outwards (Fig.18. (a) (b) (c)). Hence, when the horizontally placed grill was left open during the rains, it kept the internal environment cooler, plus stopped the rain from coming inside the apartment and also facilitated ventilation hence, reducing the cooling load. The monsoon windows were placed on the south side while the regular window opened on the north side, thus, having window on both sides maintained airy indoors due to cross ventilation (Fig.3.17.).

Fig.3.18. (a). Monsoon window. Moulmein Rise, Singapore (Pinterest)

Fig.3.18. (b) (c). Monsoon window. Moulmein Rise, Singapore (Source: Pinterest)



(a)



(b)

Fig.3.19.(a). Monsoon window detail. (Source: Pinterest)
Fig.3.19.(b). Monsoon window detail. (Hassel,2007).

Other Façade Elements: The architects have used a similar concept of *jaalis* or the lattice perforated screens that are seen in traditional Indian architecture, in Moulmein Rise (Fig.3.20. (a) (b). The aluminium perforated screens were used to hide clothesline and air conditioning units, keeping the elevation look clean. (Rowe and Kan, 2014) (Fig.3.20. (a)).

Fig.3.20.(a). North façade detail. (Archnet)

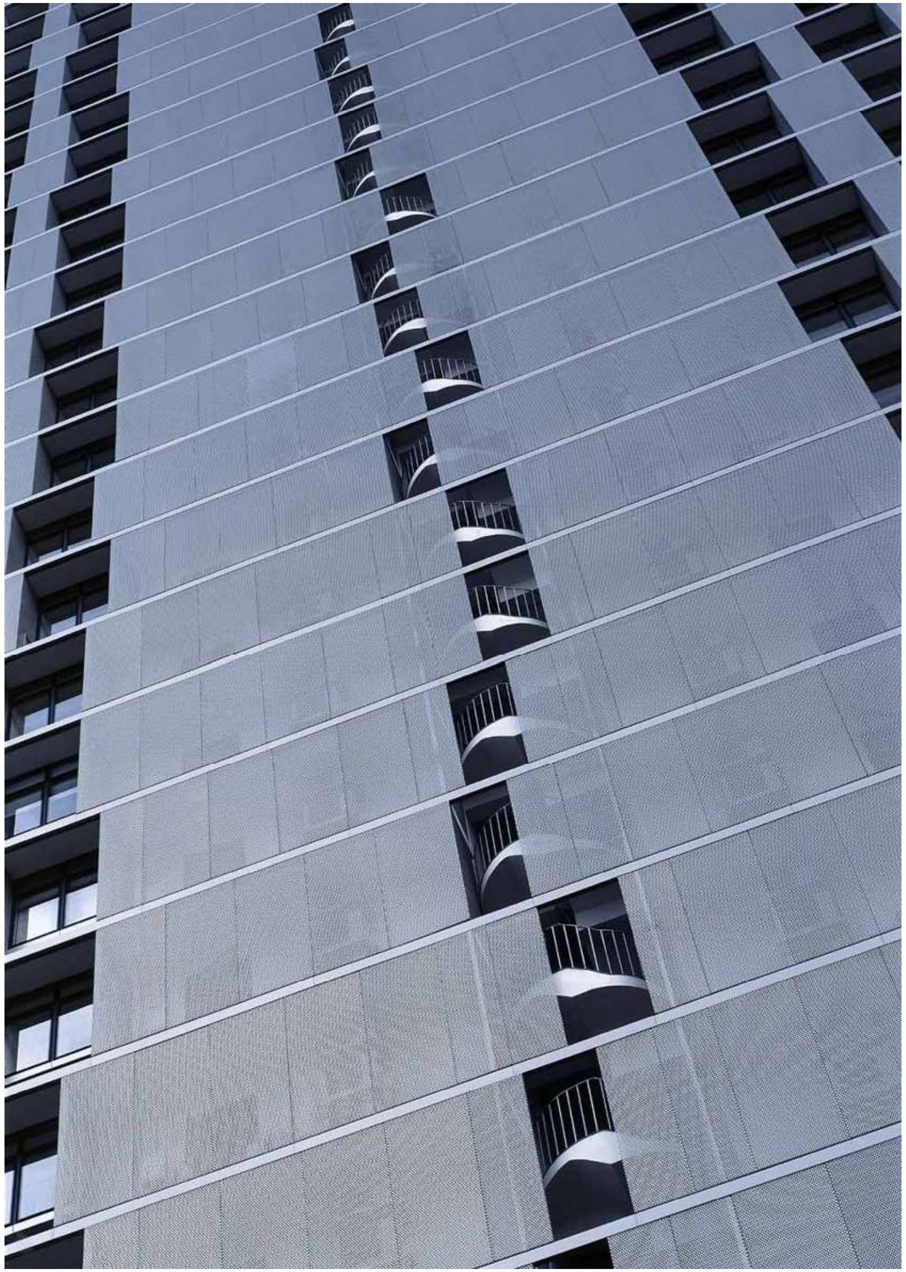


Fig.3.20.(b). North façade detail. (Archnet)

Conclusion

The *jaalis* and the *jharokhas* that are about century-old architectural design features were carefully created by keeping in mind the user requirements such as privacy of women in the house and simultaneously obtain an adequate amount of light and air indoors. Looking at the thoughtful design of these fenestrations, it can be said that, since there was no available option of using mechanical cooling or lighting during those times, fenestrations became the main source of attainment of indoor comfort.

Whereas, the State Mortgage building which was built much later, on the concepts of sustainability and with a thought that it would be naturally ventilated and lit, was not used accordingly. Instead, the open office plan was later divided into cubicles by the user due to which mechanical cooling was adopted to attain comfort, which is easily available and easy to control. However, looking at Moulmein Rise apartments, the architects have not only used the traditional monsoon window but they have further improvised on it in terms of materials, sizes, ease of operability and also the look and feel of the window. The fenestrations on each façade were carefully planned keeping in mind the weather conditions and the needs of the modern user. Therefore, apart from the vernacular learnings, modern examples such as Moulmein Rise becomes the best example to follow and to learn from.

Similar to the examples studied for this research, there are many such fenestrations all over the world, vernacular and modern, that are applied to achieve many user requirements such as controlling indoor thermal and visual comfort, noise control, to maintain privacy, for safety, for the view outside and so on.

A window has the potential to control so many user requirements, unlike other architectural elements. Hence, windows must be versatile, windows cannot be of the same design, material, size everywhere. As seen in Moulmein rise, the type of window changes with every façade orientation. Therefore, it becomes the responsibility of the designer to take into consideration various factors such as weather conditions, affordability, user requirement, the social and cultural importance of the place and people. Also, it becomes the responsibility of the user to take full advantage of the window design and window elements to attain indoor comfort, rather than opting for easy solutions of mechanical cooling and lighting.

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CHAPTER 4

INDOOR ENVIRONMENTAL COMFORT

As mentioned in chapter one, the discovery of mechanical heating and cooling systems has allowed people to control their thermal environment to some degree varying from one context to another. This development of technology has opened wide areas of research to determine the 'thermal comfort' parameters which increases the efficiency and productivity of the users (Heschong, 1979).

The research regarding 'comfort' has led in determining comfort zones for different countries around the world according to their climatic conditions (Olgyay, 2015) and has given a direction to the development of set standards for thermal comfort for the respective regions, which were also then used in building codes (for example: ASHARE or CIBSE).

Comfort is defined by ASHRAE 55 as *"that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation".* Hence, all the environmental control systems available to us today are to attain standard comfort zones within a built environment.

We have forgotten that the thermal environment has the potential for cultural roles, symbolism and sensuality that cannot be neglected and replaced by a thermally neutral world. Our fascination with the ability to control our indoor environment has made the natural thermal strategies seem obsolete and thus, the concept of 'comfort' needs to be reconsidered and redefined.

a. Rethinking Comfort

Experts such as Lisa Heschong, Fergus Nicol, Michael Humphrey and Susan Roaf have extensively analysed the concept of 'science of comfort' which was developed in the 20th century mainly to justify the use of HVAC systems to obtain neutral environment for the occupants. It has further been implied by them, that the adaptive comfort theory can only be implemented when the building design can influence the habits and behaviours of its inhabitants and provide them with opportunities to make themselves comfortable over time. Also, according to Nicol and Roaf, the research community today is challenged with the task of disseminating and making accessible the outcome of their findings in the field of comfort studies to designers, regulators, inhabitants and the decision-makers.

Hence, reassessing the definition of comfort means taking into consideration changes in culture and architecture together to provide comfort, since it is not just about achieving temperatures in a comfort range anymore, but it is an additional requirement to provide comfort that is affordable and energy-efficient.

Although we have the provision to modify our indoor environment with the help of controlled mechanical heating and cooling systems, there is a need to address the concept of adaptive comfort which is based on the application of user friendly strategies that are efficient and therefore can be adopted and implemented by the architects and builders in their designs. Furthermore, Nicol and Roaf (2017), have also asserted that the use of excess energy to attain comfort can be curtailed by emphasizing on designing resilient buildings in future.

Thus, the renewed definition of comfort must highlight adaptive approach in creating a good building design that incorporates the thermal and visual relationship between buildings and its user and determines the affordability and quality of comfort provided in them.

b. Interpreting Adaptive Comfort

Addressing the current trends in achieving comfort, an observation presented by Richard Levin and Richard Lewontin (1985) reminds us that humans share the [physiological] mechanism of temperature regulation like other mammals. However, in addition to this, we also use shelter, clothing and fuel to keep ourselves warm or cool as per our requirements, which although has enabled us to survive in any climatic condition, has also made us vulnerable. Our personal comfort and body temperature are greatly dependent on the price of clothing and fuel, whether we work outdoors or indoors, how we control our heating/cooling systems and so on. Hence, our methods of acquiring a comfortable temperature are not just a consequence of thermal needs but also a product of social and economic conditions.

To amend the above notion of comfort, first, we need to understand that our thermal preferences are shaped according to the external climatic conditions and a dependency on the mechanical systems results in the blocking of the outdoor environment (Nicol, 2011). As a solution to this, incorporating adaptive approach has been given major prevalence by various researchers such as Lamberts, Candido, de Dear and Bittencourt and it is largely agreed by them that the availability of adaptive opportunities should be built in to standards, especially focusing on thermal comfort and naturally ventilated indoor environments, air movement acceptability and their interactions (Nicol, 2017). 'A Solar Fruit Tree' by Lechner, further illustrates various energy efficient strategies that can be easily implemented to achieve comfort (Abbakyari and Taki, 2017). It shows different strategies placed at various heights according to the sequence of their affordability (Fig.4.1.). Strategies such as window size and placement are some of the most affordable ones and if their design, material, orientation, size, aperture and placement are taken into consideration at the initial stages of design, they might significantly help in reducing the initial cost of building construction and cost of energy consumption.

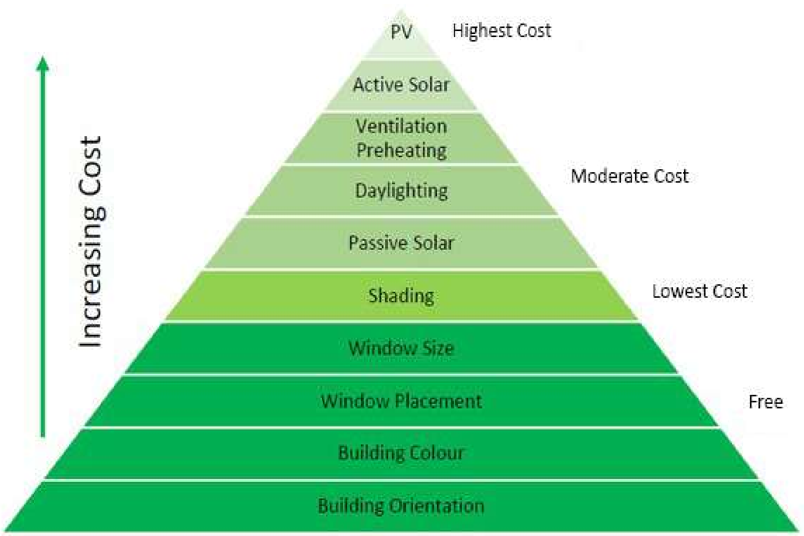

Fig.4.1. Solar tree chart showing the affordable and costly strategies that can be applied. (Dora)

Thus, referring to the research of Elizabeth Shove and de Dear, it can be said that the role of a building needs to shift from providing comfort to that of providing the means for its inhabitants to achieve their comfort goal, thus making the perception of comfort as a dynamic process rather than a static one.

c. <u>Need for operability in residences and related research studies</u>

As mentioned earlier, in a naturally ventilated building, the indoor climate greatly relies on the way in which the environmental controls are used and also on the local climate. Common controls such as windows, doors, blinds, fans and lights provide the occupants with opportunities to modify their thermal and visual environment for them to achieve a comfortable indoor environment.

Based on a worldwide analysis conducted in naturally ventilated and centrally controlled HVAC buildings, it was validated in ASHRAE RP-884, that the thermal acceptability range of the building occupants in a naturally ventilated building is broader as compared to the occupants of the air-conditioned building. One of the findings of the research reported that the users of the naturally ventilated buildings adjusted their heat balance by adaptive behaviour with the help of air speed adjustments and clothing which enables them to accommodate wide variations in indoor temperatures without adverse impacts on thermal sensations, which meant that they were actively thermo-regulating their sensations. Also, researchers such as de Dear and Brager (1998), have further suggested that since the occupants of naturally ventilated buildings have greater thermal control than air-conditioned buildings, it leads to greater tolerance of temperature excursions and relaxation of expectations. Adding on to this hypothesis was a similar explanation given by Bordass et al. (1994), stating that people accept variations from a predictable source, such as in naturally ventilated buildings, which can also be controlled subject to their preferences. Thus, to ensure good performance of a naturally ventilated building with natural daylight modulation, it is important to consider user interaction with the building control systems. In their study, Leaman and Bordass (1999), found that the building users that were provided with opportunities of user control were more forgiving as compared to the users that were highly dependent on the mechanical systems. Another study by Paciuk established a very strong relationship between thermal comfort and the degree of perceived control, which means that the users with a high degree of control over an adaptive tool such as window showed a higher level of thermal and visual satisfaction (Andersen, R.V. et al., 2009). Hence, it becomes important to consider occupant interaction with the building control systems while designing buildings because variations in occupant behaviour significantly affects the energy consumption of the buildings. Thus, it can be said that the use of control creates a sequence of relationships between the outdoor environment and comfort conditions in a naturally ventilated building (e.g. opening windows and turning the fans off etc.).

Regarding the use of controls, a lot of research is available by the way of studies conducted in buildings located in different climatic regions of the world by experts such as Fergus Nicol, Richard de Dear, Gail Brager, Charlie Huizenga, Hui Zhang, Edward Arens, Madhavi Indraganti etc. However, there are very few studies available based on occupant behaviour in terms of the use of environmental controls in residential buildings, and further fewer studies from India, since the notion of comfort varies with every occupant based on their cultural and social practices, their economic condition and so on. Therefore, before initiating the research in terms of fieldwork, it is important to look into some important research works that have analyzed the role of the adaptive controls available to the occupants in the tropical regions of the world. Few studies are discussed as below:

i. Study 1: Survey of occupant behaviour and control of the indoor environment in Danish dwellings.

In a research by Anderson et al., a questionnaire survey was conducted in summer and winter months of 2006 in Danish dwellings to identify the important factors that affected occupant's interaction with building control systems (such as solar shading, window opening behaviour, the pattern of use of different mechanical systems such as air conditioning, air coolers, fans etc.) to achieve lower indoor temperature. The survey showed that in Danish dwellings, window opening behaviour was strongly related to the outdoor environment. Some of the factors that influenced window opening were perceived illumination, perceived air quality and noise levels. It was observed that bright outdoor environment, higher noise levels and good air quality led to an increase in the prevalence of open windows in comparison to the darker outdoors, lower noise levels and bad air quality. Other factors that influenced window opening behaviour were solar radiation, ownership conditions of the dwellings, floor area, age and gender of the respondent and so on.

Hence, the survey provided a new insight on factors that influenced occupant behaviour in Danish dwellings to achieve comfort and the results obtained were believed to have the potential to form a framework in defining standard behaviour patterns that could then be implemented in building simulation programs to enhance their validity.

This research also highly signified that small actions by users such as opening a window are also entangled with several different parameters, which means that comfort and the process of achieving comfort cannot be a monotonous act of control but is a result of the influence of various other factors as mentioned above.

ii. Study 2: Adaptive thermal comfort in Japanese houses during the summer season: Behavioural adaptation and the effect of humidity.

The temperature at which the residents feel comfortable suggests customary household temperatures that might aid in minimizing the excessive energy consumption and save the overall energy expenditure of households (Rijal et al., 2015).

Considering the above hypothesis, Rijal et al., (2015) undertook an investigation to understand behavioural approach in Japanese houses by conducting occupant behaviour survey and thermal comfort survey in the living rooms and bedrooms of 120 houses in the Kanto region of Japan. The study correlated comfort temperatures with indoor relative humidity, skin moisture sensation and absolute humidity. This correlation was carried out because according to a study conducted by Fergus Nicol, it was observed that the users felt more uncomfortable in a moist environment even by a small change in temperature as compared to dry environments. His study also suggested that in a humid climatic condition where the relative humidity is higher people usually preferred 1^{o}C lower temperatures to remain comfortable. However, this study by Rijal et al. contradicts Nicol's study by stating that relative humidity does not have a significant impact on the comfort temperature. But, both Nicol and Rijal et al. agree to the role of skin moisture and evaporation in attaining comfort in hot and humid climatic conditions (Nicol, 1974; Rijal et al., 2015). Thus, this paper recommends opening a window and increasing the use of fan when temperature in hot and humid climate rises, as an effective approach in attaining comfort. Moreover, research by Berkeley and Brager et al. (2004) also suggests that an increase in the indoor wind velocity by 1m/s has a potential to raise the indoor comfort temperature by 3 or 4^{o}C. Similarly, research by Nicol (2004) also advocates that the use of air movement has the potential to reduce the indoor temperature by about 4^{o}C.

Hence, the above studies strongly emphasize on the design of the openable windows and the provision of ceiling fans in a hot and humid climate in creating an effective air movement to achieve adaptive thermal comfort.

iii. Study 3: Determining the frequency of open windows in residences: A pilot study in Durham, North Carolina during varying temperature conditions.

Many studies have shown that the Air Exchange Rate (AER) is significantly affected in residences due to the location and number of doors and windows opened. Other factors that influence AER are wind speed, indoor and outdoor temperatures, fans, air conditioners, operation of heaters, wind direction and so on (Wallace et al., 2002; Howard-Reed et al., 2002).

This research points out the lack of information available on the data base of the window opening in creating algorithms such as estimating pollutant concentration in micro-environments. To fill this gap of the lack of empirical data on the opening and closing of windows, a visual survey of doors and windows location in the residences in Durham, North Carolina was undertaken. It also aimed at obtaining data that could be useful to modellers in determining window position with respect to other conditions such as the characteristics of residences, meteorological conditions, time of the day, socio-economic level of the occupants, seasons, population density etc. Thus, for this research census data for the chosen research location was studied, such as total population, population density, percentage of residents below the poverty line, land area and housing unit density. The analysis of the collected information helped in constructing a database on the bases of 1100 residences. Several parameters such as date, time of the day, location, relative humidity, apparent temperature, wind speed and cloud cover were considered while undertaking this research. It also included specific data for each house such as housing type, number of unused doors and windows, exterior material, number of opened doors and windows etc.

Similar to the outcomes from the research conducted by Anderson et al. (2006) in the Danish dwellings, this research by Ted Johnson and Tom Long (2005), *aided in suggesting that residential openness, meaning the opening and closing of the doors and windows is mostly likely to be affected by season, population density, occupancy, housing type, housing density, exterior material, number of doors and windows, presence and type of air conditioning, temperature, wind speed, cloud cover and humidity.*

Thus, it can be said that the percentage of window/door opened is correlated with various additional factors and hence this value will always be different for different households.

iv. Study 4: Adaptive use of natural ventilation for thermal comfort in India and Pakistan

Windows connect the indoors with the outdoors – visually, spatially and physically, by allowing natural light and ventilation into the interiors and by providing external views. But, having windows does not mean that they improve the adaptive opportunity of the building (Nicol and Humphrey, 2002). Based on the above speculation, this research was an investigation into finding the relationship between the use of available adaptive controls and the thermal sensation of the occupants in residential buildings in the hot and humid climate. A survey by Indraganti (2010), recorded the use of environmental controls such as windows, curtains, doors and user comfort responses, which was carried out in five medium-sized residential apartments in Hyderabad, were 113 subjects participated during the summer (May) and monsoon (July) months.

One of the important findings of this research was that it challenged the Indian set standards for comfort (23-26°C) since the analysis suggested that with the neutral temperature at 29.2°C, the comfort band obtained was between 26-32.5°C, hence questioning the data and methodology considered in determining comfort standards for Indian dwellings. It also points out the user preference for balconies which opened in a semi-enclosed private space since they offered better sun protection, privacy and glare control.

Furthermore, this study also discovered that the availability of environmental controls such as windows, doors and curtains were used to attain thermal and visual comfort as the indoor temperature moved away from the comfort band and were effectively used to minimize the heat gain, hot breezes and glare.

In yet another study by Nicol et al. (1999), longitudinal surveys were carried out across five cities in Pakistan, using 25 subjects for a week during the two seasons of winter and summer. This research looked upon the use of different controls by the occupants to modify the indoor thermal conditions as well as their variation in clothing according to the seasons. The outcome of the study highlighted several ways in which the workers in different parts of Pakistan reacted to the wide range of temperatures. They found that the use of fans in summer and layers of clothing in winter was universal. Both the studies, in India and Pakistan, emphasize the lack of adaptive opportunities available to the occupants to ensure comfort both in summers and winters.
Thus, these studies determined the factors for which the adaptive controls were essential, and they were window orientation, sunshades, daylight penetration, privacy etc. and also various other factors that were not taken in to consideration but mattered, such as safety, availability of controls, operation and maintenance of controls, protection from stray animals and birds, mosquitoes and so on.

Both the studies focused on the importance of the provision of 'operability and openability' of a window, careful placement and orientation of windows for better adaptive use of environmental controls.

d. <u>Occupant comfort and operable windows</u>

It is important to note that all the above studies point out to the importance of windows in buildings since they were used to achieve thermal and visual comfort by air movement through building orientation, window orientation and sizes and so on. The studies highlighted how occupant control in operating windows influences occupant thermal-visual control, local thermal-visual conditions and the acceptability of thermal-visual variations. Hence, understanding the influence of windows on the indoor comfort is important because it is greatly influenced by the exterior conditions which significantly affects the radiant heat exchange between the environment and the occupant and also because windows act as the link between the indoor and the outdoor environment (Fig.4.2.).

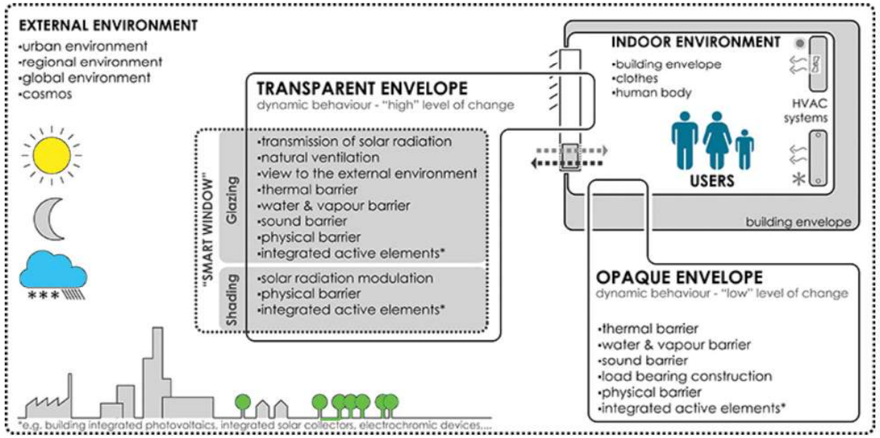

Fig.4.2. Window - as an interface between external and indoor environment. (Intechopen)

Windows tend to absorb and transmit a considerable amount of solar radiation. The temperature of the glass is affected by the absorbed radiation hence influencing the Mean Radiant Temperature of the indoor space (Indraganti, 2010) and a person sitting next to a window experiences heat gain because of the transmitted radiation, which often causes discomfort if it directly falls on the occupant (Arens et al., 1986). In tropical parts of India like Mumbai, thermal comfort is generally not related to the U-value but is closely interconnected with the solar transmittance (Lyons et al., 1999). One such study conducted by Sengupta et al. (2005), demonstrated summer daytime (780W/m2 solar radiation) scenario where a simulated comfort in a room indicated that a change from single glazing to double glazing did not improve the thermal conditions of the room. However, thermal comfort was significantly improved by reducing the glass-to-floor area ratio from 40% to 20%. Considering the above research, it can be said that for hot-humid or hot-dry regions, the occupied zones should receive minimal or no direct solar radiation since higher glass-to-floor area results in higher solar gains and higher illuminance levels, thus creating uncomfortable environmental conditions and ultimately gives rise to the use of mechanical systems to achieve instant comfort. Hence, the increasing number of glass buildings with maximum glazed facades in major Indian cities needs to be reconsidered. Therefore, to achieve minimum solar radiation, building design, window design and effective solar shading devices must be taken in to consideration (Olesen & Parsons, 2002).

All the studies discussed in this chapter also suggests the need to consider solar transmittance and air movement as the two most important factors to obtain indoor comfort. Behavioural adaptations such as window opening and fan use can increase air movement to achieve adaptive comfort, whereas effective shading strategies can reduce excessive solar gains and at the same time also aid in achieving required illuminance levels. Moreover, the above research also lays an emphasizes on the importance of the study of occupant behaviour and various factors that influence their behaviour since they form a significant parameter in explaining the mechanism of the adaptive model. In continuation to the above literature, this research further documents an investigation into finding the relationship between the use of adaptive controls and the thermal-visual sensation of the occupants in residential buildings in the hot-humid and hot-dry climate of Indian cities.

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IMAGE REFERENCES

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Fig.4.1. Abbakyari, M and Taki, A. (2017). The solar fruit tree chart showing the free and costly strategies. Adapted from: Lechner (2014). Available from https://www.dora.dmu.ac.uk/handle/2086/14213 [Accessed 28 September 2017].

Fig.4.2. Kosir,M (2016). Building envelope as an interface between external and indoor environment and corresponding primary functions of the transparent and the opaque part. Available from https://www.intechopen.com/books/automation-and-control-trends/adaptive-building-envelope-anintegral-approach-to-indoor-environment-control-in-buildings [Accessed 28 September 2017].

CHAPTER 5

INTRODUCTION OF CASE STUDIES

Western India : MAHARASHTRA

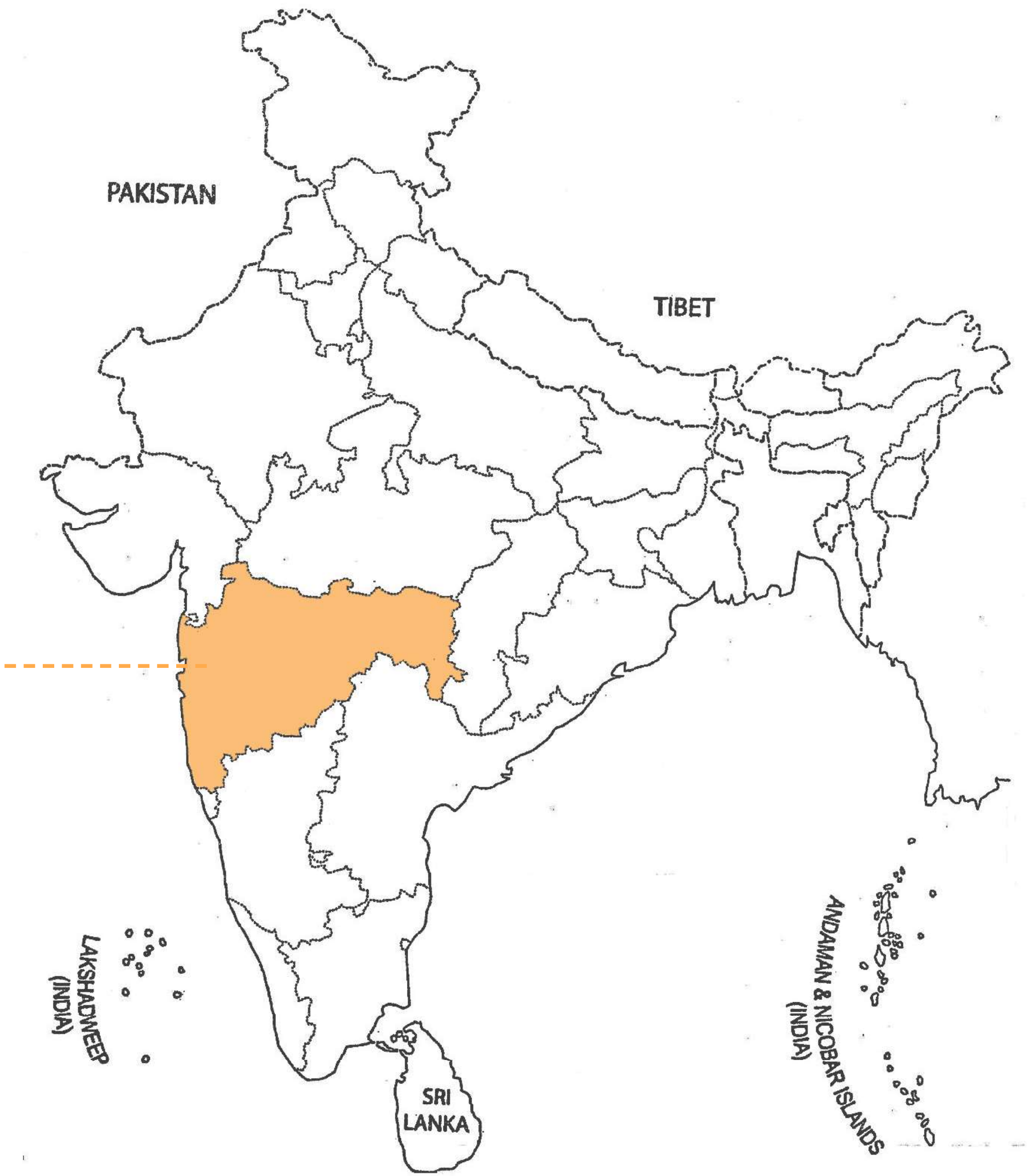


Fig.5.1. India map outline (Pinterest)

Roti (food), *kapda* (clothes) and *makaan* (house), to provide these basic amenities to its population has been the main objective of the Indian government post-independence till this date. According to the 2011 census, 13.7 million households in Indian cities live in the informal settlements. Around 64 million people live in these slums which is about 17.4% of the total urban population of India (Kaul, 2015). To cater to the issue of housing, the present government has launched 'Pradhan Mantri Awas Yojna' that aims to provide 20 million homes by 2022 (National Building Organization, 2016). While, the government as well as the private bodies are building millions of homes all over India, very little attention is being given on the sustainability of these homes. There are no major guidelines available regarding the quality of life that needs to be provided since the scheme talks only about supplying a certain number of houses.

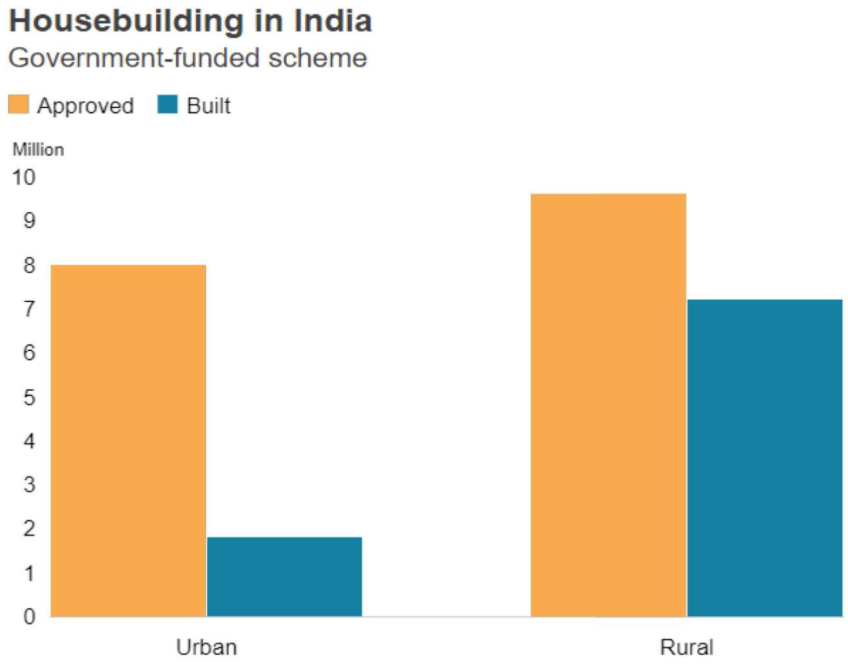


Fig.5.2. Housebuilding in India (BBC)

Apart from constructing new affordable housing by the government of India, the other type of residential uprise is of redevelopment projects. There are two reasons for this uprise. One is the amendment to the Maharashtra Apartment Ownership Act (MAOA) which allows the redevelopment of old buildings with 51% consent from apartment owners, as opposed to 100% owner consent (Rawal, 2018). It means that if 51% of the total apartment owners of a building are willing to demolish their old building and construct a new one, it is allowed and very much possible. It is expected that this will allow the reconstruction of old residential buildings at a much faster rate. This is to speed up the development plan of a city like Mumbai and provide the owner with better living spaces. However, it is also argued that the developers have a greater advantage since there are high chances that the redevelopment would turn out as per the developer's preferences rather than the owner's requirements, which might be to retain the culture, tradition and relations that are built over time. The second reason for the uprise, especially in the city of Mumbai, is the 'Self-Redevelopment Scheme 2018'. This scheme allows the co-operative housing societies to redevelop their buildings on their own without handing it over to the developer (Dhanorkar, 2019). A single window system to acquire all the permissions makes it easy for the housing societies to avoid unwanted delays, which means that all the required permissions to construct a new building can be obtained from the town planning department at the same time without having to go to the different authorities. The Maharashtra Housing and Area Development Authority (MHADA), the supervisory authority, also provides the housing societies with a panel of professionals such as architects, contractors and so on required for the redevelopment along with loan provision from the Central Cooperative Bank (Jain, 2018).

The government is adopting all the necessary steps that can aid in providing housing for the growing population. However, contrary to the government's agenda to provide housing for all, some reports suggest that the housing demand of the country is already met. According to these reports about 10.10% urban homes and about 6.2% of homes in the rural areas lie vacant (Mammen, 2017) (Sharma, 2018). It is the unaffordability of these homes that leave them unoccupied. At present, millions of dwellings are being constructed and with millions of newly constructed unoccupied dwellings, there are very few reports on how sustainable these residential blocks are or will be. Neither does 'Housing for All' scheme looks into the issue of sustainability of the millions of homes nor the existing buildings have integrated any features in terms of design, material or construction techniques to make them sustainable. Hence, although the Indian government might be able to provide the basic necessity of housing for everyone, there lies a more serious issue of providing sustainable and low-energy consumption housing stock.

Therefore, looking at the rapid growth in the housing sector it is of utmost importance to identify and reform the current housing trends to reduce the possible substantial amount of energy that is being consumed and will be consumed in future (refer Chapter 01, p15).

For this reason, this chapter looks at two different urban areas, one that is already a mega-city and the other that is a developing city, with two different climatic conditions i.e. hot-humid and hot-dry. The field studies are of three completely diverse housing typologies within these cities, that are either trending apartment designs at present or hold rich historic importance and are climatically responsive buildings. The three case studies chosen are as follows:

1. **Apartment, Andheri (Mumbai) (Fig.5.3.)**
2. **Chawl, Parel (Mumbai) (Fig.5.4.)**
3. **Wada, Shivaji Peth (Kolhapur) (Fig.5.5.)**

The reasons for selecting these buildings are described below:

1. Apartment (Fig.5.3.): It was important to first and foremost understand the ongoing housing trends in Indian urban areas such as Mumbai. It was essential to look at the current design of residential structures, the materials used, the technology, the comfort of the occupants, their pleasure or displeasure over their living spaces and if there was any room for improvement. The focus of this study, however, was to understand the comfort condition of the user.

Since the research focuses on the importance of windows, it was essential to identify the common window trends, their contribution to the indoor environment, to the comfort of the user, their role in creating social interaction and their importance in the daily life of the user. It was important to analyze the current trend in window design, user satisfaction and dissatisfaction regarding the same so that suggestions could be made in terms of design, materials or techniques to further improve the role of windows in creating indoor environmental comfort and be affordable as well.

2. *Chawls (Fig.5.4.):* They are considered as buildings that are designed in a way that enhances the social and cultural essence of the occupants. It was necessary to study these 80-year-old dwellings be-

cause even today they have the potential to provide indoor thermal and visual comfort to its user. In spite of being tiny usable spaces, these units are preferred by the occupants over apartments. Hence, it was essential to look into the quality of life these spaces provided and highlight the role of openings in providing better living conditions to the occupants in a dense city like Mumbai.

3. *Wada* (singular) (Fig.5.5.) *or wadis* (plural) are about 125-year-old residential units. The design of the built form, the use of materials, the openings are some of the factors that contribute to the comfortable indoor environments of these spaces even today. It was, there-

Fig.5.3. Apartment

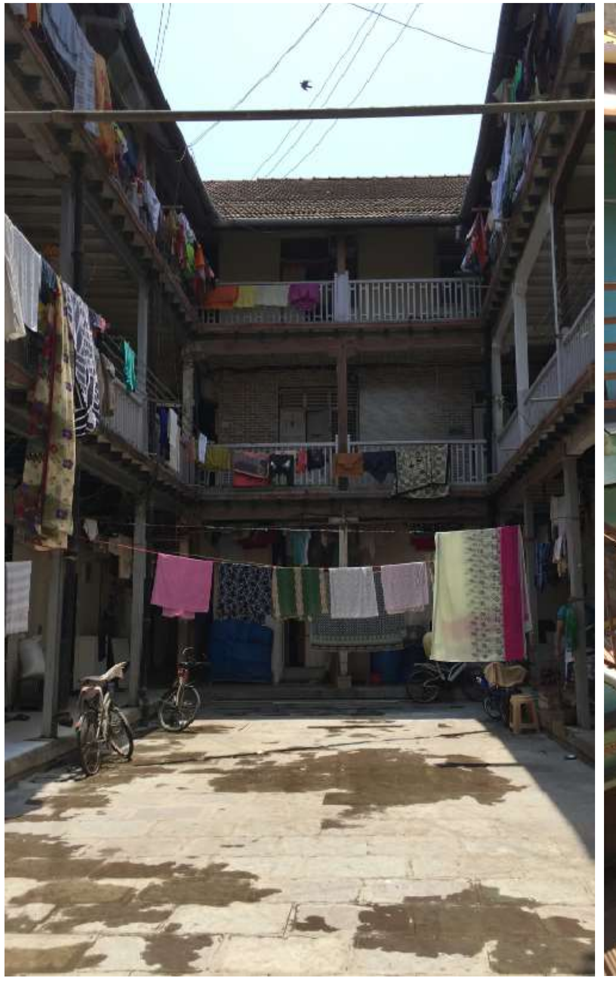


Fig.5.4. Chawl

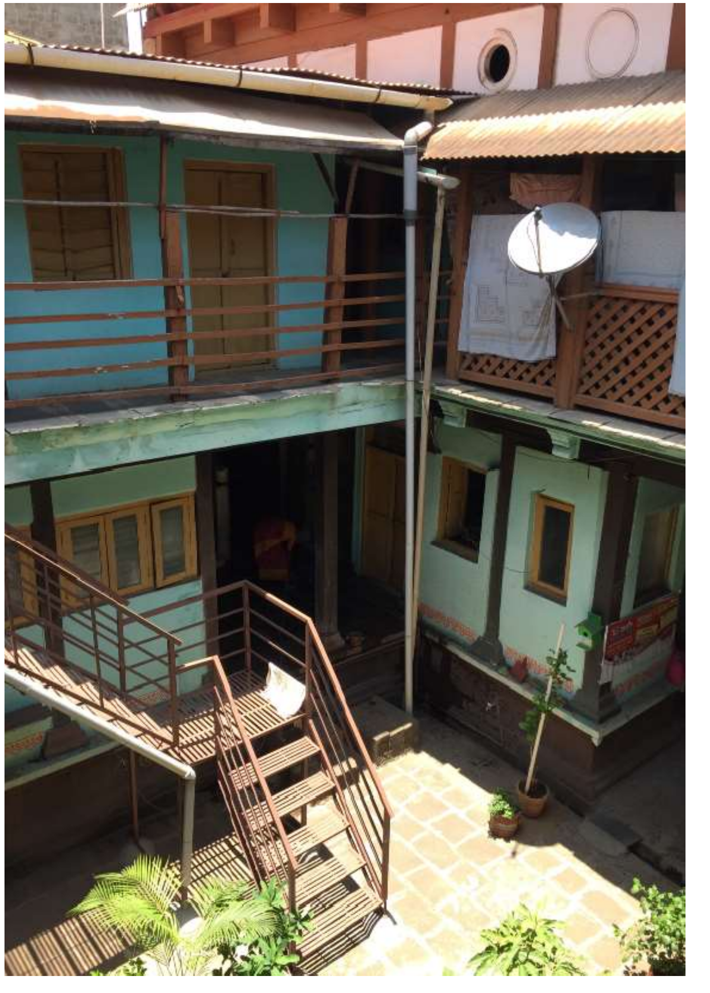


Fig.5.5. Wada

fore, essential to understand the influence of these elements in creating such an environment and address the role of windows in doing so.

The aim of taking up these three completely diverse housing typologies was mainly to identify their window systems. To explore how they performed in the current climatic conditions and the present urban settings and how affordable they were. With the three housing typologies, 3 window types that were identified are as follows:

1. The Contemporary Window from an Apartment, Andheri (Mumbai)

2. Hot & Humid Window from *Chawl*, Parel (Mumbai)

3. Hot & Dry Window from *Wada,* Shivaji Peth (Kolhapur)

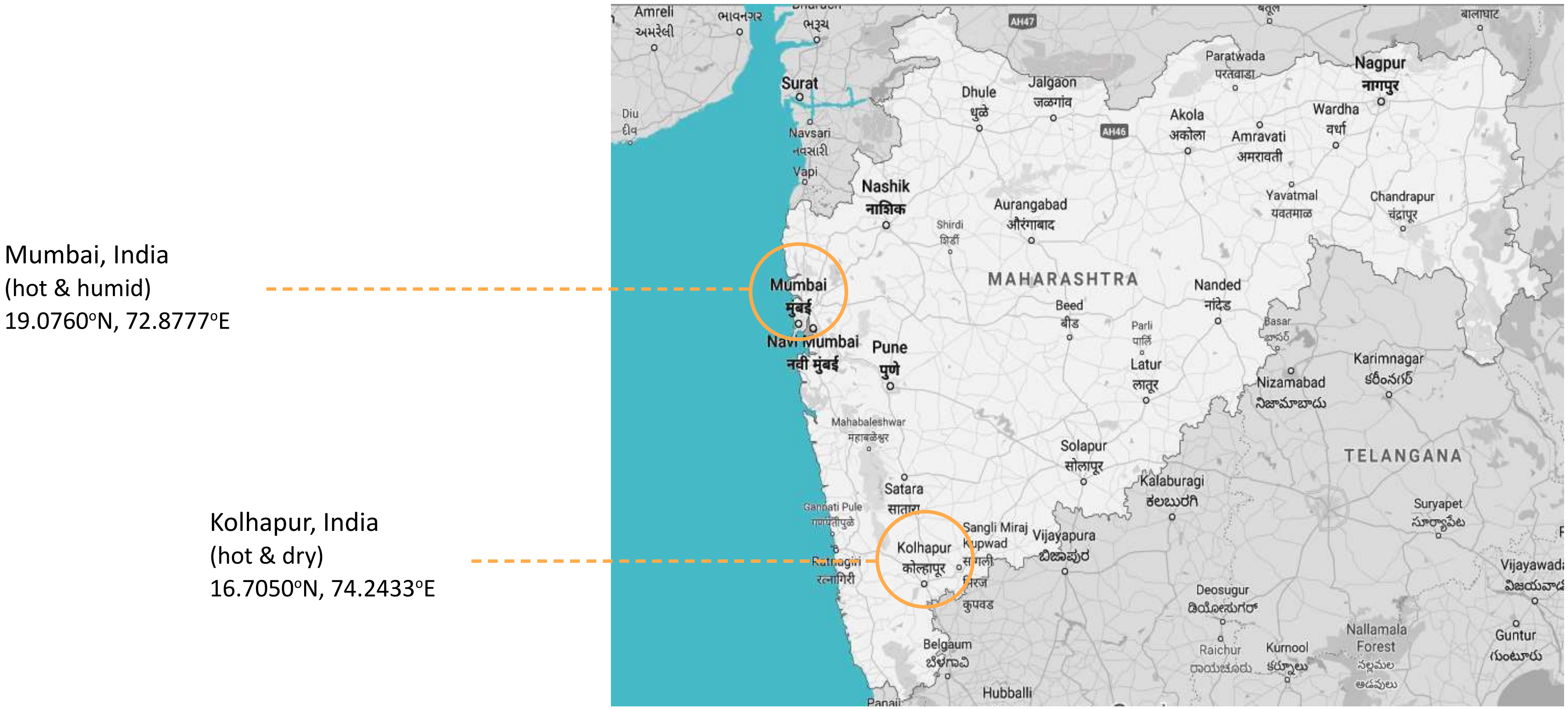


Fig.5.6. Location of Mumbai and Kolhapur (Google Maps)

WEATHER DATA

FOR MUMBAI

Meteonorm, an online weather source, was used to acquire weather data for Mumbai region. A climate database that has been developed for over 30 years, is based on the data collected from various weather stations throughout the world and from geostationary satellites (Remund, 2018). For radiation parameters, the data period is 1991-2010 whereas for parameters such as temperature, wind speed, humidity etc., 2000-2009 data periods are available. Meteonorm produces monthly, daily, hourly files and is available in various predefined formats for different building simulation software.

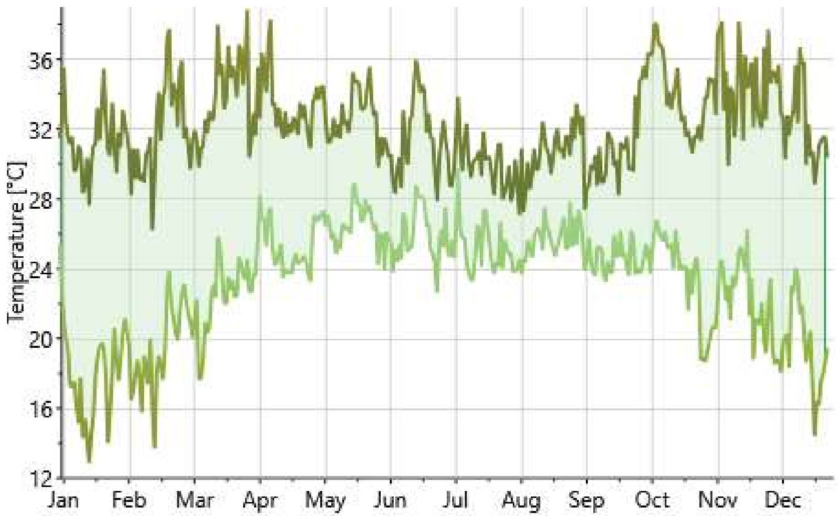


Fig.5.7. Daily Annual Temperature (Minimum & Maximum) - Mumbai (Meteonorm)

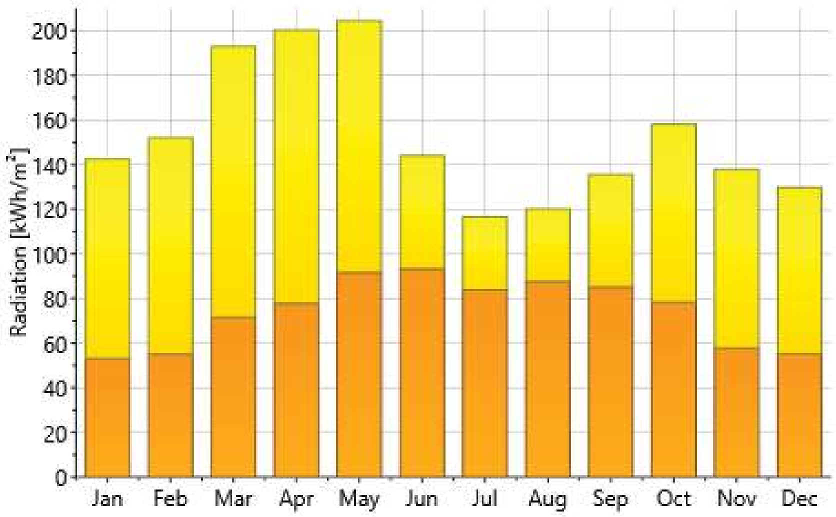
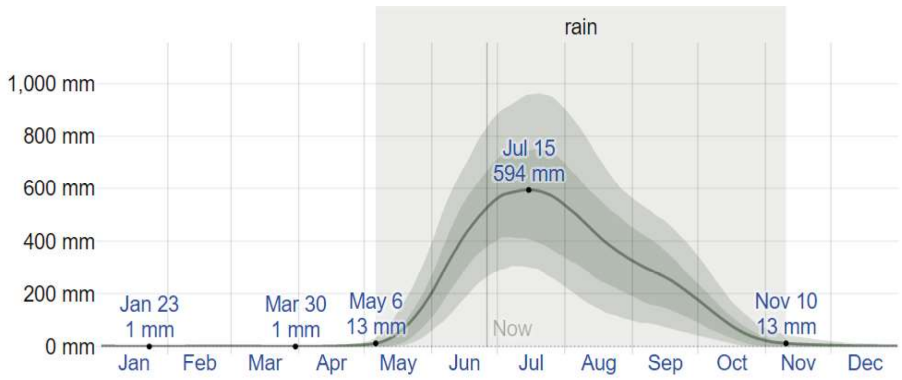


Fig.5.8. Solar Radiation (Global and Diffused) - Mumbai (Meteonorm)

Apart from Meteonorm, Weatherspark was also used to acquire weather data for Mumbai region for which the geographical coordinates taken for the city were 19.0760ºN, 72.8777ºE.

The Climate:

The weather of the city can be distinctly categorised into three main seasons of summer (March-May), monsoon (June-September) and winter (November-February). The first graph represents the annual maximum and minimum temperature (Fig.5.7) recorded for Mumbai, whereas the second graph shows global and diffused solar radiation (Fig.5.8) received. Comparison of both the graphs indicates that the maximum temperature recorded during the summer months – from March till May is when the temperature crosses 36ºC mark and receives the highest solar radiation. The maximum and minimum temperature difference during winters and summers



The solid line is the average rainfall over the course of 31-days while the thin dotted line is the corresponding average rainfall.

Fig.5.9. Average Monthly Rainfall - Mumbai (Weatherspark)

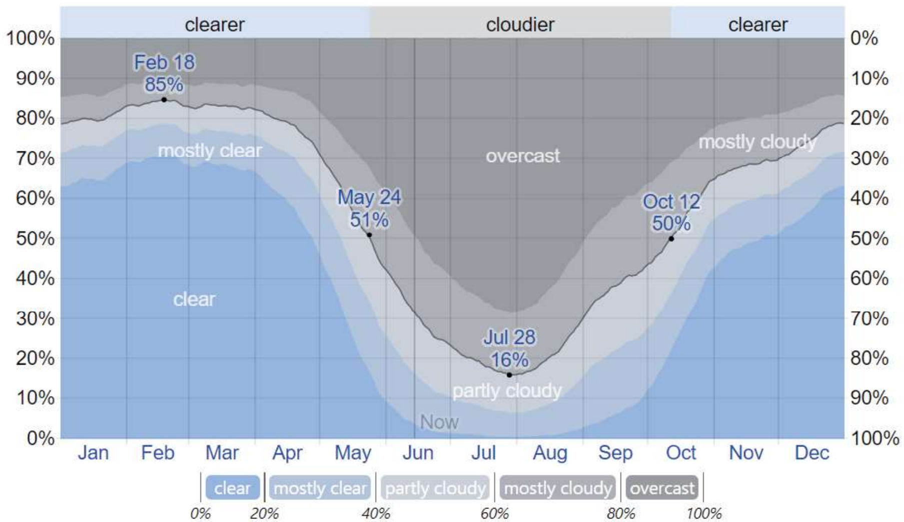


Fig.5.10. Cloud Cover - Mumbai (Weatherspark)

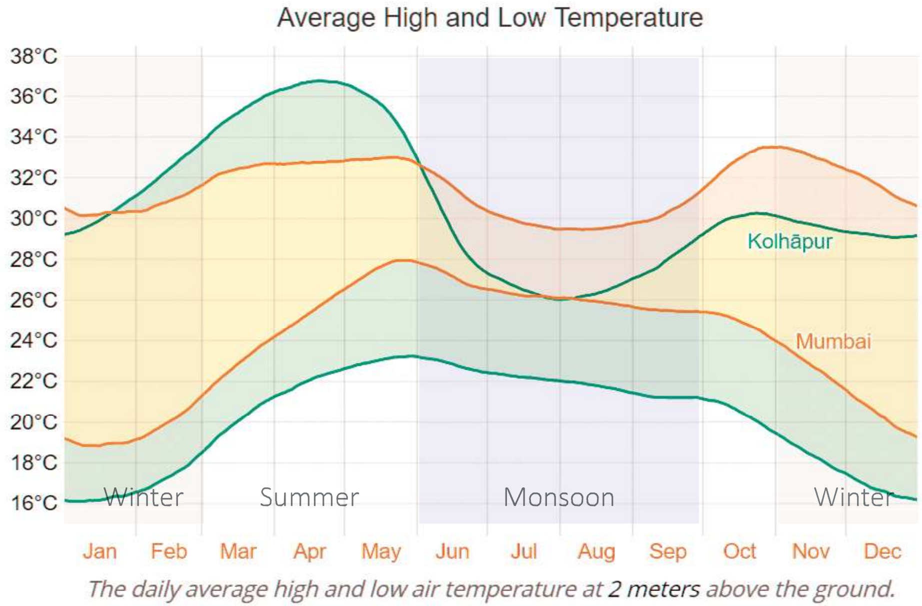
Fig.5.11. Share of Wind Direction- Mumbai (Meteonorm)

is greater as compared to the monsoon period. The city experiences rainfall from May end till October with maximum rainfall during the month of July. Although the skies are generally clear in the city throughout the year, the maximum number of overcast skies are observed during the months of monsoon. The lower solar radiations (Fig.5.8) received due to overcast skies during monsoons (Fig.5.10) result in lower daytime temperature (Fig.5.7). Thus, except for the monsoon season, the temperature soars during the day due to high solar radiation, while at night it drops.

With respect to winds, Mumbai mostly receives west, southwest and northwest winds (Fig.5.11) throughout the year.

CLIMATE COMPARISON

The climatic data analysed here is taken from Weatherspark.com. This website was chosen over Meteonorm because the climatic data for Kolhapur (the 2nd city) was not available with Metonorm but with the later. The graph on the right-hand side compares the daily average high and low air temperatures of Mumbai and Kolhapur since the housing typologies from these two cities are studied further. It is important to compare the climate of both the regions just to understand the similarities as well as the differences with respect to the climate and to determine the potential of bio-climatic features that can be in-cooperated in the window design of the habitats of these places.



The graph illustrates the typical weather for Kolhāpur and Mumbai, based on a statistical analysis of historical hourly weather reports and model reconstructions from January 1, 1980 to December 31, 2016.

Fig.5.12. Daily Average Low and High Temperature of Mumbai and Kolhapur. (Weatherspark)

Temperature

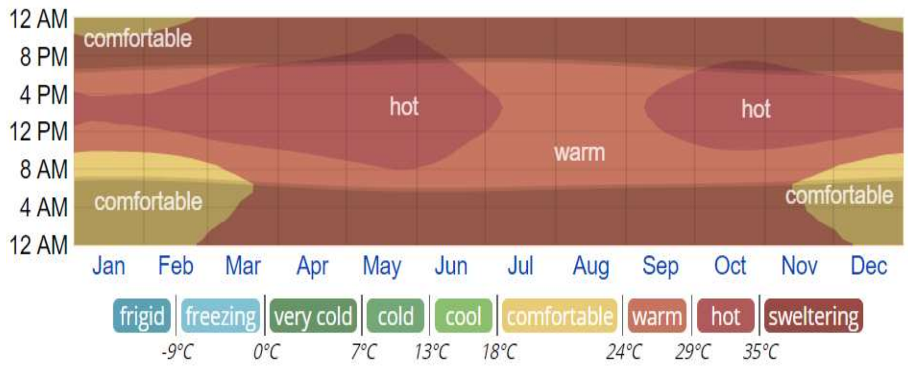
Throughout the year the temperature in Mumbai varies between a minimum of 19°C and maximum of 34°C. Seldom the temperature drops below 16°C or rises above 37°C. Whereas in Kolhapur the temperature during summers can be as high as 38°C and as low as 16°C during the winter season. Also, being close to the coastal belt, the air in Mumbai always contains lot of moisture, due to which the temperature throughout the year in Mumbai does not fluctuate a lot as compared to the temperature in Kolhapur that experiences a high fluctuation in summer and monsoon temperatures (Fig.5.12.).

Another observation is the greater difference between high and low air temperatures in Kolhapur especially during the summer months. On the same day, the day-time temperature in Kolhapur during summers can be as high as 37°C and can be as low as 22°C i.e. a temperature difference of 15°C. On the other hand, the maximum and minimum temperature difference during monsoons is lower in Kolhapur and further lower in Mumbai. This is due to higher humidity levels during the monsoon season and comparatively cooler temperature. It should also be noted that, before the onset of winter, both the cities experience the 'October heat'. During this time the southwest monsoon winds start withdrawing gradually from the Indian sub-continent, thus marking the transition from hot rainy season to dry winter season (Guwalani, 2009).

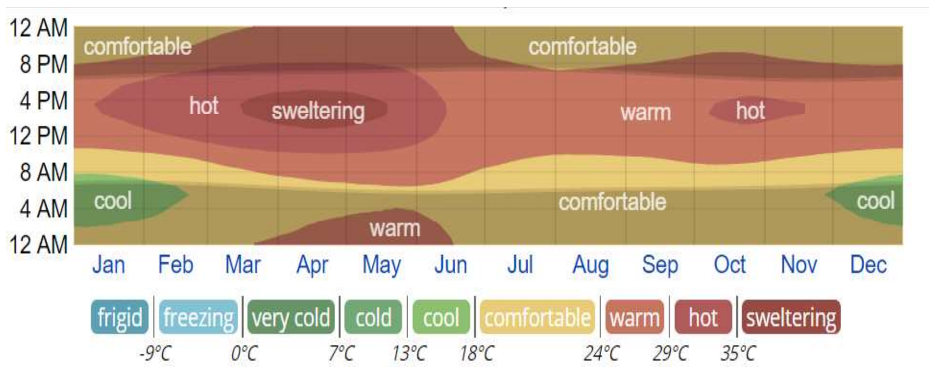
Furthermore, the figures below give a compact characterization of the average hourly temperature throughout the year for Mumbai and Kolhapur (Fig.5.13.(a) (b)).

The temperature in Mumbai is generally comfortable at night during winters i.e. from 8 pm to about 7 am. However, the summer nights, as well as the nights during the monsoon season, are comparatively warmer. With respect to Kolhapur, which experiences hot and dry climate, the winter temperature at night time can be very pleasant and cool. Although the summer and monsoon nights are relatively comfortable i.e. the temperature during this time is between 18°C to 24°C, the summer nights, especially from May-June are warm.

The daytime climatic condition in Mumbai is warm for a maximum period, irrespective of the season, while Kolhapur ranges from comfortable to warm to sweltering (Fig.5.13.(b)). The period from 12 pm to 4 pm is usually hot in Mumbai, especially during the summer and winter season. While the summer months in Kolhapur can be extremely hot i.e. the daytime temperatures crosses 35°C. Similar high temperatures in both the cities were also noted during the fieldwork and were recorded during continuous measurements as well and are presented later.



5.13.(a). Mumbai, India



5.13.(b). Kolhapur, India

The average hourly temperature, color coded into bands. The shaded overlays indicate night and civil twilight

The graph illustrates the typical weather for Kolhāpur and Mumbai, based on a statistical analysis of historical hourly weather reports and model reconstructions from January 1, 1980 to December 31, 2016.

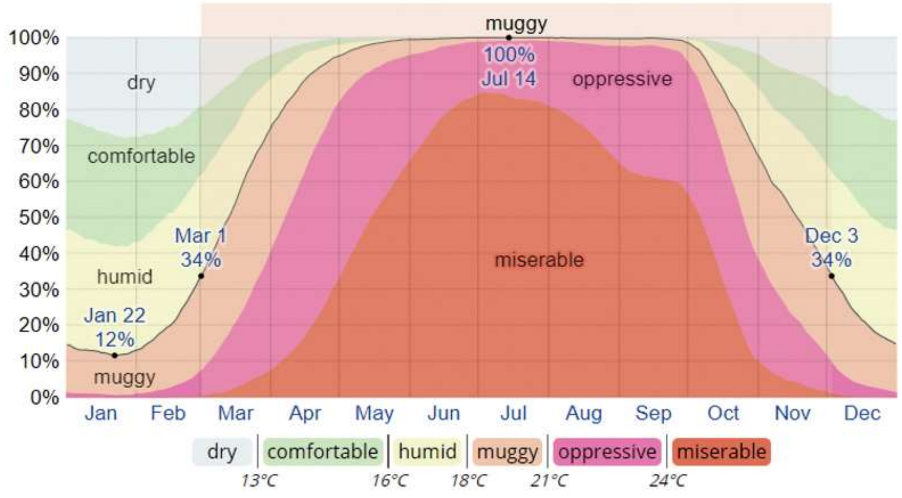
Fig.5.13. (a) (b). Climate Comparison of Mumbai and Kolhapur - Average Hourly Temperature.
(Weatherspark)

Humidity (Fig.5.14 (a) (b))

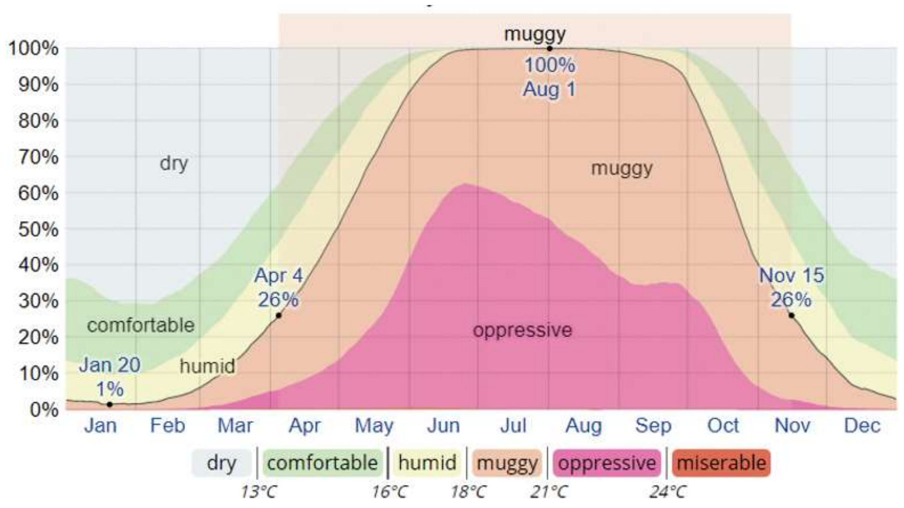
The data for humidity from Weather Spark, a weather database, is based on dew point. Since dew points regulate if perspiration will evaporate from the skin, higher dew points feel more humid which means less evaporation of perspiration and lower dew-points feel drier. Dew point temperature changes slowly as compared to temperature, which means a muggy day is followed by a muggy night.

With three distinct seasons of summer, monsoon and winter, Mumbai experiences the maximum number of muggy days which is about 9 months (Fig.5.14.(a)).

Being away from the coastal belt, Kolhapur has a pleasant climate with respect to humidity. The humidity levels are higher for about 7 months, but as compared to Mumbai are still much more comfortable (Fig.5.14.(b)). Thus, it can be said that both Mumbai and Kolhapur experience higher temperatures, especially during the summer months and most of the year, is also hot. Due to the proximity to the sea, Mumbai encounters higher humidity levels because of which the night time temperature does not drop drastically as otherwise seen in Kolhapur. Hence, the nights in Kolhapur are relatively pleasant while Mumbai experiences warm nights almost throughout the year.



5.14.(a). Mumbai, India

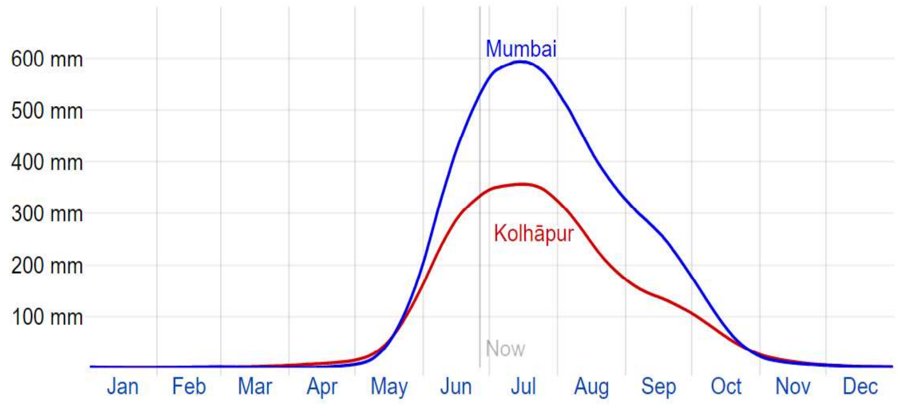


5.14.(b). Kolhapur, India

Fig.5.14. (a) (b). Climate Comparison of Mumbai and Kolhapur - Humidity Comfort levels. (Weatherspark)

Average Monthly Rainfall (Fig.5.15)

The graph indicates a distinct monsoon season, for both Mumbai and Kolhapur that begins in the month of May. The highest rainfall received by both the cities is in the month of July. As compared to Kolhapur, Mumbai experiences higher rainfall. Thus, apart from the close proximity to the sea, the high humidity levels in Mumbai (Fig.5.9 (a)) can be also be correlated with the higher rainfall levels during the monsoon period.

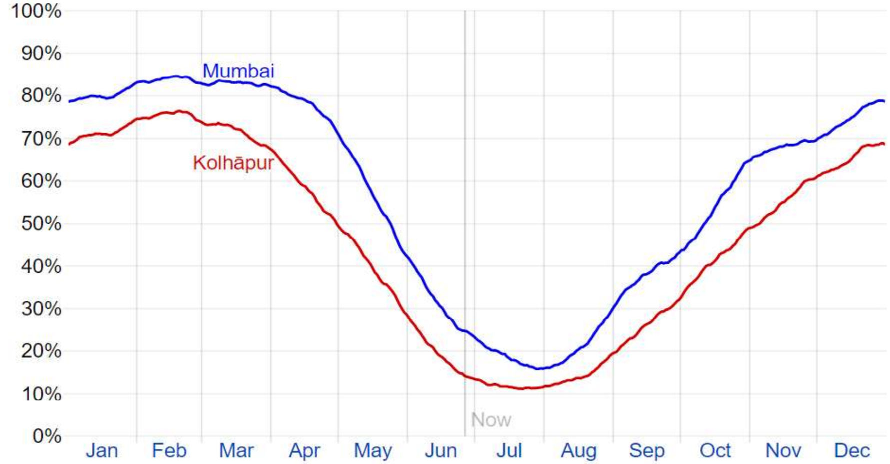


The average rainfall accumulated over the course of a sliding 31-day period centered on the day in question.

Fig.5.15. Climate Comparison of Mumbai and Kolhapur - Average Monthly Rainfall. (Weatherspark)

Chances of Clearer Skies (Fig.5.16)

Although Mumbai experiences higher rainfall, the percentage of clear skies in Mumbai, throughout the year, is greater as compared to Kolhapur. The percentage of clear skies in Kolhapur is between 40 to 70% during the summer and winter months and drops to about 10 to 40% during the monsoons. Whereas, in Mumbai, the percentage of clear skies is between 50 to 90% during the summer and winter months and drops to about 18 to 40% in the monsoon season.



The percentage of time the sky is clear, mostly clear, or partly cloudy (i.e., less than 60% of the sky is covered by clouds).

Fig.5.16. Climate Comparison of Mumbai and Kolhapur - Chance of Clearer Skies. (Weatherspark)

Reflections:

The climate of Mumbai can be summarised as hot and humid with heavy monsoon. Being close to the sea, the humidity levels in the city are high throughout the year.

The climate of Kolhapur can be summarised as hot and dry. The amount of rainfall received in this region is comparatively lower than Mumbai.

MUMBAI

the city of dreams

Andheri, Mumbai
19.1136°N, 72.8697°E

Parel, Mumbai
19.0213°N, 72.8424°E

Fig.5.17. Field-study sites - Andheri & Dadar (Google Maps)

Brief History of Mumbai:

The city of seven islands (Fig.5.18.) was a fishing hamlet until the 16th century. In the 1630s, this city was surrendered to the Portuguese by the Mughals, who named the city as ‘Bom Bai’ or ‘the Good Bay’ (Risbud, 2001). In 1662, King Charles II of England was gifted this Portuguese territory as dowry, which was then rented out by the King to the East India Company (Clark and Moonen, 2014). It was during this time that the city saw a distinct transformation. The building up of ports, customs house, warehouses, causeways, hospitals, forts and castles attracted people from within the country as well as from Britain to invest in this territory. By 1864, Mumbai was connected with rail services with the cotton-growing areas, which led to the growth of cotton textile industries. The emergence of various job opportunities led to a great influx of skilled and unskilled labour from various parts of the country. Hence, over the years this fishing village evolved to become an industrial hub to the financial and commercial capital of the country.

Today, it is the most globalized city in South Asia with major corporate headquarters, centre for foreign investments and joint ventures. It is a hub for small entrepreneurs. Mumbai is home to the economic centres of the State Bank of India and Reserve Bank of India (Risbud, 2001) (Clark and Moonen, 2001). However, with the overall progress, the city is also simultaneously experiencing growth in terms of population and simultaneous growth in housing demand. At present, the population of Mumbai is estimated to be over 22 million with a population density of approximately 73,000 per square mile (Census, 2011).

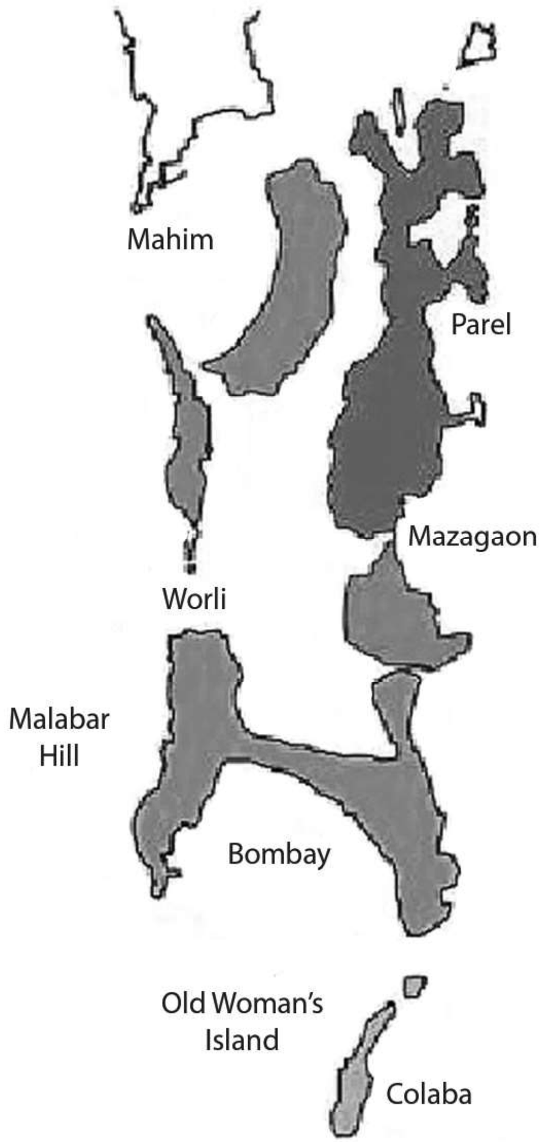


Fig.5.18. The Seven Islands (Housing.com)

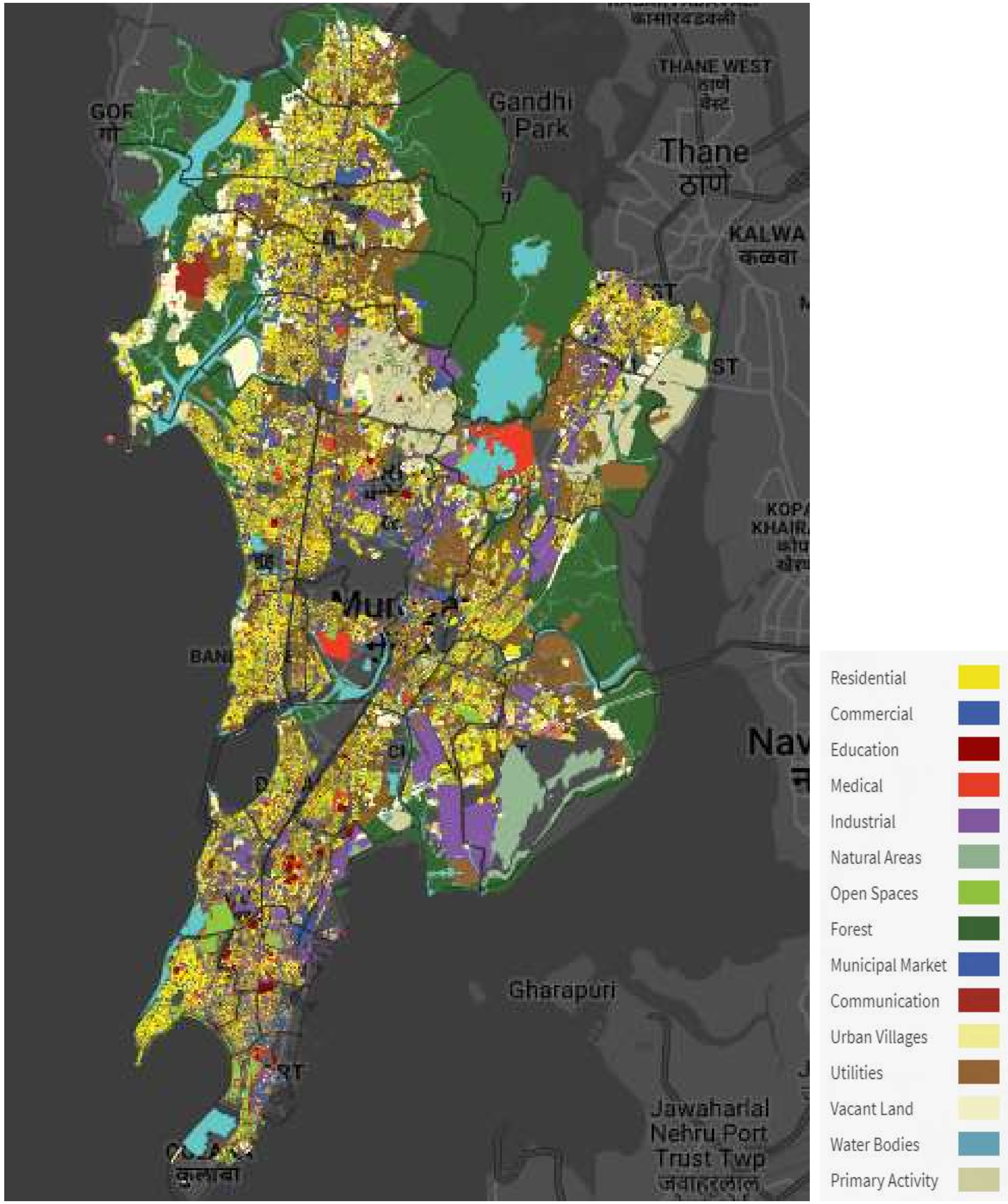


Fig.5.19. Land-use Plan of Mumbai (Mumbai Data)

Brief History of Housing in Mumbai:

Over the years the city of Mumbai has constantly evolved along with a simultaneous rise in population. There have been rulers, locals, migrants, visitors belonging to different parts of the world as well as the country, who made Mumbai as their 'home'. Each settler brought-in their own culture and living style. Hence, like various trades, Mumbai has a timeline of the development of various residential typologies as well.

Some of the prominent typologies are described briefly below:

- ***Gaothans*** (Fig.5.20.): which means villages, were once was a prominent part of Mumbai's landscape. It consisted of bungalows lined together along narrow alleyways (Shetty et al., 2007). These were mainly owned by the Maharashtrian community. Today, these more than 100-year-old *goathans* are almost non-existent.
- ***Chawls*** (Fig.5.21.)**:** In 1856, the American Civil War that led to the discontinuation of cotton supply to England marked as the main reason for starting up the industrialization process in Mumbai (Sassen, 2007). This period is known as 'Cotton Boom' were textile mills were set up in Mumbai (Sanyal, 2018). Apart from cotton other industries such as shipbuilding, dyes, tram and railway workshops, chemicals, oil and paper mills were also set up which led to the creation of hundreds of job opportunities. Thus, during this period Mumbai saw a great influx of people, especially from the rural areas of India migrating to Mumbai. To cater to the growing housing demands, private entrepreneurs bought land close to the industrial areas and built one-room apartments with shared toilet facilities. These buildings were called '*Chawls*' (Shetty et al., 2007).

Fig.5.20. Khotachiwadi (DNAIndia)

Fig.5.21. Haji Kasam Chawl (Flickr)

- **1st Apartments** (Fig.5.22.)**:** The Bombay Improvement Trust (BIT) was set up in 1899-1900 following the plague epidemic of the 1890s (Global Energy Network Institute). This trust aimed to construct a planned suburban scheme in Mumbai to relieve the growing housing crisis in the city. Approximately 440 acres of land was developed with residential buildings that were 3 storeys high with proper in house sanitation facilities. Hindu Colony and Dadar Parsi colony are some of the examples of the first planned apartment type housing in the city and probably also the first in the country (URBAN, 2012). These apartments saw a prominent influence of the Art Deco style of architecture, which featured environmental design elements (Marpakwar, 2015). According to Jon Lang (2002), in his book 'A concise history of modern architecture in India', he specifies some of the environmental design features used in these buildings, like, central air shaft, horizontal projecting surfaces to protect the indoors from the eastern and western sun, operable windows to work during power failure, cement *jaalis* and so on. Even today, Mumbai has the highest number of Art Deco buildings in the world (Thomas, 2017) and the most extensive examples can be seen in Churchgate, Malabar hill, Cumbala hill and Bandra areas of Mumbai.

Fig.5.22. A Building in Parsi Colony (Suitcase of Stories)

With the success of the 'apartment typology', Mumbai then saw a rise in the number of apartment buildings. They were now built by government agencies for the high-income group, middle-income group, low-income group, by private developers etc. Although they were not built in Art Deco style, yet they had a similar basic concept of generous room sizes (as compared to the *chawls*) with separate rooms for sleeping, living and cooking. They also provided privacy in terms of in-house sanitary facilities as opposed to the facilities provided in *chawls.*

- **Slums** (Fig.5.23.)**:** 902,015 huts in 2335 pockets were identified by the State Government in the 1st official slum census report (Risbud, 2001). The constant rise in population meant increased demand for housing in Mumbai. The unaffordable transport system led to encroachment of open public and private spaces, which gave rise to the haphazard development in the form of sheds or huts with bare minimum civic facilities and extremely poor living conditions. Today, Mumbai is also very well-known for the largest slum in Asia known as 'Dharavi'.

Fig.5.23. Housing in Dharavi.
(Development Works)

- **High-rise Residential Buildings** : According to Dobrucka (2014), who has produced a series on 'The Life on a New High', states that Mumbai is experiencing a boom in high-rise building construction with more than 15 buildings taller than 300 meters under construction, were 2500+ high-rise buildings are already constructed (Frearson, 2014) (Kavilkar and Patil, 2014). With international designers designing them, these high-rises are transforming the cityscape along with the lifestyle of the user. The need for high-rise buildings is the growing population and limited piece of land (Misra, 2015). Thus, although Mumbai is experiencing this boom in the high-rise residential sector (Fig.5.24.), it is estimated that the city has enough vacant apartments, but lie vacant since they are unaffordable and are high maintenance for the low-income group as well as the middle-income group population (Das et. al., 2018).

In spite of the unaffordability issue, the Indian cities are experiencing a boom in the construction of high rise residential buildings, it is a trend which is multiplying at a very fast pace. This trend has also brought with it a repetitive mode of construction style of residential buildings. With the difference in the quality of materials, construction work, fittings such as doors, windows, floorings and so on, the basic design strategy is the same for all the high-rise residential construction. Since this research focuses on windows, if we look at the current window design trend, it leads us into a thought process of how to make it more sustainable, affordable as well as more adaptive and user-friendly. Therefore, the main aim of this research becomes the analysis of architectural as well as the environmental performance of windows and to find out how climatically responsive they are and to what extent they benefit the user in terms of comfort.

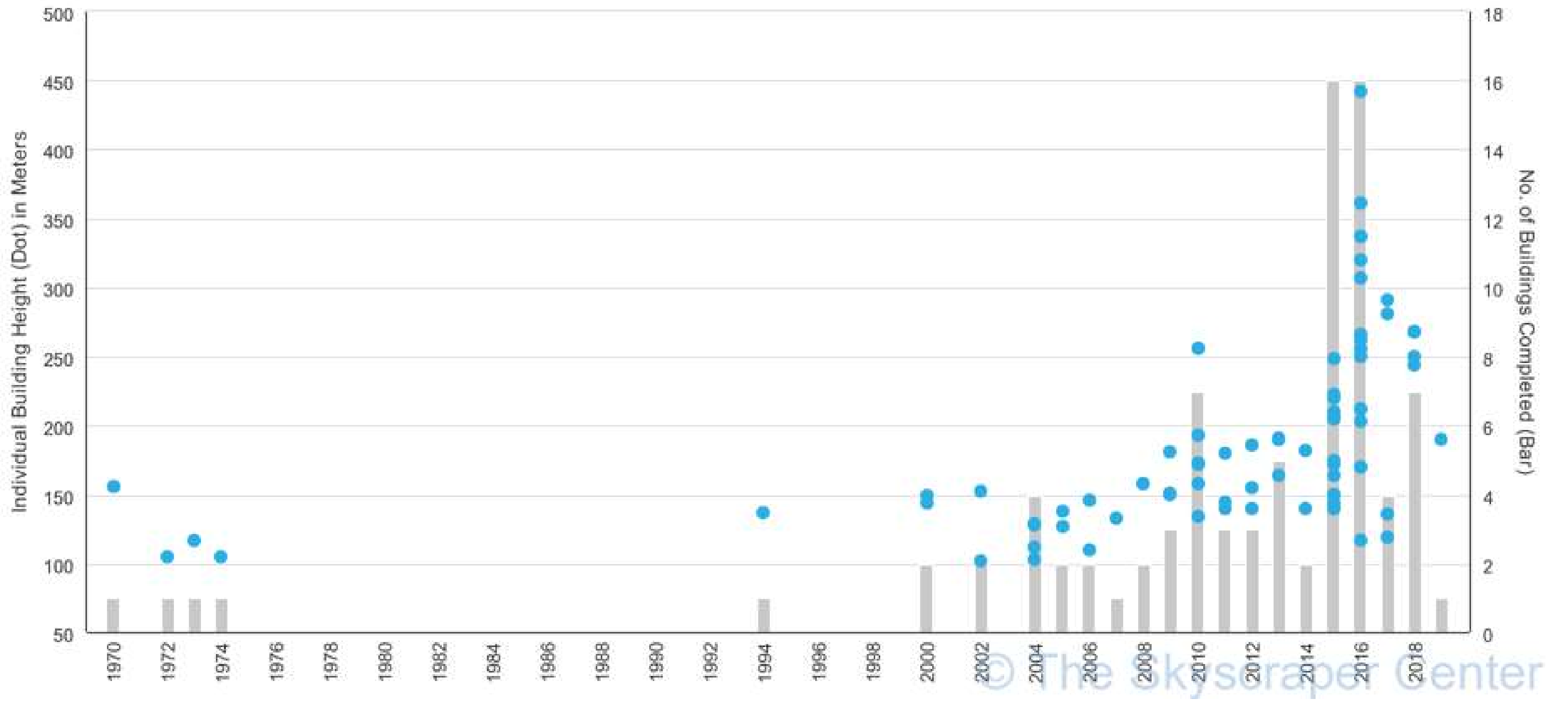
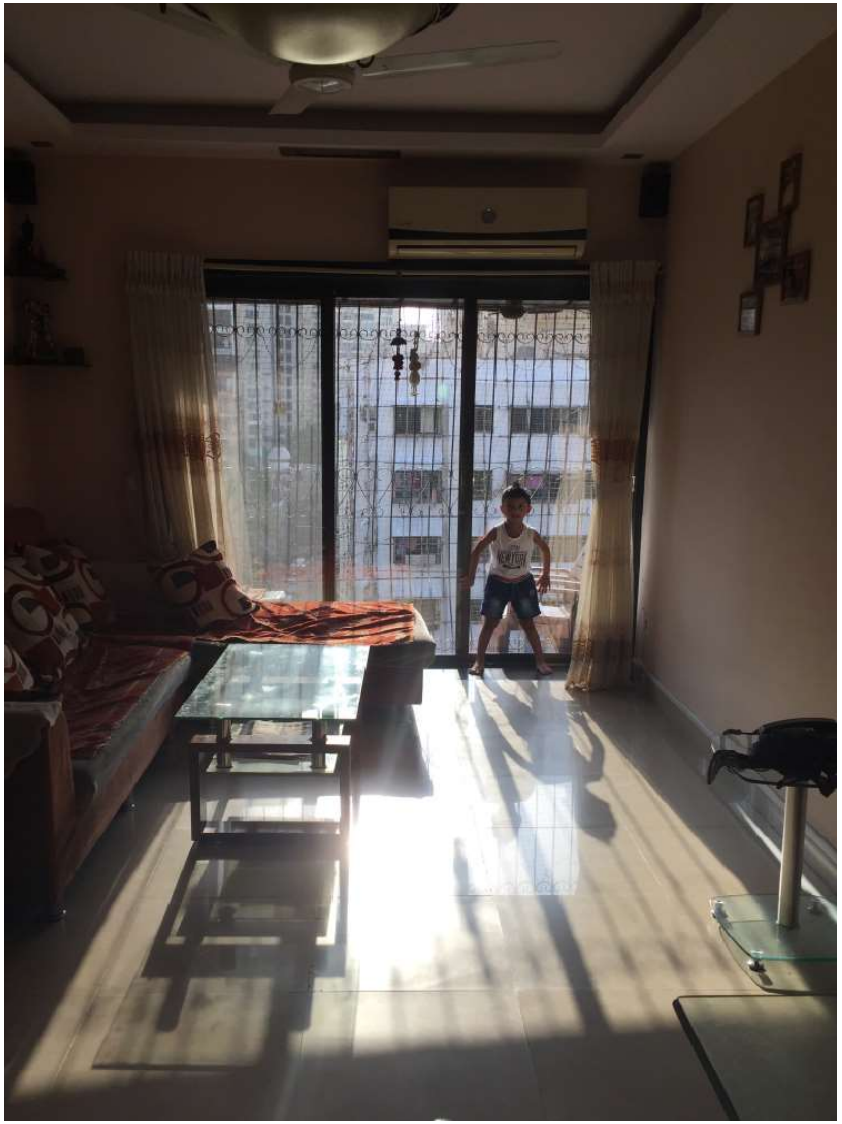


Fig.5.24. A timeline of highrises built in Mumbai shows the construction boom of recent years (Citylab)

The Contemporary Window from an Apartment
Andheri (Mumbai)



APARTMENT INFORMATION

Name of the Residential Building: Panorama Tower, Andheri, Mumbai

Built in: 2005 (which means that the building is about 14 years old)

Number of Floors: G+18

Built by: Prathamesh Builders.

APARTMENT NUMBER: 703 on the 7th Floor

Owner: Mr. Oza

Area of the apartment: 70 sq.m.

Fig.5.25. Panorama Tower Location.
(Google Maps)

The co-operative housing society is located in the sprawling suburbs of Mumbai known as Andheri (Fig.5.25.). Panorama tower (Fig.5.27.) (highlighted in yellow) is located along the Veera Desai Road (orange dotted line). With proximity to Mumbai Metro and the Western Express Highway, this tower is surrounded by high rise buildings on all three sides (highlighted with blue). The front face of the building is parallel with the main road, followed by a public and private park (highlighted in green).

The Ground+18 tower comprises of 94 apartments (Fig.5.26.) and was built in 2005 by Prathamesh builders and designed by Design Duo. The cosmopolitan building is maintained by the residents themselves, where each resident is charged a monthly maintenance fee according to the area of their apartment. The building consists of 1BHK, 2BHK, 3BHK and 4 BHK apartments. *(Note: BHK - Bedroom, Hall, Kitchen).*

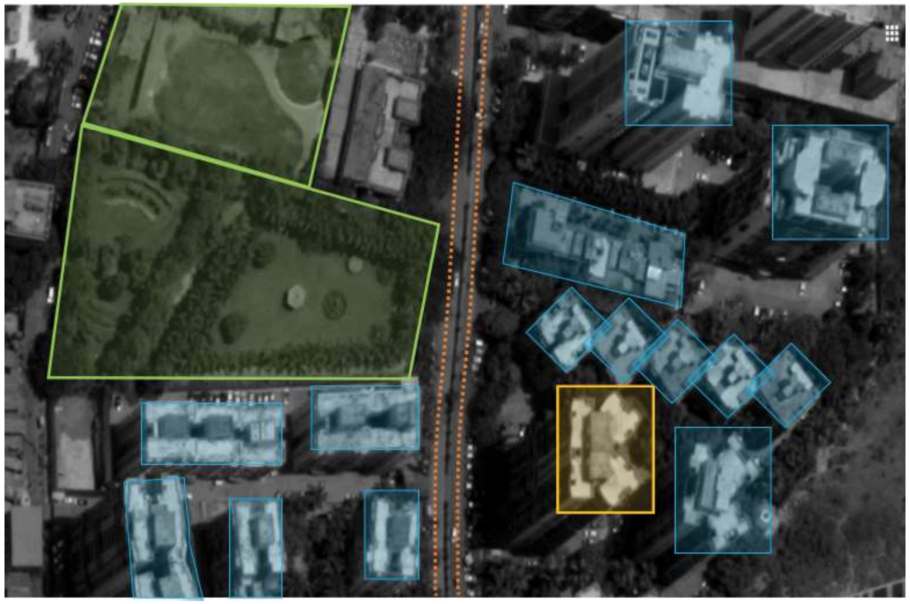


Fig.5.27. Panorama Tower Location.
(Source: Google Maps)

Fig.5.26. Panorama Tower Location.

LOCATION OF MR.OZA'S APARTMENT

The apartment chosen for the first case study belongs to Mr.Oza. Located on the 7th floor, the apartment lies between two occupied apartments and faces the main road (Fig.5.29.). There are 7 apartments on each floor (Fig.5.28.).

Building Construction

The building has an R.C.C (Reinforced Concrete) construction. The walls are 230 mm thick brick walls with vitrified flooring. The windows provided by the developer are single glazed tinted sliding windows with a sill height of 350 mm. Other materials used in the apartment are discussed in detail further.

Fig.5.28. Floor Plan

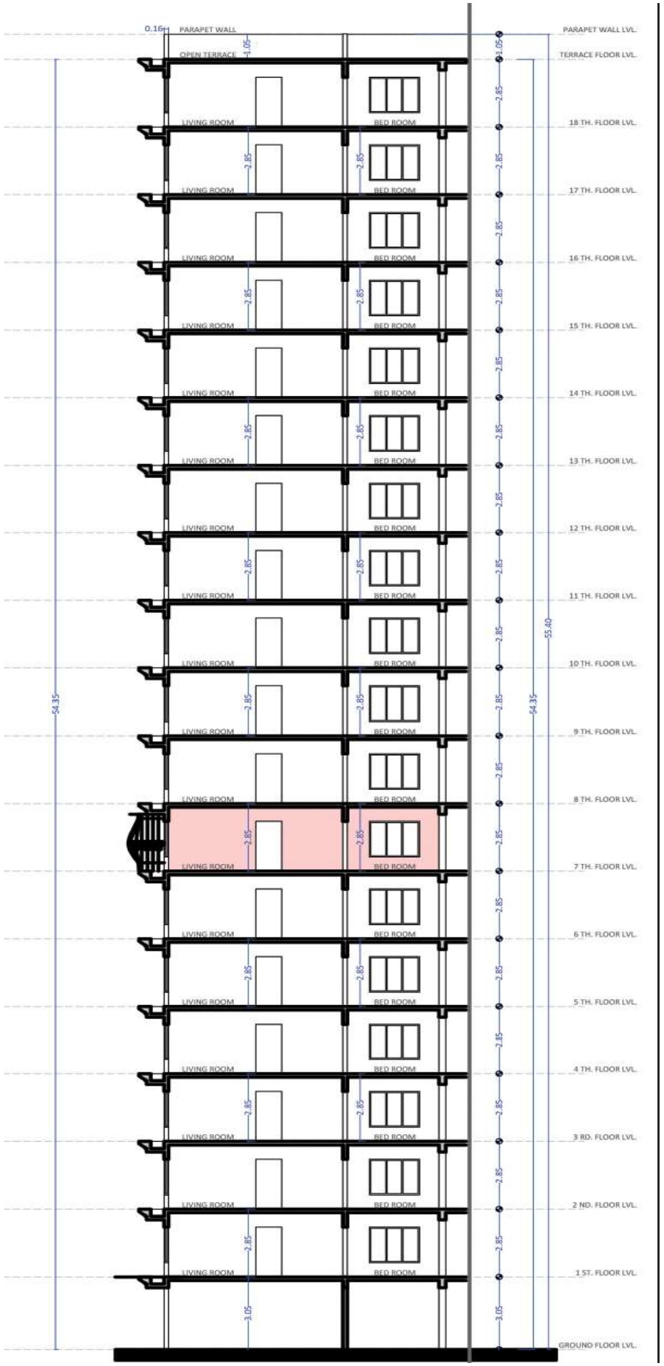


Fig.5.29.Section A-A'

Fig.5.30. Panorama Tower - Rear Elevation

Fig.5.31. Panorama Tower - Front Elevation

Description of Mr. Oza's Apartment.

The 2 BHK block is owned by Mr. Oza and he has been living here with his family since 2006, which is approximately for about 13 years. Mr. Oza is a retired bank officer while Mrs. Oza is a homemaker and their daughter works at an MNC (Multi-National Company).

Number of people occupying the apartment.

Initially, the family consisted of 4 people i.e. Mr. and Mrs. Oza and their 2 daughters. However, with the marriage of one daughter, the apartment is now occupied by 3 people most of the times.

Occupancy Pattern (Fig.5.32.)

Since Mr. Oza is retired, he is at home most of the times. His activities throughout the day involve reading, taking the dog for a walk, watching TV. and doing society work and household work if any.

His wife is a homemaker. She usually cooks in the mornings and evenings.

Their elder daughter is at home mostly in the evenings, early mornings and on weekends and holidays, since she is at work on the other days.

The younger daughter who is married, visits them every alternate evening with her 6-year-old son for a period of about 2 - 4 hours. Sometimes they both visit the family on the weekends for the whole day.

The house remains shut only when the family goes for annual holidays or some cultural functions and festivities.

Lunch & Siesta Time: 1:30 to 4:30 - This is when the air conditioning is used in the living room and bedroom.

Dinner Time: 8:00 to 9:00 - This is when the air conditioning is used.

Sleeping: Afternoon naps and from 23:00 to 7:00 - air conditioning is used in the bedroom whenever they feel hot.

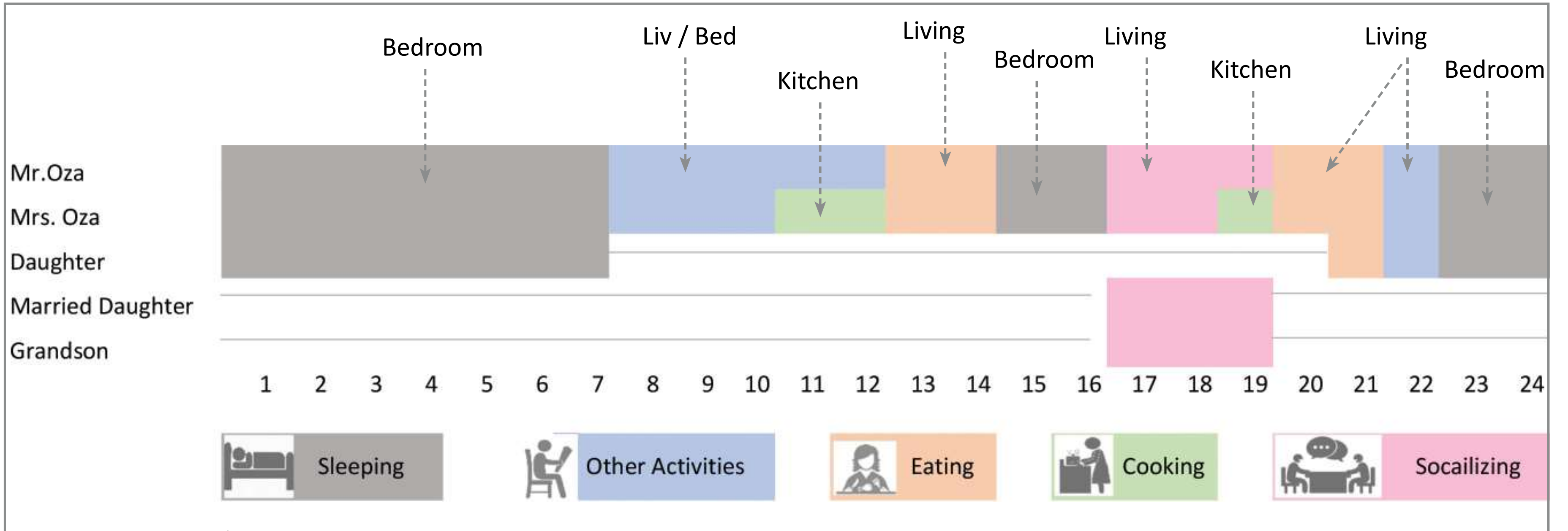


Fig.5.32. Average Daily Occupancy Pattern

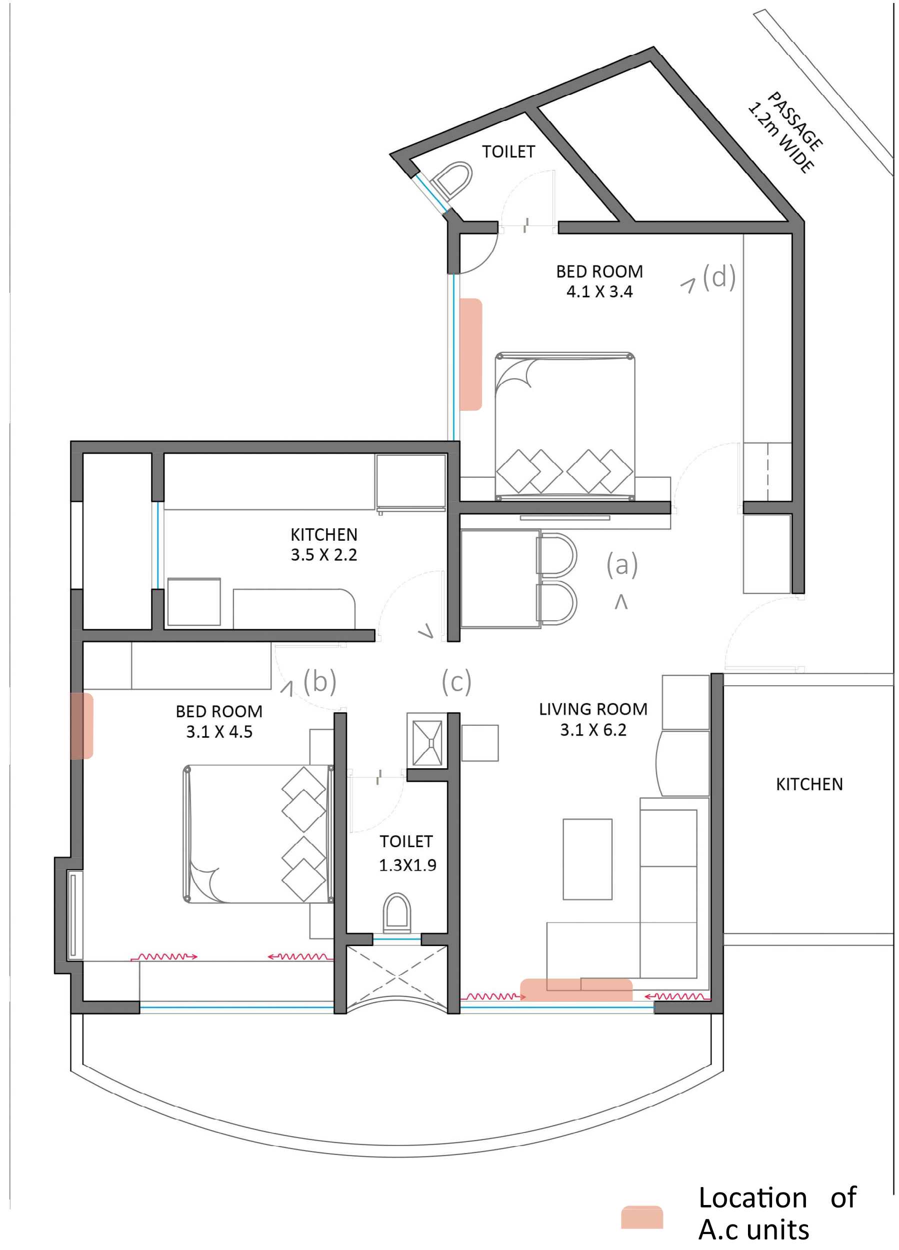


Fig.5.33. Apartment Layout

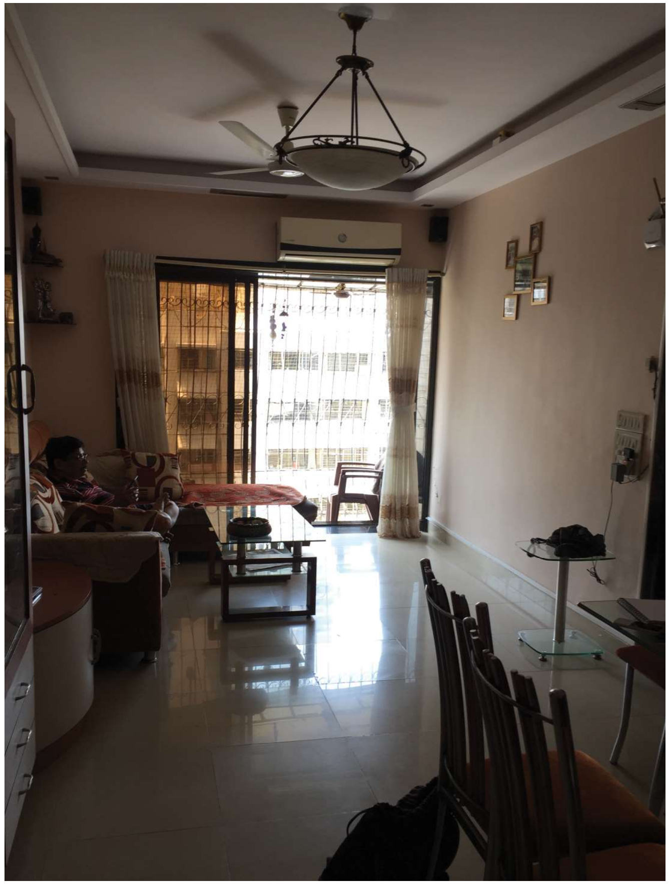


Fig.5.34. Living Area (a)

The Spaces:

Living & Dining: These two areas are combined to form an elongated space (Fig.5.33.) It is used for socializing as well as for having their meals. The maximum amount of time is spent by the occupants in this room which is west oriented and hence receives a lot of direct sunlight from afternoon onwards. It makes the space warm and uncomfortable for the users because of which air conditioning is widely used in this area post noon, almost throughout the year.

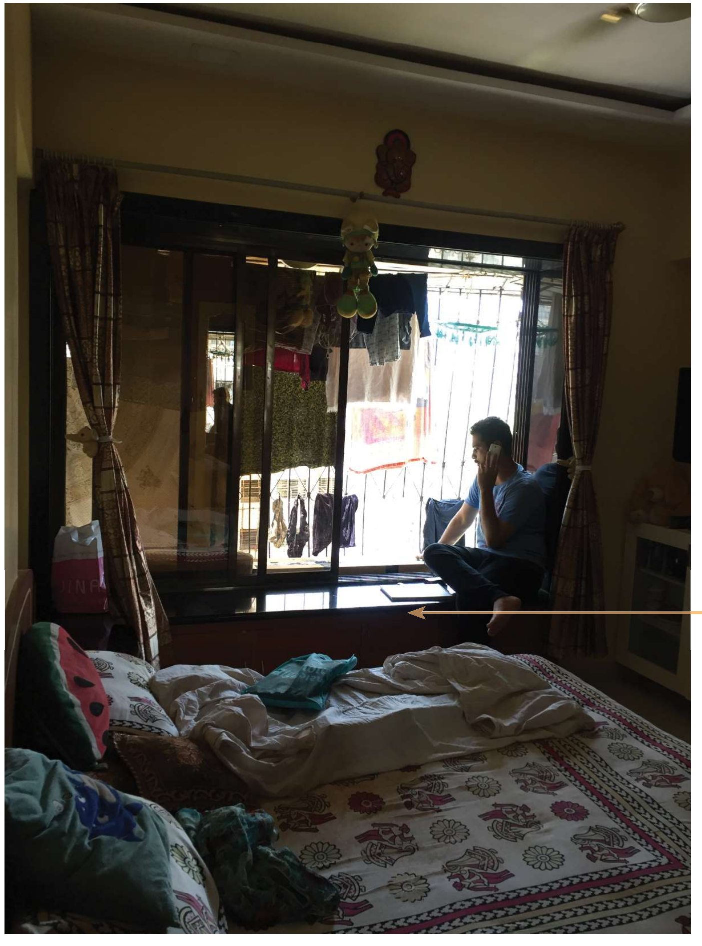


Fig.5.35. Master Bedroom (b)

<u>Bedroom:</u> The master bedroom faces the main road and is also west facing, similar to the living room (Fig.5.35.). The air-conditioned room is mostly used by the occupants during afternoon naps and at night.

Both the rooms (living room and bedroom) have windows of different sizes that are altered according to the requirement of the users. Also, both the rooms have a common projecting balcony, which is termed as the 'extra space' and is now incorporated into their living spaces. On one hand, the living room window is altered to become full height, acting as an access point into the balcony space (Fig.5.34.), while on the other hand the bedroom window is made smaller in height to introduce a sitting-cum-storage space, this makes it more private (Fig.5.35).

<u>Kitchen:</u> It has a linear layout and is relatively smaller (Fig.5.36.). The sill height of the kitchen window is 0.9m which is just above the cooking platform. The sliding window of the kitchen has a provision for an exhaust fan to throw the smell from cooking in to the outdoors.

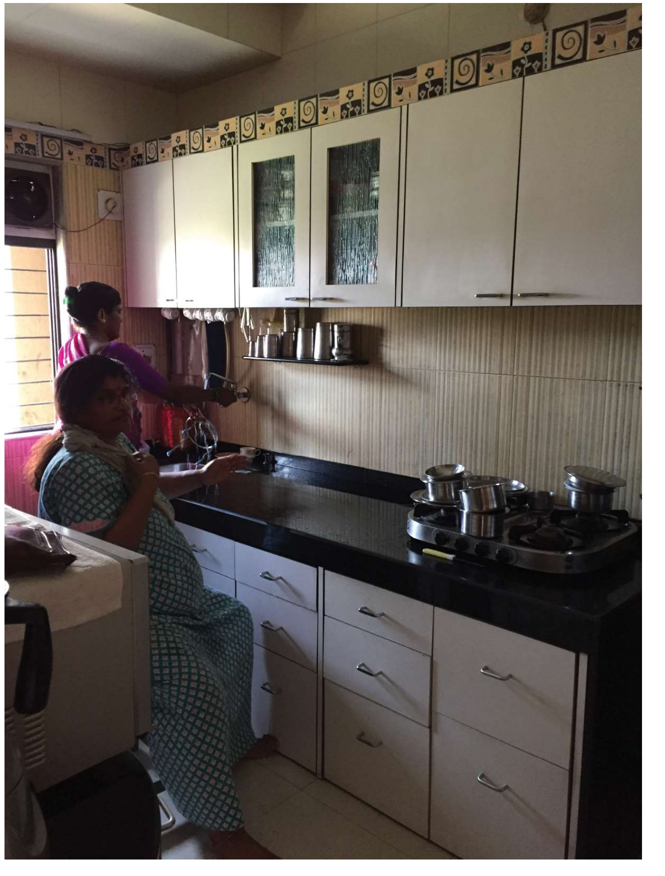


Fig.5.36. Kitchen (c)

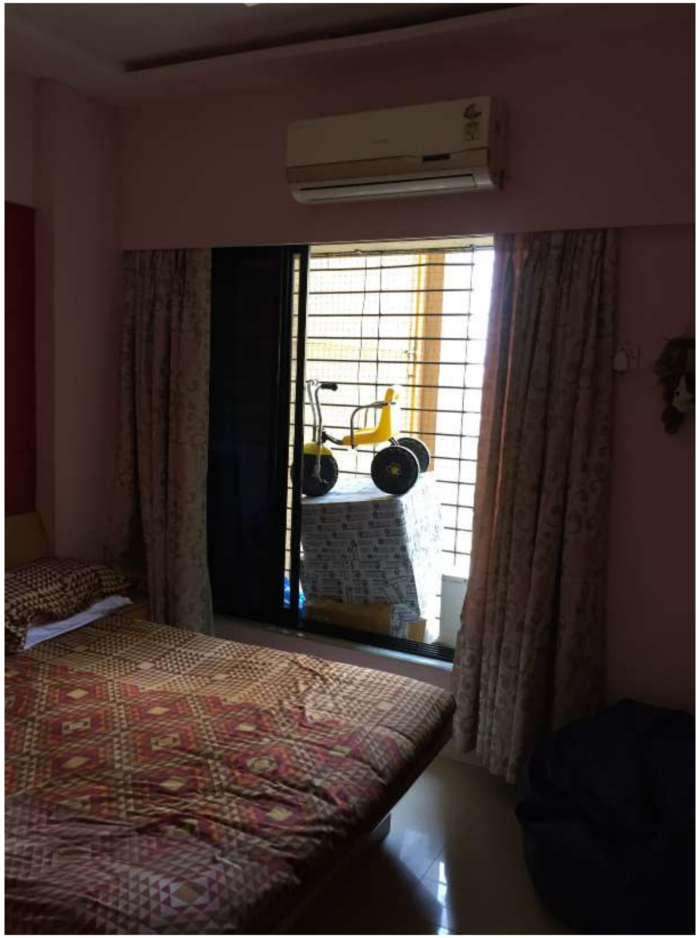


Fig.5.37. Rear Bedroom (d)

Rear bedroom: It belongs to the daughter and is mostly used by her during the nights to sleep and during the weekends. Like the other rooms, this room also has an air conditioning unit, placed just above the window.

The window of this bedroom is not altered. The glass sliding window is kept open most of the day since this bedroom does not receive direct sunlight unlike the other rooms and also because it is not used throughout the day. The space outside the window, which is between the window and the safety grill, is used as a storage space (Fig.5.37.), that partly blocks the light entering the room and also blocks the view outside.

Reflections:

It was observed that although the kitchen window is small and the rear bedroom is partially blocked, both the spaces received sufficient light, and ventilation was adequate too. However, the living room (which is the most used space) and the adjacent master bedroom received excessive daylight and vertical solar radiation, thus making the west facing rooms very bright and hot from afternoon till evening, almost throughout the year.

The window from the living space is discussed further alongwith the alterations made to the window and its impact on the indoor environment.

THE CONTEMPORARY WINDOW

The reason to choose the living room window is that:

1. It is attached to a space that is extensively used by the family every day, throughout the year.

2. Alterations have been made to this window for better performance and to acquire more living space as per the needs of the users (Fig.5.39.).

Therefore, it was interesting to study and draw a comparison between the original window provided by the developer and the modified version (Fig.5.38) (Fig.5.39) (Fig.5.40 (a)) (Fig.5.40 (b)). Moreover, it was also essential to find out how the altered window performed on a daily basis as well as on the seasonal basis and if the users were satisfied with the changes made to the existing window.

Fig.5.38. Original Window provided by the builder

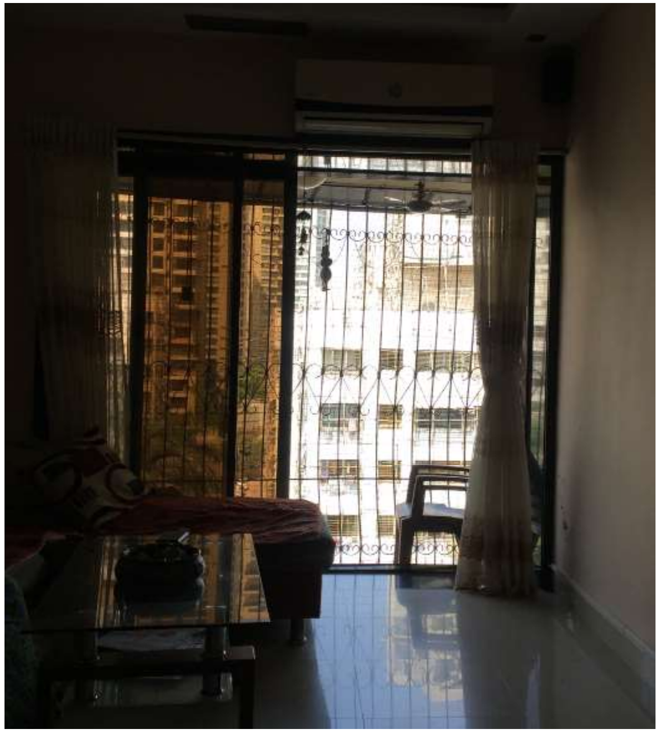


Fig.5.39. Window from the living room

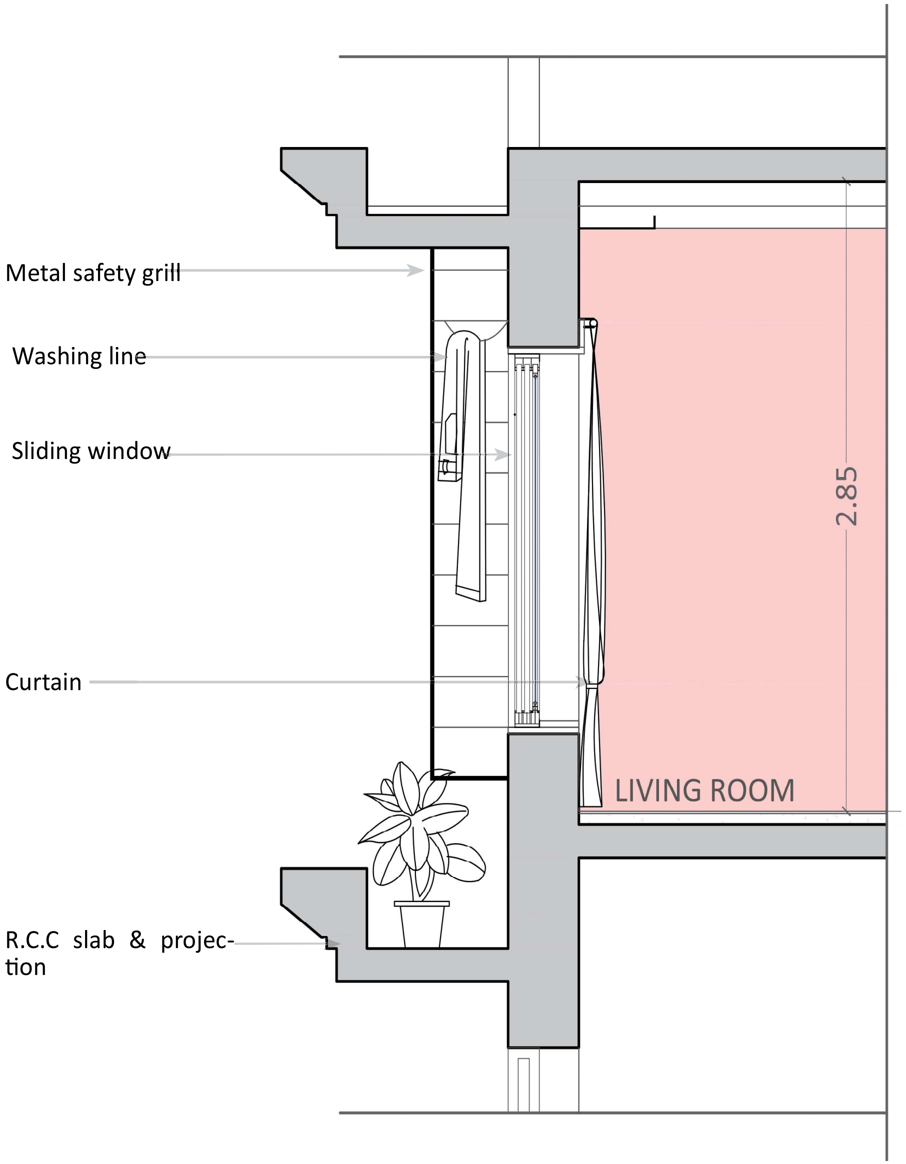


Fig.5.40.(a) Living room window detail section - Existing

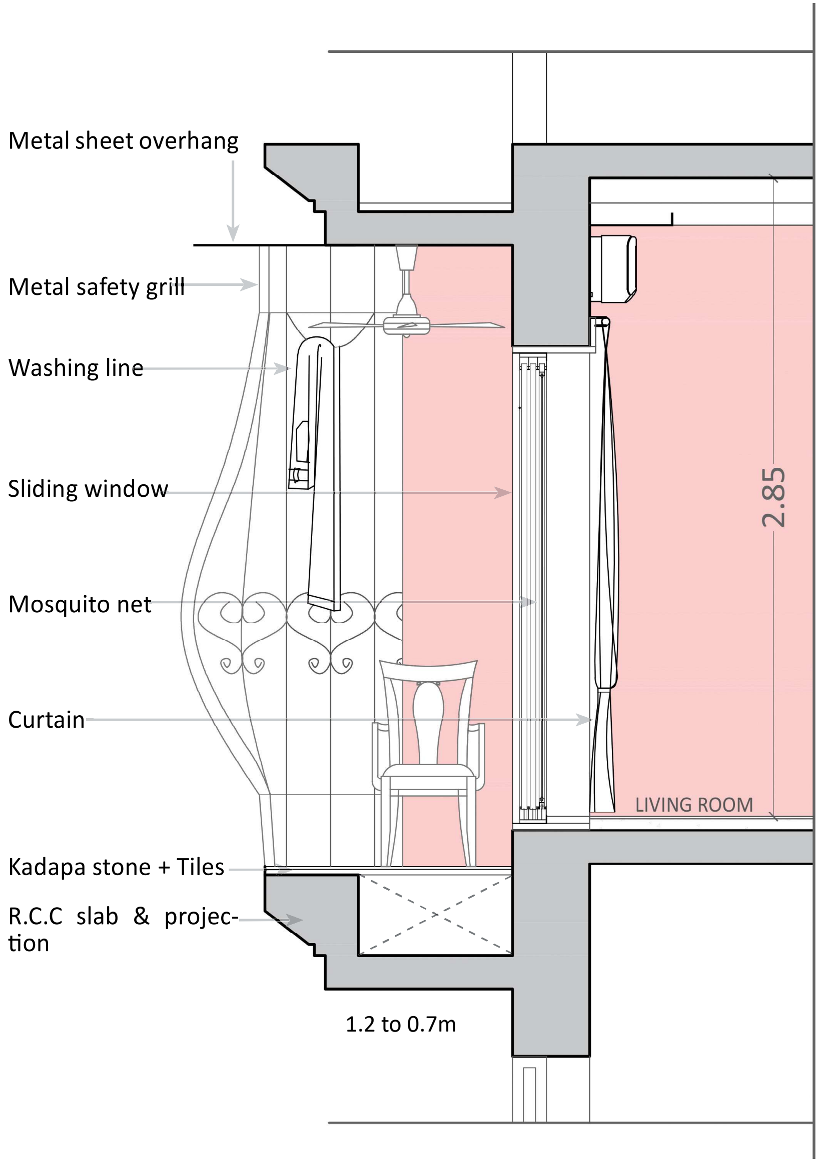


Fig.5.40.(b) Living room window detail section - Modified

Existing Window (Fig.5.40 (a)): The windows provided by the developer is a simple single glazed glass window with a light brown tint (Fig.5.38). The window sill is approximately 350mm high from the finished floor level. There is a curved cantilevered projection *(chajja)* that extends from 0.7m to a maximum of 1.2m from the window.

Modified Window (Fig.5.40 (b)): One of the prominent characteristics of the altered window is the addition of the many layers to this opening that resolve the many issue faced by the occupants of the house (Fig.5.40.(b)). These layers are discussed and analysed further:

1. The height of the window is changed and made bigger. It is 2.1m after the alteration. The changes have been made to gain access to the projected space, to match the level of the cantilevered space, so that the original structure is not hampered much and also, so that the living space and *chajja* space combine to form a bigger living area. Another important reason was to get more light and air into the room.

2.Safety grill - The shape of the grill is changed and is more protruding on the outside (Fig.5.41.). Also, the location of the grill is changed from under the *chajja* to on the edge of the *chajja (Fig.5.42.*). The safety grills are placed for security.

3. Net on the grill - A checkered net is fitted on the safety grill to prevent pigeons, and rodents to enter in the apartment (Fig.5.41.)

4. The space between the safety grill and the sliding window - This space, which was provided by the developer as a flower bed is now a multi-purpose space. It is used as a storage space, as a space to dry clothes (Fig.5.41.), a seating space (Fig.5.42.), to keep the compressor of the air conditioning unit (Fig.5.42.) and for potted plants etc.

5. The sliding window - the full height sliding window (Fig.5.43.) acts as an access point to the cantilevered space as well as the window.

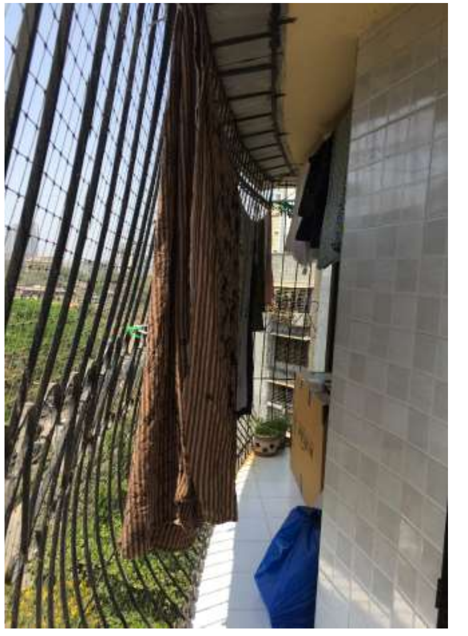


Fig.5.41. Window as storage space, for potted plants, washing line.

Fig.5.42. Window as seating space and for the compressor.

This single glazed window is tinted in brown to reduce the excess solar radiation entering the room as well as for privacy. However, the tinted glass is of very little use, since the solar radiation received during afternoon and evenings is still very high as seen in Figure 5.43., the image shows the radiation received in the living space after the sliding windows are closed.

7. Mosquito nets - Although there is an installation of the net on the outer safety grill, it does not provide any safety with respect to mosquitoes. In India, it is a very common feature to have mosquito nets fixed to an aluminium frame which becomes a part of the sliding window, that can also slide (Fig.5.44.). This mosquito net window panel is used after the sunset and throughout the night if air-conditioning is not used. Apart from keeping the mosquitoes from coming into the indoor space, the net also allows ventilation. Hence, the use of net forms an important part of the modern Indian household since it fulfils the requirement of health, safety and environmental comfort.

8. Curtains - In addition to the tinted glass and mosquito net, curtains also form the part of this window system (Fig.5.43.). Like glass, the main purpose of these curtains is also to achieve privacy and minimize solar radiation entering the living space.

The above description of the contemporary window design showcases the many layers that the modern window has. Each of these layers has its purpose and are used accordingly. But the question is, in spite of having so many skins that cater to different functions, does the window provide the desired comfort, does it provide health and safety?

As per the observations made during the fieldwork it can be said that

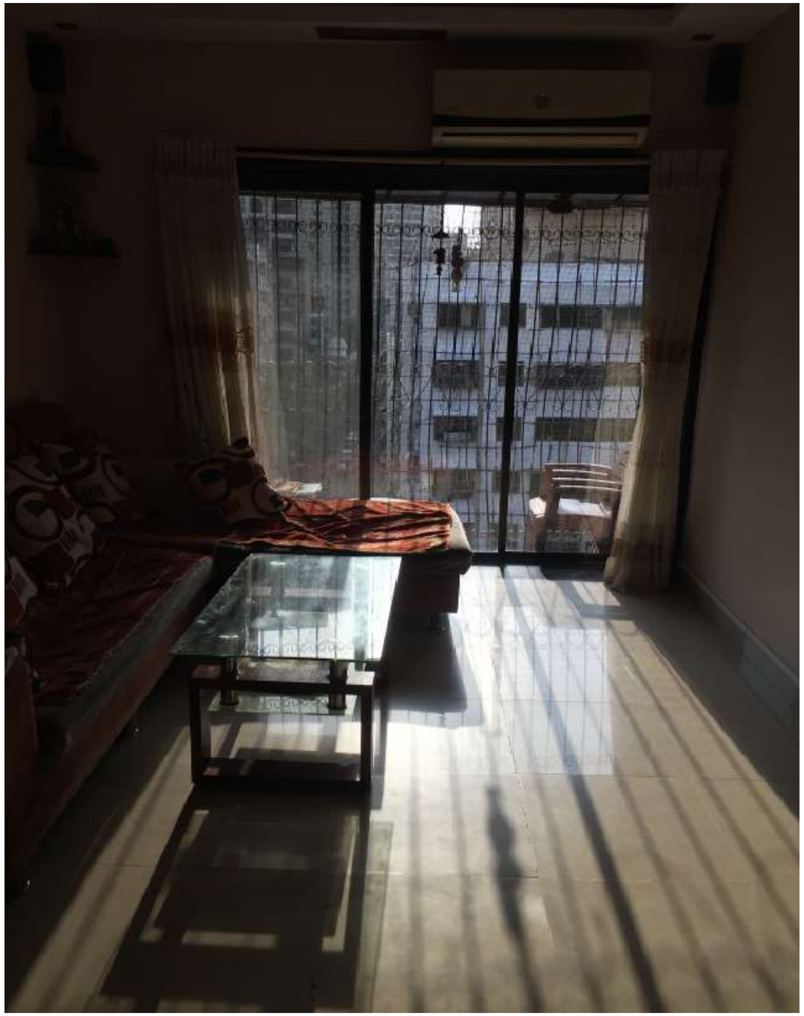


Fig.5.43. Window when closed at about 4pm.

Fig.5.44. Window - mosquito net

the contemporary window does provide safety from the mosquitoes, birds and rodents, it also provides privacy but only when the curtains are pulled. The position of the window with the cantilever in the front prevents rain from entering the apartment thus protecting the internal spaces from heavy Mumbai rains. But, having said that, the fieldwork also demonstrated that in spite of tinted glass, curtains, mosquito nets and so on, the occupants use air conditioning during the day especially during meals in the afternoon and dinner time and almost throughout the year. The reason being excessive radiation and glare from the west sun. Thus, it can be said that even after so many alterations, the window does not serve the purpose of comfort.

Some of the comments from an interview with the occupants regarding their satisfaction level with respect to their living space are as below:

Q: How does the apartment perform during different seasons (summer, winter and monsoon)?

A: Winter and rainy seasons are comfortable. It becomes hot in summer and is very uncomfortable. The afternoons are especially very hot.

Q: Are there any alterations made to the existing windows? If 'yes', then what? Why were they made?

A: Yes, for extra space. The living room window has been converted into a French window. The glass panes are tinted and are one-way for privacy and to reduce the solar gains in the rooms. One net panel is added in the living room window for ventilation (this was done when there was no air conditioning installed). We have also put up bird net on the window grill to keep pigeons and crows away. We have installed light curtains since the windows are tinted.

Q: When was the air-conditioning installed? Why was it installed? In which rooms? (if there is any).

A: Was installed 2 years back in the living room and both the bedrooms because it got very hot during the summer.

Q: How important are the windows in terms of pollution, external noise, privacy? How do the existing windows help?

A: We do not face any privacy issues as such. Since last 3 months, we have been facing a lot of disturbance due to an increase in the noise level and dust because of the increase in the traffic due to the construction of a flyover nearby. Because of this, we keep our windows shut and use air conditioning more frequently now.

Reflection

If we look closely at Fig.5.31., it showcases different window alterations on different floors. This allows in establishing that since the users of these apartments were not satisfied with the windows provided by the developer, the existing windows were altered to suit their daily requirements and expectations from their window, adding their own culture and tradition to it such as addition of wet curtains on windows that received high solar radiation which let the cool air into the living space.

Further, if we look at Fig.5.30., it can be said that since the developer was sure that the occupants might not be comfortable with the living spaces provided by him/her, a provision was made to install air conditioning units. The image clearly shows that 98% of the occupants have made use of this provision and have installed air conditioning units to achieve indoor environmental comfort.

Therefore, it can be said that, irrespective of the modifications made on the existing window, the occupants rely on mechanical systems. This only shows that the designers and the developers have failed to understand the meaning of a window, its purpose and the need for an adaptive window. The main purpose of a window should be to achieve indoor comfort in terms of light, air and noise. However, nowadays all of it is mostly achieved through mechanical systems.

Based on the observations discussed in this chapter detailed field work was carried out where spot measurements were taken for a single summer day and along with this, an iPhone application known as Aftab Luminance was also used. This application facilitated the evaluation of the quantity and quality of natural light received in the usable spaces. Furthermore, continuous measurements were recorded for two months during summer when the temperatures in Mumbai rise to the maximum i.e. in April and May. Detailed fieldwork is discussed in the next chapter.

The Hot-Humid Window from the '*Chawls*'
Parel (Mumbai)

By 1911, about 80% of Mumbai's total population lived in *chawls* that were constructed by the mill owners, private developers or the government body such as Bombay/Mumbai Development Department (Sanyal, 2018). The rise of 'the *chawl*' typology took place during the Industrial boom which Mumbai witnessed post the American Civil War in 1856 (Shetty et al., 2007), to house the growing migrant population which were mainly the mill workers that comprised of single men. The *chawls* were anywhere between two to six-storey high load-bearing structures that were built in timber and brick with sloping roofs (URBAN, 2012). Due to high maintenance and being expensive, they were later replaced by R.C.C structures.

The typical layout of any *chawl* consisted of a central courtyard that was meant for socializing, a corridor or balcony that was used as a transition space, a room unit which was about 8 to 15 sq.m including a *mori* (washing area) and common toilet facility on each floor. With a density of 3000 persons/ha, each unit in this typology was occupied by approximately 4-5 mill workers (Shetty et al., 2007).

Although the original dwellers of this typology were single-male mill workers, the possibility of acquiring better opportunities for the other family members and with no agricultural land left for farming due to debt, the migration of entire family to the city resulted in families, of about 6-10 occupants, living in single *chawl* units. Even today, most of the units are occupied by families who have been living in these spaces for generations.

At present most of the *chawls* are maintained by the Mumbai Municipal Corporation and according to their survey, out of the 36,000 *chawls* in Mumbai, 49% were built before 1905 and around 20,000 buildings are in poor and unlivable conditions (Risbud, 2001).

(a)

(b)

Fig.5.45. The existing chawls in Mumbai.

But even today, *chawls* are considered as an integral part of the urban fabric of Mumbai. They are widely studied for their form and their climate-responsive performance. Therefore, the reason to study *chawls* was to find out if the form, the design and the location of its windows and openings were responsible for the positive performance of this typology.

(c)

Fig.5.45. The existing chawls in Mumbai.

CHAWL **INFORMATION**

Name of the Building: Ahmed Sailor Chawl No.5

Built in: 1930 (which means that the building is about 90 years old)

Number of Floors: G+2

Built by: Ahmed Sailor

Apartment Number: Block Number: 13

Owner: Mr. Chavan.

Area of the apartment: 16 sq.m.

As stated earlier (p 100, p121) *chawls* were in demand due to the rising job opportunities produced by the mills. Ahmed sailor *chawls* were also developed due to the same reason. The Ahmed Sailor chawls (yellow area) are in very close proximity to the mills' area (blue zone) and are also located close to Elphinstone road (orange dotted line) and Parel railway station (Western Line) (orange zone) (Fig.5.46). Thus, with a fantastic road and rail network and also being closer to the workplace makes the location of these *chawls* central and of prime importance. Although now, many new buildings have come up around the chawl area (seen in white), other chawls can be seen on the right-hand side of the Ahmed sailor chawl in grey. During earlier times preference was given to Brahmin tenants for their cleanliness and in timely payment of rent. However, today, the Brahmin's are replaced by Gujratis and Marwaris (the business class) since central Mumbai has become a major trade hub.

Fig.5.46. Location of Ahmed Sailor Chawl, Parel - Mumbai (Google Maps)

Fig.5.47. Ground Floor Plan

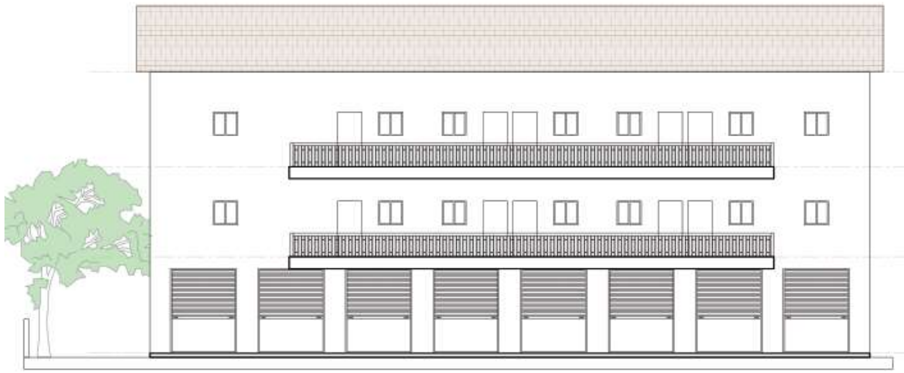


Fig.5.48. Front Elevation

LOCATION OF MR.CHAVAN'S BLOCK

Mr.Chavan's block is located on the ground level. In all, there are 45 such units with 15 blocks on each floor along with shared toilet area on each level (Fig.5.47). Mr. Chavan's block is number 13. Although 4 generations of Mr.Chavan's family have been living in this block, they follow a *'Pagadi system'*, which means that the family still has to pay a minimum rent to the owner per month (around Rs.30) and if the family decides to sell the house, around 30 to 40 % of the total resale value goes to the original owner (in this case the Ahmed Sailor family).

Fig.5.49. Ahmed Sailor Chawl, Parel - Mumbai

Building Construction: The building is a G+2 structure, where the road facing the front portion on the ground floor consists of shops plus living units. The building has a timber frame structure which was recently partially replaced with cast iron I-beams (Fig.5.49) at some places to support the dilapidating structure during the maintenance of the *chawl* by the Mumbai Municipal Corporation. The walls are 600 mm thick brick walls and *kadapa stone* flooring is laid on timber sections. The windows provided by the owner are fully openable wooden frame shuttered windows with no *chajja* (overhang) to protect the indoor space from direct solar radiation and the rains.

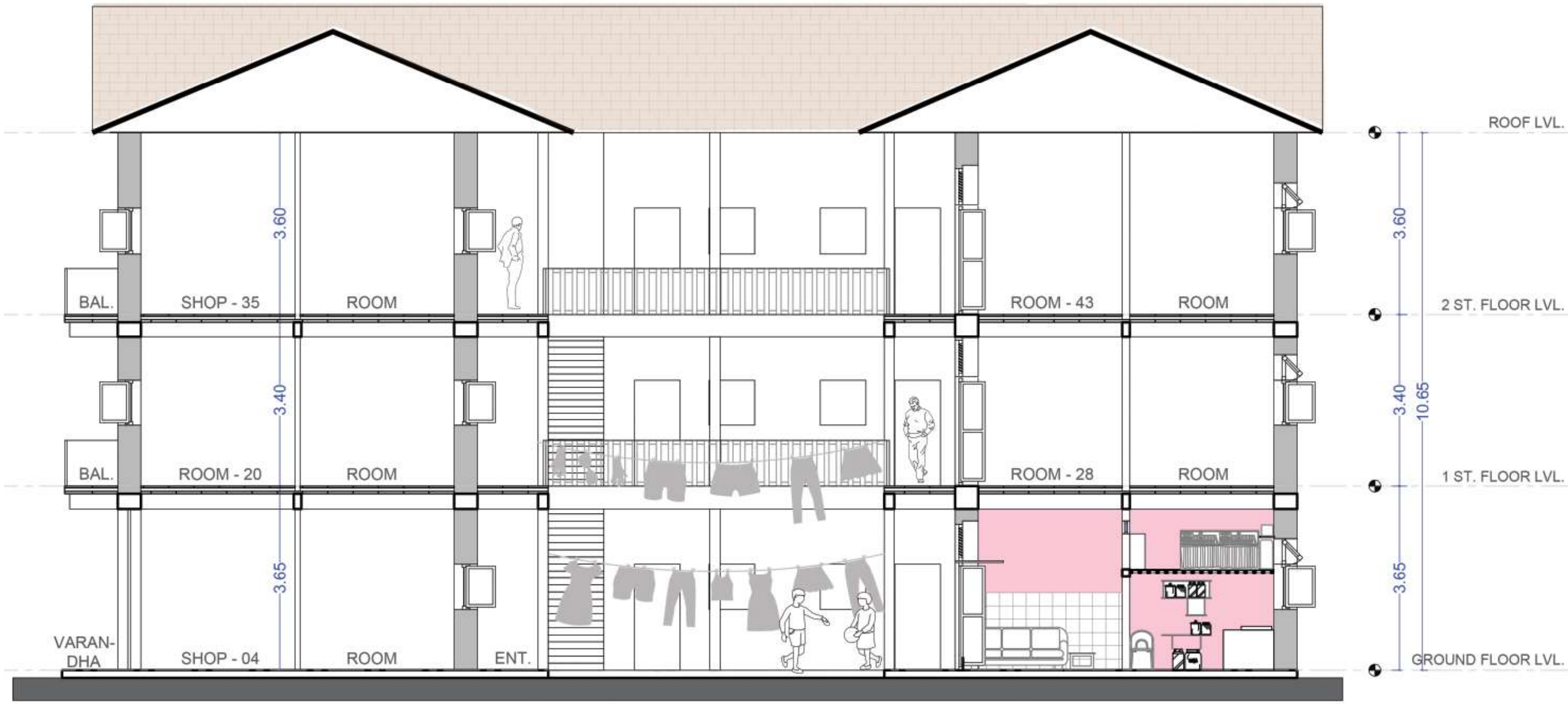


Fig.5.50. Section A-A’

The residential blocks are around 15sq.mts in area. While some have retained the original form of the apartment, many have made minor to major alterations to their living space as per their requirements. Lofts have been added in some (Fig.51.5.(a), (b)), *mori* (washing space) has been converted in to a proper bathroom (Fig.5.52.(a),(b)), the entrance door-window combination (Fig.5.53.(a)) which is the most typical and at the same time distinct characteristic of such typologies is completely replaced with solid doors to accommodate and facilitate the working of an air-conditioning unit (Fig.5.53.(b)).

Fig.5.51.(a). Room height (original)

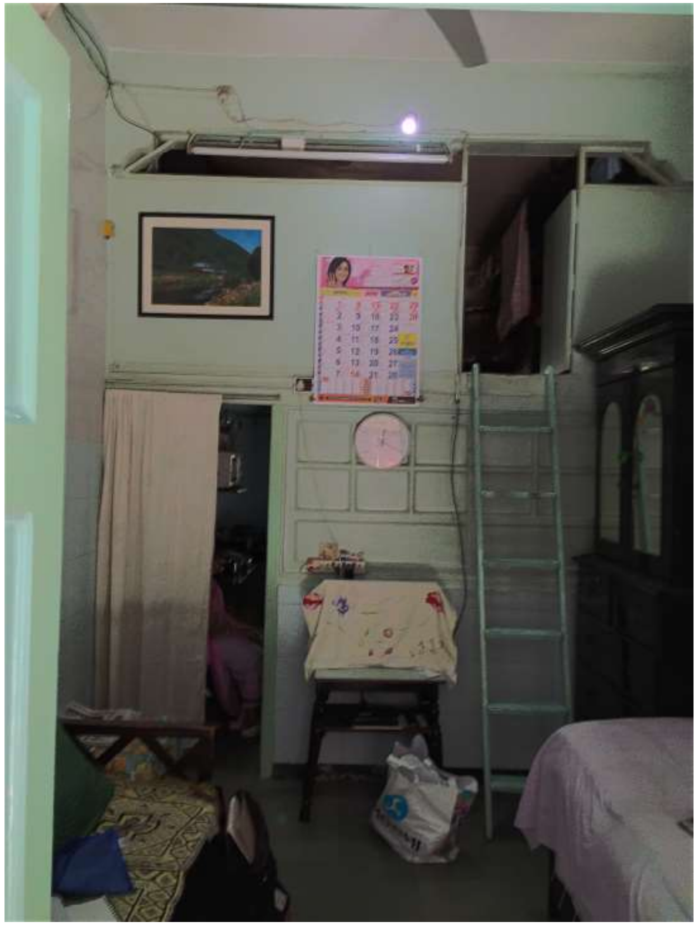


Fig.5.51.(b). Addition of loft (altered)

Fig.5.52.(a). Mori (original)

Fig.5.52.(b). Mori (altered)

Fig.5.53.(a). Door - window combination (original)

Fig.5.53.(b). Addition of A.C. and changes to door-window design (altered)

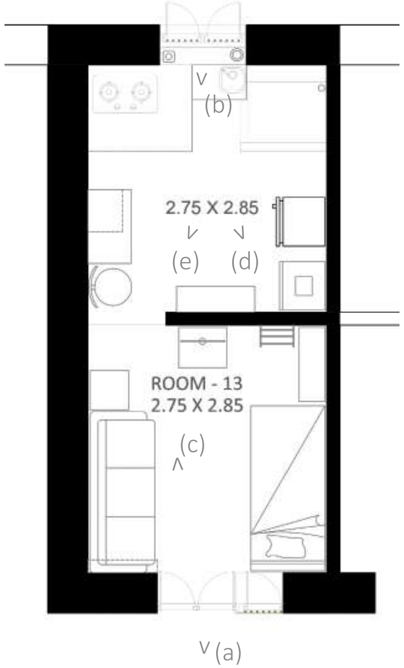


Fig.5.54.(a). Mr.Chavan's Unit Plan

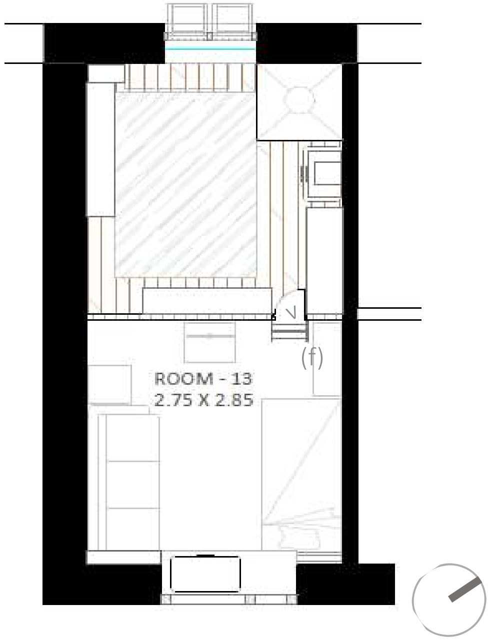


Fig.5.54.(b). Mr.Chavan's Unit Loft Plan

Fig.5.55.(a). Mr.Chavan's Unit - Entrance

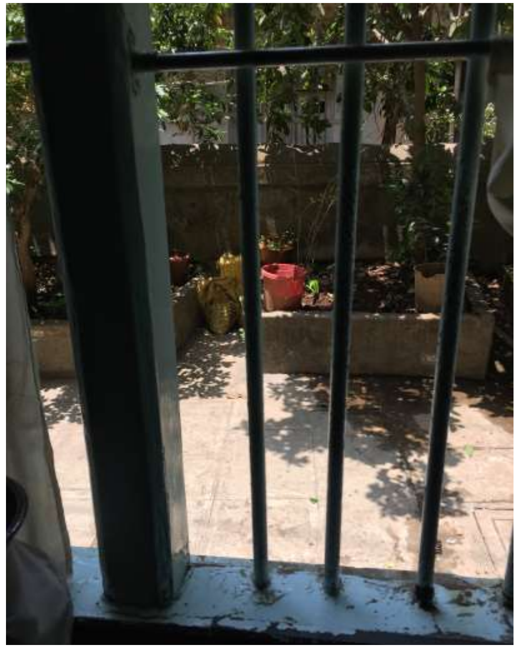


Fig.5.55.(b). Mr.Chavan's Unit - Kitchen Garden

Description of Mr. Chavan's Block

The 16 sq.mt., 1 Room + Kitchen + Loft unit of Mr.Chavan is located on the ground floor of the Ahmed Sailor Chawl. The unit opens in to an internal central courtyard (Fig.5.55.(a)) while the kitchen overlooks the kitchen garden in the rear (Fig.5.55.(b)) (Also refer Fig.5.47.)

The living area (Fig.5.54.(a)) (Fig.5.49.(c)) is used by the family to socialize, for having meals, for taking naps, to read and so on. While the kitchen (Fig.5.55.(d)) is used for cooking and washing up. The *mori* (open washing area) (Fig.5.55.(e)) is located in the kitchen where apart from washing, it is used for bathing as well. Since it is an open space, the kitchen door is shut and kitchen window curtains are pulled to maintain privacy while taking bath.

Fig.5.55.(c). View of the court-yard through door+window

Fig.5.55.(d). Kitchen - Worktop & Window

Fig.5.55.(e). Kitchen - Mori

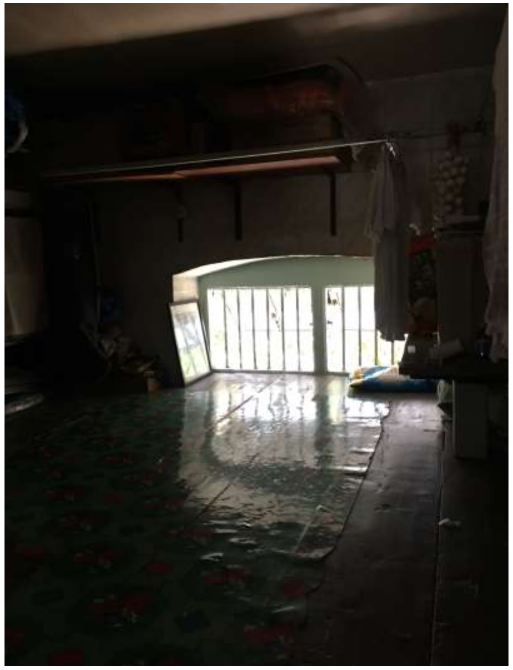


Fig.5.55.(f). Loft

Originally, the unit was to have only one room and kitchen, however, to create a private space, the occupants added a loft (Fig.5.55.(f)). It was built around 20-30 years back when the rules were lenient for refurbishment. With a headroom of only 1.5m, the loft space is used as a storage area. It contains water storage tank, books and other stored items. The remaining space is used by the son as a private space to sleep and to work from home i.e. to do his research or write article for his magazine. Thus, although the spaces are tiny and cramped up, every space is well-defined and well-utilized.

Number of people occupying the apartment.

Even though four generations have been living in this unit, the number of people currently occupying the space are three, that comprises of the father, mother and a son. Father is retired and is at home most of the times. Mother is a house maker. Mr.Chavan (son) is a freelance writer and works from home most of the times.

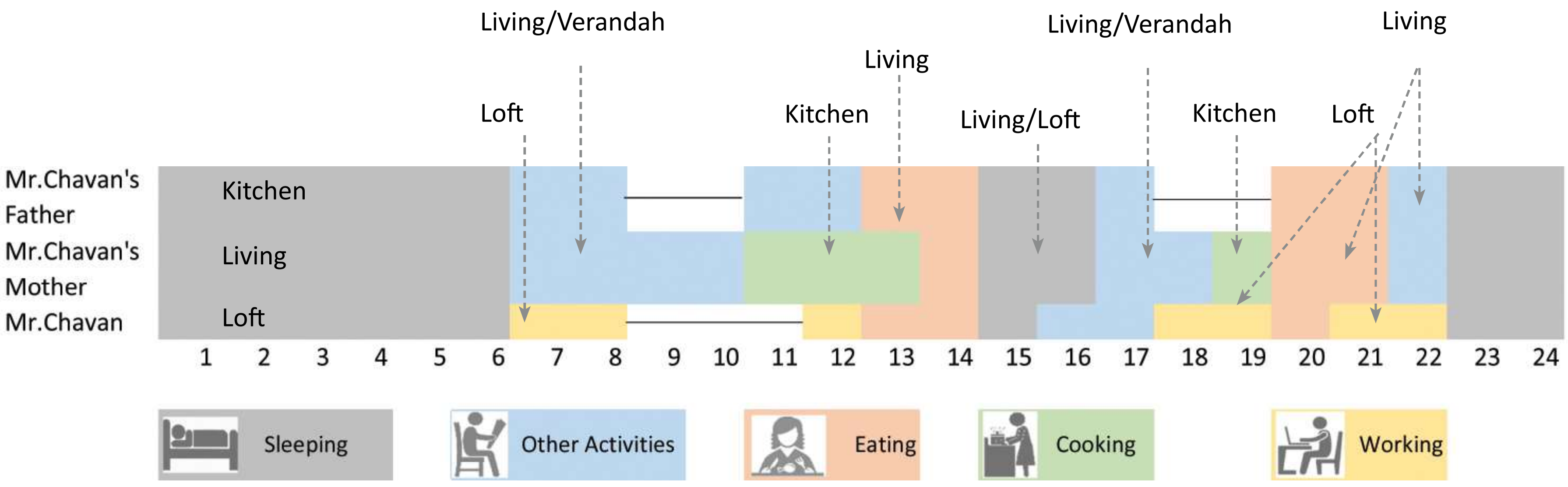


Fig.5.56. Average Daily Occupancy Pattern

Occupancy Pattern (Fig.5.56.)

The limited space is occupied by all three members since all of them are mostly home. The living area is used for the maximum period during the day because it acts as a multi-purpose space, while at night it is used by the lady of the house to sleep. Throughout the day the living space is used for having meals, for watching television, for reading newspaper, for naps, to entertain guests and so on. Due to the extensive use of this space, the main door and the adjacent window are always kept open (Fig.5.55.(c)). The *verandah* (porch) in front of the main door acts as a spillover space and is used to store water, to dry clothes, to have evening tea and to socialize (Fig.5.55.(a)). This overhang also protects the indoor space from heavy monsoon rains. The kitchen space (Fig.5.57.), which is separated from the living area with a wooden partition is widely used by the lady of the house for cooking, cleaning and washing up. Therefore, the kitchen is mostly used from 10 am to 1 pm and in the evenings from 7 pm to 8 pm for cooking. Apart from this, the *mori* or the open washing area in the kitchen is used in the mornings from about 7 am to 8 am for taking bath. While at night time i.e. after 11 pm the kitchen is occupied by Mr.Chavan's father for sleeping. The loft space is mostly occupied by Mr.Chavan. It is used by him throughout the day mostly since he works from home. The elevated, secluded loft space provides decent privacy and a quiet environment, as per Mr. Chavan's requirements, as compared to the other spaces. At night, the loft space is used by him for sleeping.

Thus, apart from occasional guests, the block occupancy remains the same throughout the year.

Fig.5.57.Kitchen Occupancy Pattern

Fig.5.58. The Door + Window + Ventilator Combo

THE HOT-HUMID WINDOW

The beauty of a simple *chawl* unit lies in their openings and the form of the building. The common central courtyard acts as a place to socialize where everyday children are seen playing and men and women chatting, performing their chores, etc. The courtyard is also extensively used for occasional celebrations such as, during festivals like Diwali and Holi or for wedding ceremonies. During the fieldwork, it was observed that the doors and windows that open in to the courtyard are always kept open throughout the day by the occupants, which means that neighbours are always welcomed in each other's unit and also because they feel okay to leave it open without any safety concerns. Keeping the door open also allows the spillover semi-open *verandah* (porch) space to be included in the everyday routine activity of the inhabitants. The porch space is used as a storage area, for having tea or reading newspaper, to have a chat, to dry clothes etc.

Apart from the social importance these two features of the *chawl* (courtyard and openings) also play a very significant role in creating a micro climate within the common spaces and also indoors. The form of the building and the design and location of the openings are one of the reasons most of the units in this *chawl* do not have air conditioning unit installed yet, neither do they have bird nets or mosquito nets or tinted sliding windows. Therefore, it becomes important to understand the role of the unique opening style noticed in chawls that comprises of a combination of door + window + ventilator (Fig.5.58.). Other than the above, this section also discusses the opening in the rear end (kitchen) of the unit which consists of another window. The single window is being divided in to two spaces i.e. the ventilator part serves the loft and the window part serves the kitchen area (Fig.5.55.(d) (f)).

The Form & Openings:

Around 90 years ago, the load bearing structure of the Ahmed Sailor chawl was built using timber sections. Even today, most of the units stand on the timber sections, while some are replaced by mild steel I-sections to support the dilapidating structure during the maintenance work done by the Mumbai Municipal Corporation. With 600mm thick external brick walls, the internal walls are either 150mm masonary walls or they are wooden partitions. The flooring is mainly in *kadapa stone* laid over 50mm thick P.C.C (Plain Cement Concrete). There are two openings for each unit. One which forms the part of the entrance door (Fig.5.59.(a)) that extends into verandah, overlooking the internal courtyard and the other on the opposite side, in the kitchen area (Fig.5.59.(b)) that overlooks the kitchen garden.

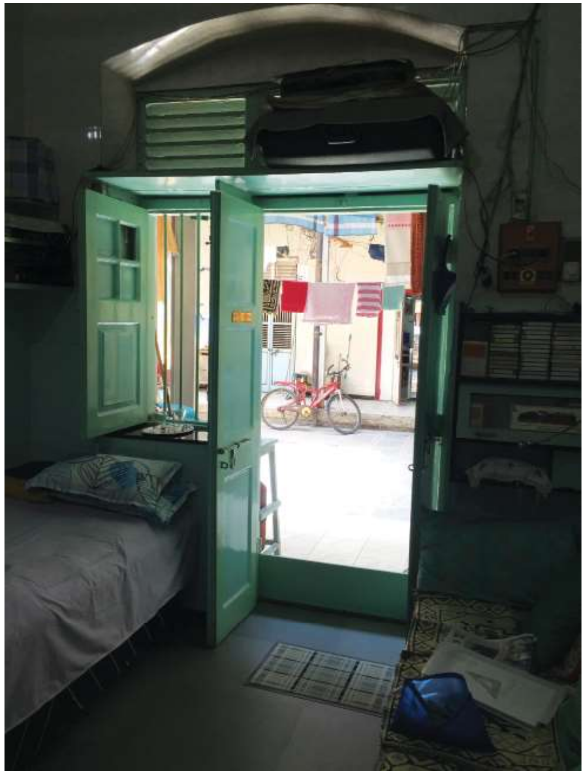


Fig.5.59. (a). Entrance Opening

Fig.5.59.(b). Kitchen Window

The Combo:

Chawls portray a strong culture and are often referred to be the best residential examples of Mumbai that encourages social interaction and provides a sense of security. Apart from the central courtyard, the combination of entrance door, adjacent window and a ventilator on top of the door plays a very significant role in the development of this rich culture (Fig.5.59.(a)) (Fig.5.60.(a) (b)). The contribution of this simple opening design feature is also to provide the user with a number of operative options to regulate their indoor environment.

A detailed description of each element of 'the Combo Opening' and the number of alternatives the individual elements provide are discussed further.

1. The door (Fig.5.59.(a)) (Fig.5.60.(a) (b)): A part of this unit is the main access door. The teak wood double shuttered door provides

Fig.5.60.(a). The Door + Window + Ventilator Combo

Fig.5.60.(b). The Door + Window + Ventilator Combo

the occupants with an option of opening one or both the shutters as per their needs. *'Falli'* meaning a vertical wooden plank, is fixed by the occupants which is around 0.3m in height (Fig.5.62) that prevents rodents from entering the house.

In the Chavan household, the double door is opened at 7:30 am and remains open till their lunch time, which is usually at 1:00pm. The doors remain shut till 4:30 pm, during which the occupants have their meals and take the afternoon nap. They tend to shut one shutter after sunset, the time when they watch television and have their dinner. At around 11:00pm when they go to sleep both the doors are closed for privacy and safety reasons. Keeping the door open throughout the day facilitates ventilation (Fig.5.63.) which in turn keeps the internal air temperature lower (further discussed in the next chapter).

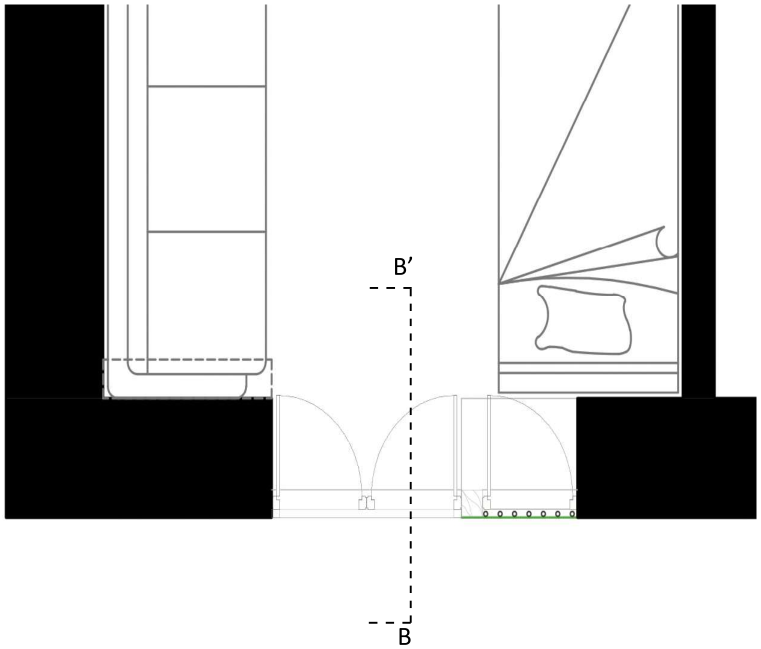


Fig.5.61. Zoom-in Plan show the Opening Detail

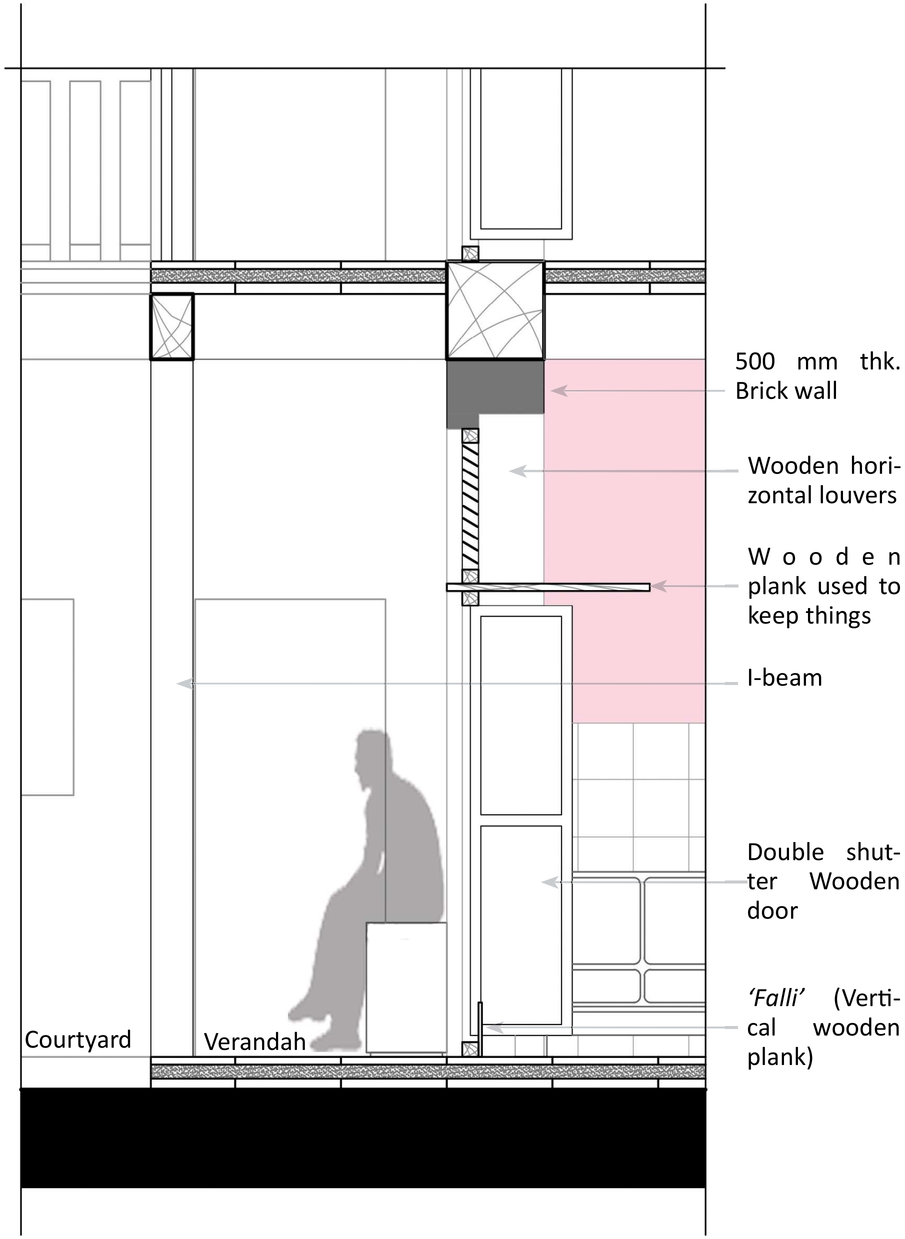


Fig.5.62. Detail Section B-B' - Door + Window + Ventilator Combo

Also, opening the full length shutters allows the required daylight in the living space. The provision of 1.4m deep verandah prevents direct solar radiation, thus maintaining lower indoor temperatures. Furthermore, it also blocks the rain from entering the house.

This daily routine with respect to the doors that is followed shows the importance of giving an 'option' to the user to modify their living environment.

2. The Ventilator: It is located above the main door and the adjacent window in Mr. Chavan's unit (Fig.5.63). The timber ventilator is kept open at around 30-35^{o} angle throughout the year. When the doors and the window are shut at night time and during heavy rainy days, the ventilator on top provides the required air exchange. The wooden plank jutting out, in between the door and the ventilator is used to stack and store things such as suitcases which also partially blocks the ventilator.

3. The Window (Fig.5.63.): The single shutter window is kept open throughout the day. There are safety grills in iron on the outer side of the window. The sill height at which this window is placed is 1m. The 0.6m x 1.2m window is also the source of ventilation and light. However, unlike the door, the window is kept open throughout the day and is shut partially during night time.

Similar examples of this type of opening design shows the use of curtains on the window to maintain privacy (Fig.5.60.(a))

The combo opening along with kitchen window allows continuous air exchange in the house. The rear kitchen window (Fig.5.64.) consists of openable double shutters in teak wood and a ventilator above it. The shutters are the part of kitchen (Fig.5.64.) (Fig.5.65.) whereas the ventilators provide light and ventilation to the loft space (Fig.5.66.)

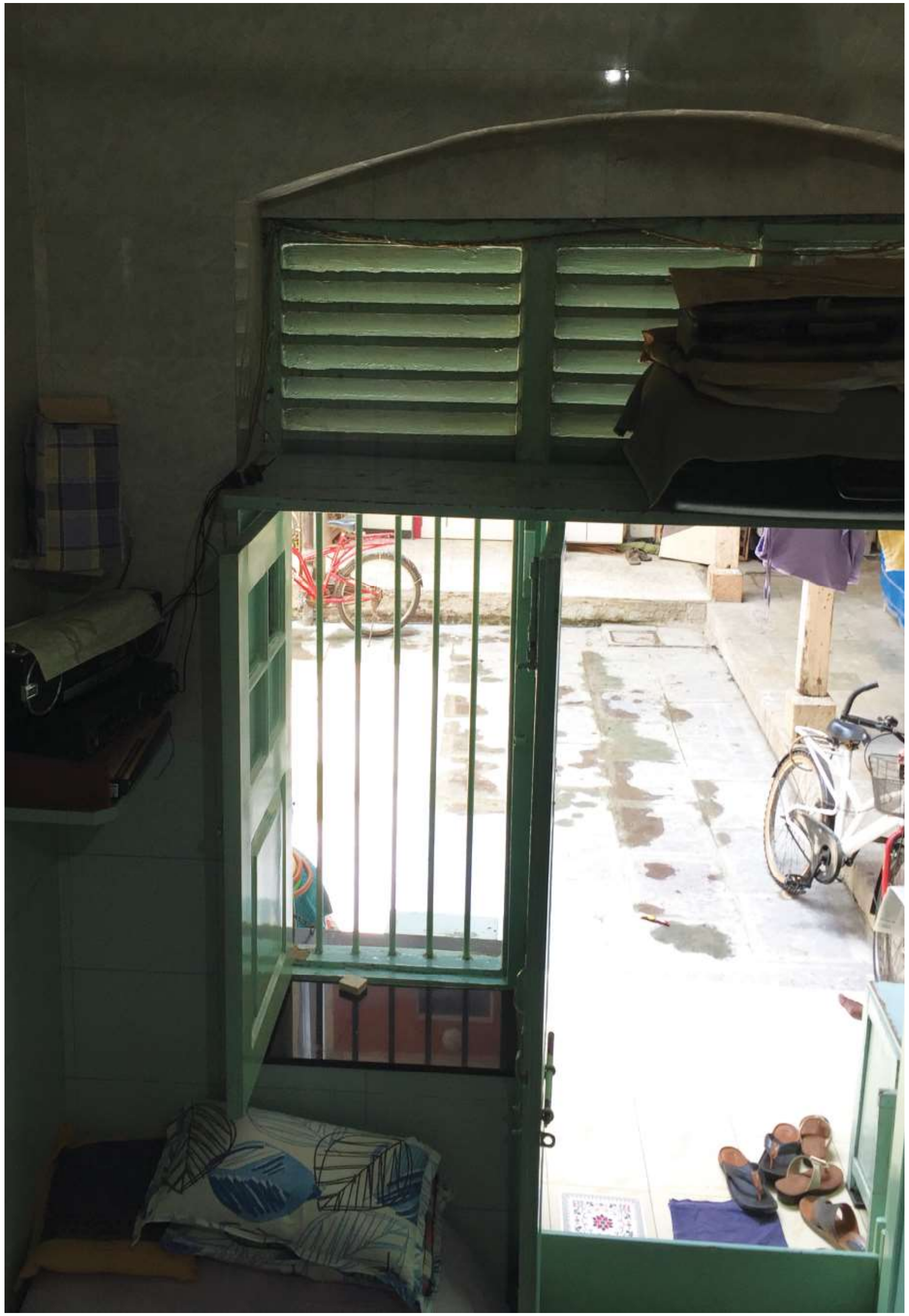


Fig.5.63. Detail Section B-B' - Door + Window + Ventilator Combo

(Fig.5.67.) above the kitchen area. Half curtains are used in the kitchen window for the purpose of privacy since the area is mostly used by the lady of the house and also because there is an open washing area (mori) in the kitchen plus it is also used to prevent wind to blow out the gas from the gas burners (Fig.5.65.). According to Mr. Chavan, the ventilator in the loft provides satisfactory daylight and air exchange. However, during monsoons half the ventilator is covered with plastic sheet to avoid the rain water from seeping inside the loft space.

Fig.5.64. The rear kitchen window -from outside

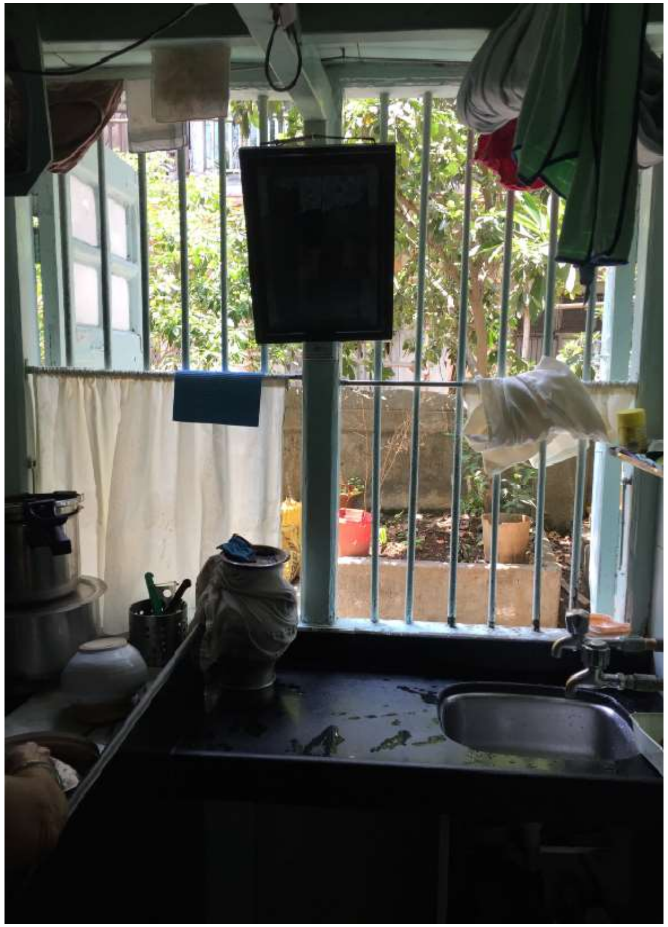


Fig.5.65. The rear kitchen window -from inside

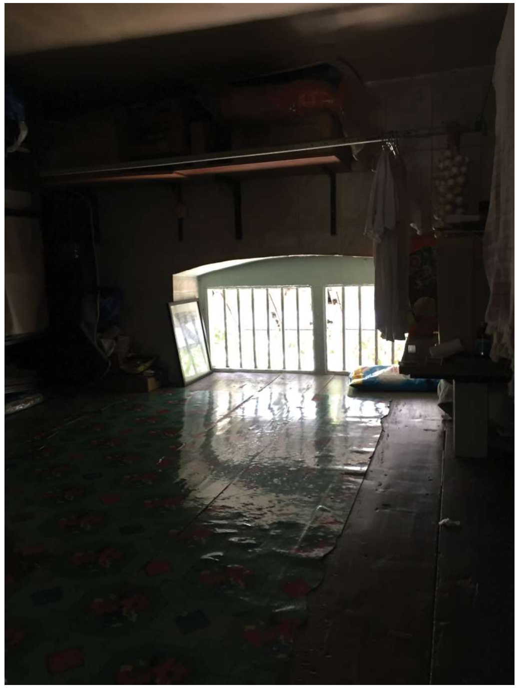


Fig.5.66. Loft window

Fig.5.67. Loft window

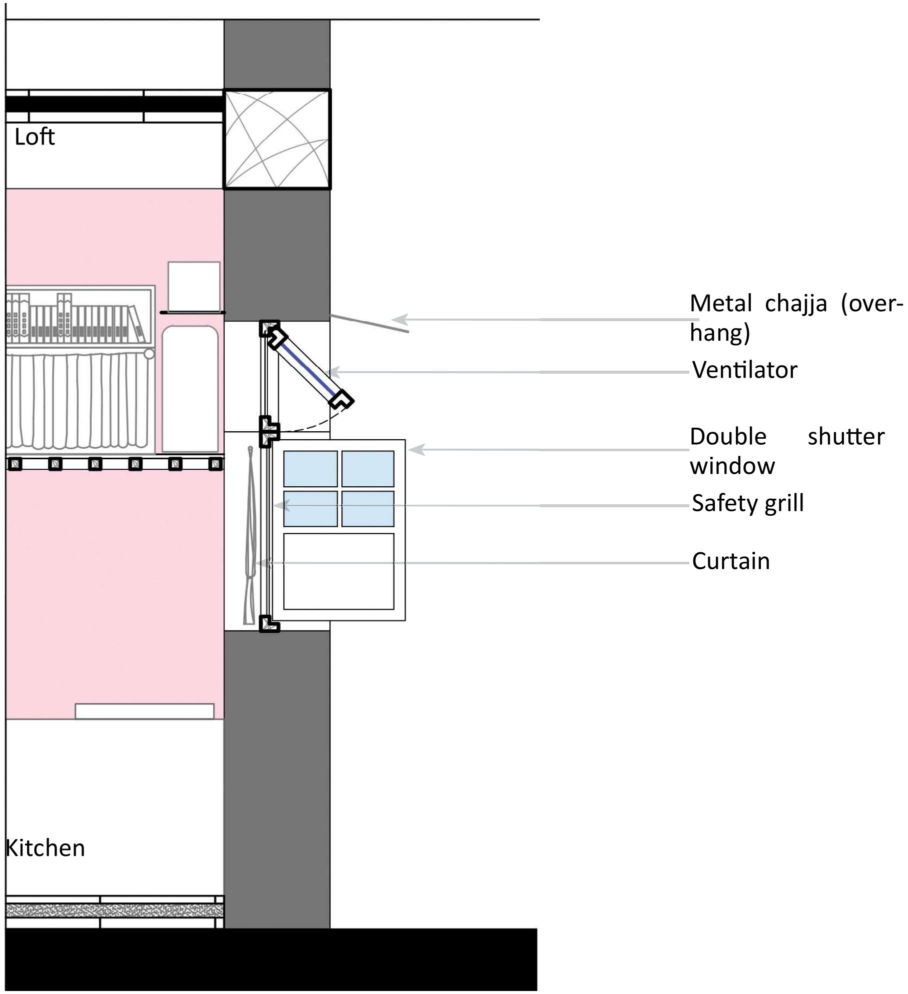


Fig.5.68. Section through rear window

It is of utmost importance to take into consideration the simple form and opening design of this typology. The central courtyard and the placement of windows that allows continuous cross ventilation are the factors responsible for comfortable indoor temperature as well as the quality of light. The entire system works together in such a way that cool air enters the kitchen area through the rear window, the hot air inside the unit escapes through the door + window + ventilator and further, the hot air escapes in to the central courtyard (Fig.5.69). Thus, this continuous flow of cool air into the habitable space and the hot air exhaust is the reason why the occupants do not feel the need to introduce air conditioning units in their homes yet.

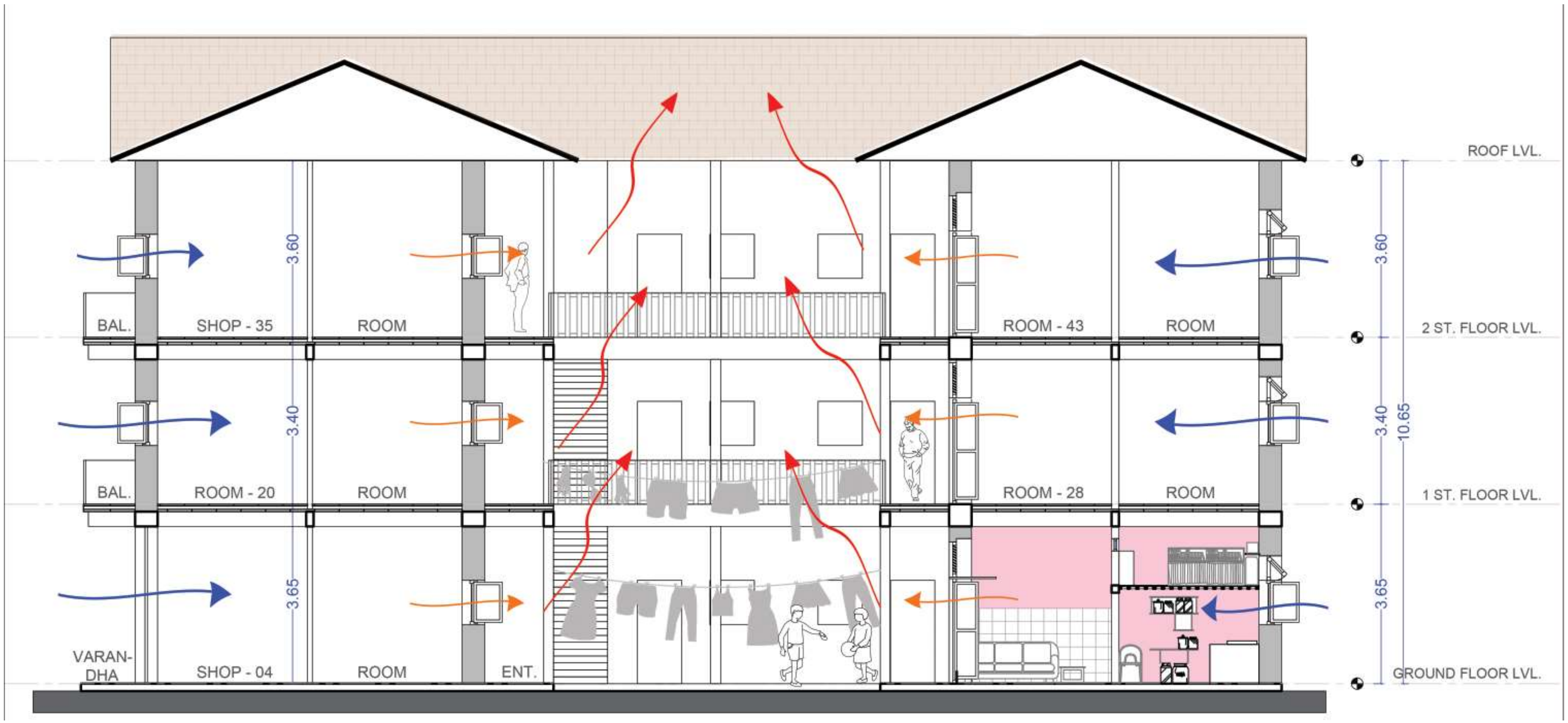


Fig.5.69. The environmental role of openings and the form of the building

Some of the comments from an interview with the occupants are as follows:

Q: How does the apartment perform during different seasons (summer, winter and monsoon)?

A: Pleasant throughout the year. Monsoon: Rain sweeps in through the window and hence there is moisture problem on the walls. The residents in general face lot of mice and cat problem throughout the year. To solve this problem, the residents have installed 'falli' on the main door. The main door window is partially closed at night while the kitchen window is closed completely at night.

Q: What features do they like about the building/house and their apartment block?

A: Cross ventilation. Never felt the need for an air conditioning.

Q: Are there any alterations made to the existing windows? If 'yes', then what? Why were they made?

A: No alterations have been made.

Q: What do you think about the windows in the house? Would you like to change them or modify them? Why?

A: No. Very satisfactory window design.

Q: What role do you think the windows play in maintaining indoor comfort?

A: A very strong role in maintaining ventilation and maintaining indoor comfort.

Q: How important are the windows in terms of pollution, external noise, privacy? How do the existing windows help?

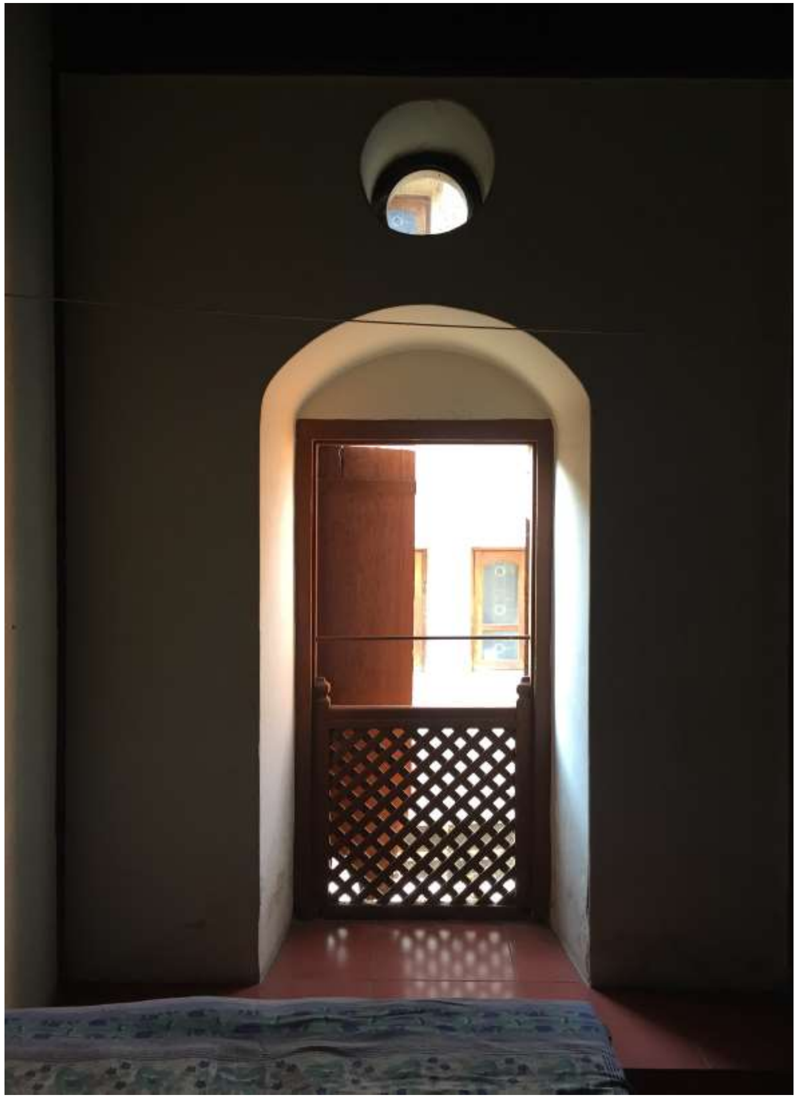
A: Since the main window-door-ventilator system opens in the central courtyard, the noise is only from the residents of the chawl (like children playing, people chitchatting etc.) and similarly we do not face any problem with respect to pollution. In terms of privacy, it is a very open society because of the way it is designed and hence there is a basic difference in the quality and concept of privacy in chawls and apartments. So, it can be said that the occupants lack privacy however they treat it as a social thing.

Reflections:

Thus, the form of chawls and the well-designed openings together contributes in the creating a micro-climate and also a social fabric. Whereas, on the indoor level, the combination of openings allows the user to modify their indoor environment according to their needs and requirements, be it in terms of environmental comfort with respect to light and temperature or be it in terms of privacy, safety and the changing use of the living space. Apart from additional features such as curtains, safety grills, etc., the simple design of the window + door + ventilator gives a number of permutations and combinations for the user to play with, something that we are lacking in the contemporary style of designing windows today.

The Hot-Dry Window from a '*Wada*'

Shivaji Peth (Kolhapur)



KOLHAPUR

the holy city of the south

Kolhapur, India
16.7050°N, 74.2433°E

Fig.5.70. Kolhapur Location
(Google Maps)

History of Kolhapur

Dakshin Kashi (Holy city of the South) or Kolhapur has a history that dates back to the 17th century (Government of Maharashtra, 2019). The mention of this city is in the Hindu mythology. It is believed that goddess Mahalakshmi destroyed the demons named *Kolhasur* and *Karaveera*, saving the local people from the misery caused by them. Hence, as per one of the theories, this is how the place got its name.

Coming to the recent history, Chatrapati Shahu Maharaj was the fifth successor of the Peshwa's and ruled Kolhapur for a period of 28 years (from 1894 to 1922) which was a princely state during the British rule in India (Latthe, 1924). During the rule of Shahu Maharaj the city saw a major transformation in its social, cultural and economic condition. Today, with the availability of abundant natural resources, Kolhapur has the highest per capita income in Maharashtra and is now on the way of becoming an industrialised city (Ghadyalpatil, 2018).

History of Maratha Architecture

The Peshwa's belonged to the warrior clan, they fought with the Mughal Empire in the 18th century. During that time, they ruled the present day Maharashtra state which was divided in to five broad regions named as Konkan, Vidarbah, Desh, Khandesh and Marathwada (Fig.5.71.) (Dengle, 1993). The present region of Mumbai, Thane, Ratnagiri, Raigad and Sindhudurg formed the part of Konkan subdivision. Whereas, the present regions of Kolhapur, Pune, Nashik formed the part of 'Desh' subdivision (Desai, P. (no date)). These regions were ruled by the Mughals for three centuries before they were conquered by the Peshwas. Due to an extensive rule by the Mughals in Maharashtra, Maratha architecture featured Indo-Islamic style of architecture that is quite visible in various architectural elements.

Fig.5.71. Maharashtra regional classification (Google Maps. Edited in: Photoshop)

	REGIONAL				
	Konkan	Desh	Khandesh	Marathwada	Vidharbha
SOCIOLOGICAL		Fort/Palace wada			Palace wada
	Noblemen wada	Noblemen wada	Noblemen wada	Noblemen wada	Noblemen wada
	Ordinary wada	Ordinary wada	Ordinary wada	Ordinary wada	Ordinary wada
FURTHER SOCIOLOGICAL	Tenement wadas				
		Temple wada			
		Ghat wada and temple complex		Ghat wada and temple complex	
	Muslim wada				
	Wadas of merchants	Wadas of merchants	Wadas of merchants	Wadas of merchants	Wadas of merchants

Fig.5.72. Wada typology (Gupta, 2013)

The History of *Wadas*

Courtyard houses are prevalent in many parts of India. They have similar basic structure with difference in construction techniques and materials. A courtyard house in Kerela (coastal south India) is called *Nalukettu*, *Haveli* in north India, *Deori* in Hyderabad (southern Indian plateau), *Rajbadi* in Bengal (east India) and *Wada* in Maharashtra (west India) (Gupta,2013)

The name '*Wada'* is derived from a Sanskrit word called '*vata'* means a piece of land meant for building a house (Dhepe & Valson, 2017). *'Wadas'* were largely built in the state of Maharashtra during the Peshwa rule from 1700-1900 A.D (Archimony, 2016). The residential typology can be defined as a large building which is two-three storey high with an introvert plan, where the rooms are aligned around one or more courtyard(s) (Kotharkar and Deshpande, 2012). With an identical basic concept, *wadas* can be classified based on region which are further sub-divided by societal stratification (Fig.5.72.).

Fig.5.73. Wadas, Kolhapur

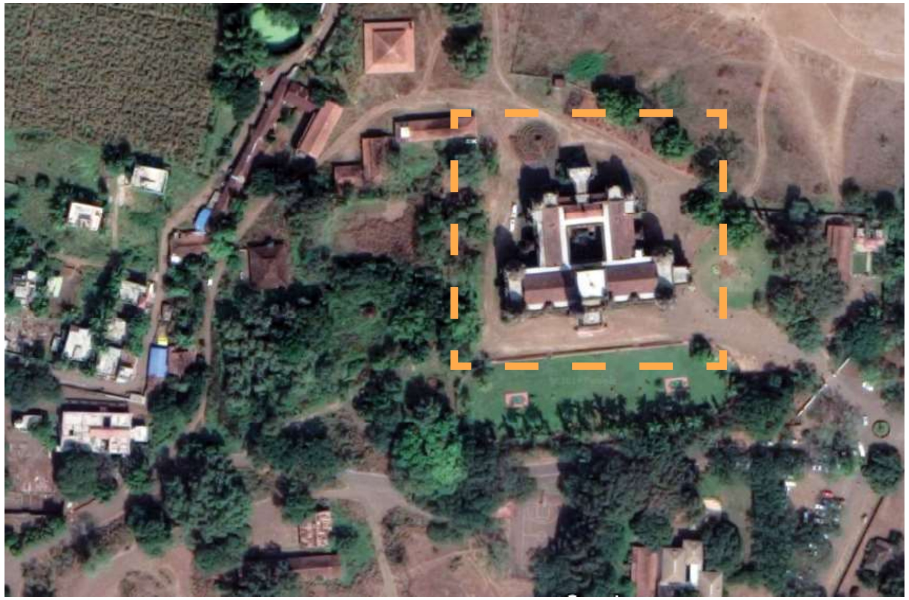


Fig.5.74. Shahu Palace, Kolhapur (Google Maps)

A brief description of the types of *'wadas'* are as follows:

1. Fort/ Palace *Wada:* Also known as *'Rajwada'* in the regional language. These are palaces built by the ruler and form the focus of the town. The smaller wadas grew around the *'Rajwada'* in hierarchical fashion.

One of the examples of *'Rajwada'* in Kolhapur is the Shahu Palace (Fig. 5.74.) where Chatrapati Shahu Maharaj resided.

2. Nobleman's *Wada*: The nobles were regarded as the important and respectable class. These *wadas* were built on large square plots but were smaller than the *'Rajwadas'.*

3. Tenement *Wadas*: These were the *wada's* with common central courtyard and single rooms lined around it with common washing and toilet facilities. The single rooms were rented out by the owner, mainly to the lower section of the society. The 'design of the *chawls*' is believed to be based on tenement *wada*, which served similar purpose.

4. Temple *wada*: As the name suggests these *wadas* were built along with temples.

5. Muslim *wada:* These were predominant in Konkan region which is the western coastal belt of Maharashtra. The Muslim *wadas* generally had two courtyards which also served as the place to perform prayers.

6. *Wadas* of the Merchants: Merchants were vivid travelers and they brought with them different features and customs from all round the world. Although the basic structure remained the same, merchant *wadas* were distinct due to their ornate facades and detailed lattice work.

6. Ordinary *wada:* These were built around the Rajwada's and formed the streetscape. They were built by individuals on a smaller piece of land and were two storey high. Ordinary *wadas* were found throughout Maharashtra since this was the traditional as well as typical dwelling unit during that period.

Today, *wadas* are rapidly becoming extinct giving rise to buildings and towers in many parts of Maharashtra especially in cities like Mumbai, Pune, Kolhapur and other developing regions of the Konkan belt. However, some *wadas* have survived for hundreds of years and are occupied by families even today. Therefore, it was essential to document *wadas,* since *chawls* (case study 02) are also said to be developed from the basic concepts of *wada* architecture. The built form and various elements of this structure are studied with an emphasis on the role of windows and other openings on the performance of this residential typology and also on occupant comfort.

Fig.5.75. (a). Wada Location - Shivaji Peth, Kolhapur (Google Maps) (Edited in: Photoshop)

WADA INFORMATION

Name of the Building: Pangu *Wada*

Built in: 1894 (which means that the building is about 125 years old)

Number of Floors: G+1.5

Built by: Pangu ancestors

Owner: Current owners are three Pangu brothers.

Total Number of Rooms: There are 18-20 rooms out of which only 10 are used throughout the year.

As stated earlier, *wadas* were predominately built in Maharashtra during the Peshwa rule. Pangu *wada* was also built during the rule of a Peshwa king, Chatrapati Rajashri Shahu Maharaj, in 1894. Based in the heart of the city, this *wada* is located in Shivaji Peth (means market place or business district), that is adjacent to the Rankala Lake (Fig.5.75.(a)). Today, the *wada* is surrounded by contemporary buildings and the entire area is demarcated as *'gaothan'* which means village. The Municipality bye laws for gaothans are extremely lenient and has led to an informal development around the existing wada (Fig.5.75.(b)) (Fig.5.76). Looking at the congested development around the *wada,* it was interesting to study the performance of this building in the current scenario. With no breathing space around the house, what role did the windows play along with the form of the building in providing comfort in this hot-dry climate was explored further.

Fig.5.75. (b). Location - Pangu wada
(Source: Google Maps)

Fig.5.76. Pangu Wada - View from the narrow approach road.

PANGU *WADA* (Fig.5.78.)

Pangu *wada* is of 1.5 floors, which means it is ground plus one with a loft space on top. Owned by three brothers, the *wada* is at present partially occupied by one of the brother and his family. The front portion of the *wada* is converted and rented out as shops. Also, some parts of the upper floors are rented out to students to live and to coaching classes for taking tuitions. About half the house remains vacant almost throughout the year, since it is owned by the other bothers who live outside the country most of the time. Thus, for bearing the maintenance cost of the building, the spaces are rented out by the Pangu family.

The entry to the *wada*, is simple but at the same time it is grand and is raised above the outside road level. The niches along the main door are provided to keep *diyas* (lamps) in the evenings (Fig.5.77.).

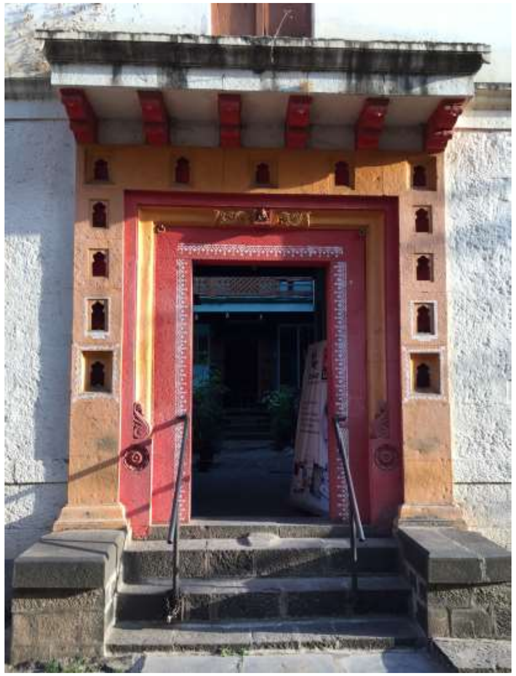


Fig.5.77. Pangu Wada - Main Entrance

Fig.5.78. Pangu Wada, Kolhapur

Ground Floor

The highlighted part in Fig.5.79. is currently used by the occupants and is taken in to consideration for the purpose of this study.

The ground floor of the house rests on a stone plinth (Fig.5.78.). The shop on the right hand side near the main entrance of the house is rented out. The narrow entrance leads to an open courtyard or *chowk*, around which the habitable spaces are structured (Fig.5.80.(b)). Thus, with an introvert plan, the courtyard becomes the main focal point of the *wada*. Apart from acting as transition space, the courtyard has been a place for socializing for generations. Whenever the entire Pangu family is together, the central open space is used by the children to play, by the men and women of the house to sit and chat, to dry spices, etc. It is extensively used during festivals such as Diwali to light crackers, to decorate and celebrate.

The open courtyard consists of tulsi plant and other potted plants Fig.5.80.(a)). Every *wada* has a *tulsi* plant, due to its medicinal qualities and sacredness (Gupta, 2013). There are two external metal staircases which are recent additions, that connect the 1st floor area. The used spaces by the Pangu family on the ground floor are living area (that is partly used and is partitioned by a swing), *deo ghar* (prayer room), kitchen, bathroom and toilet and bedroom. It can be seen from the ground floor plan (Fig.5.79.) (Fig.5.78.) that majority of the windows open in the central courtyard. The external walls are 900mm thick solid stone walls with very few windows that open towards the road side. Thus, although the internal space is cooler than the outdoor space, no windows on the exterior surface restricted the amount of natural light to enter the habitable spaces, making them a bit darker, which seemed to be the reason why the lower level spaces

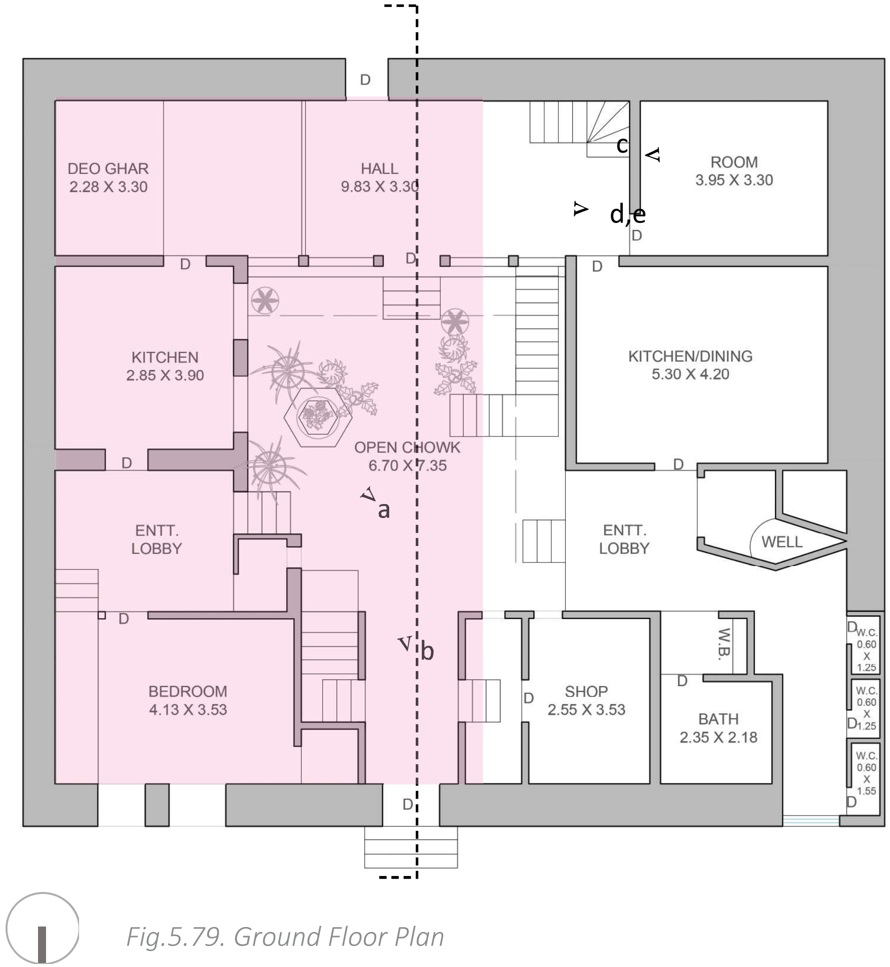


Fig.5.79. Ground Floor Plan

b c

a d e

Fig.5.80.(a). Tulsi Plant   Fig.5.80.(b). Narrow Entrance
Fig.5.80.(c). The other side of the living room divided by swing.

Fig.5.80.(d). Living space - without sliding partition.
Fig.5.80.(e). Living space - with sliding partition.

were not very deep. But still, artificial lights are used in the living room even during day time (Fig.5.80.(d)). No window on external side resulted in narrow living area with 3.3m depth and is divided into two between the brothers by a swing (Fig.5.80.(c)). To solve the issue of darker living area, half of the living room windows are modified. They are now longer, tinted sliding windows with mosquito nets (Fig.5.82.(c)). The windows of the occupied living area are not modified (Fig.5.82.(b)). The double shuttered windows with wooden frames are comparatively smaller. The occupied living area is further divided by a sliding door partition (Fig.5.80.(e)). While one side is used as the living space the other side (adjacent to *deo ghar*) is occupied by their daughter, a special child, so that she could be looked after easily from the kitchen and the living space. The *deo ghar* (prayer room) is an enclosed private space with no windows at all. The kitchen is a well-lit space with two openable double shutter windows (Fig.5.82.(d)). This is also a dining area (Fig.5.82.(e)). The kitchen further continues into washing area, toilet and bathroom spaces (Fig.5.82.(g)). followed by a bedroom. Overlooking the road, the bedroom (Fig.5.82.(f)., with attached bath, is used by the family mostly during nights. The bedroom window, that was initially a door is now used as a window and is usually kept open for the purpose of cross-ventilation and light.

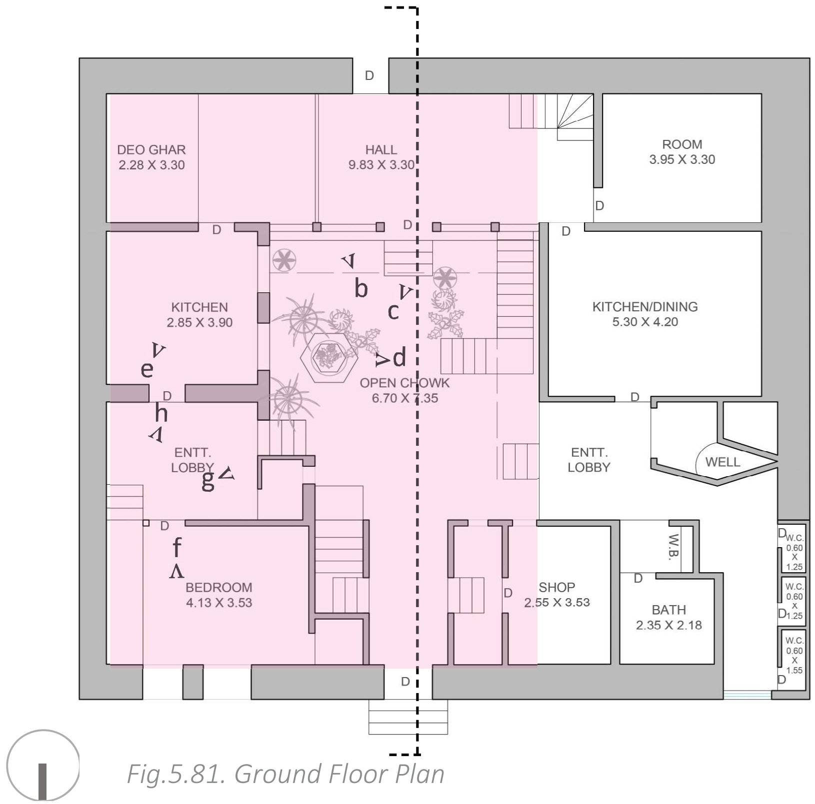
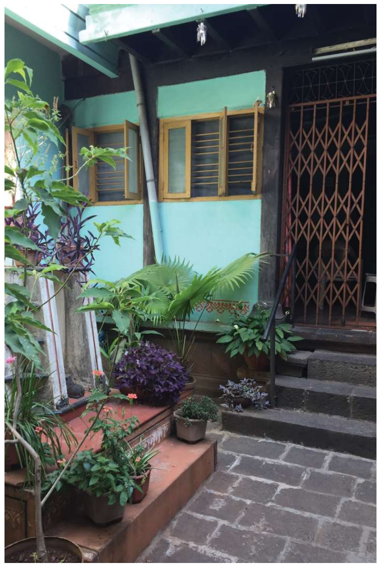


Fig.5.81. Ground Floor Plan

a



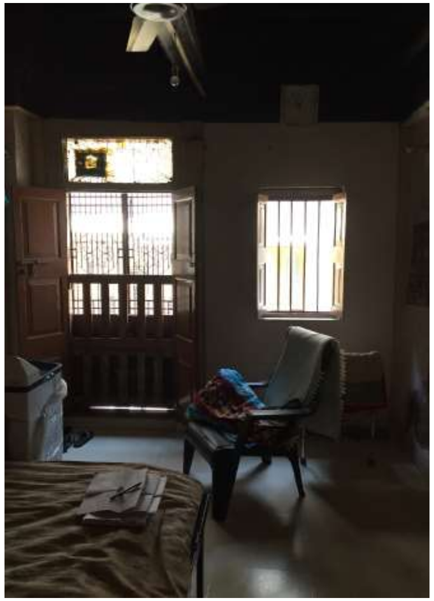
b

Fig.5.82.(a). Different windows on either side of the main door
Fig.5.82.(b). Old Window
Fig.5.82.(c). New Window
Fig.5.82.(d). Kitchen Window from central courtyard
Fig.5.82.(e). Kitchen space
Fig.5.82.(f). Bedroom
Fig.5.82.(g).Washing space
Fig.5.82.(h). Internal staircase leading to the 1st floor.

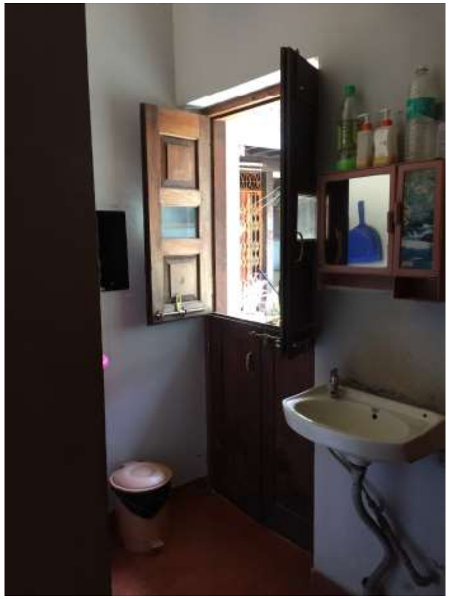
c

d

e



f



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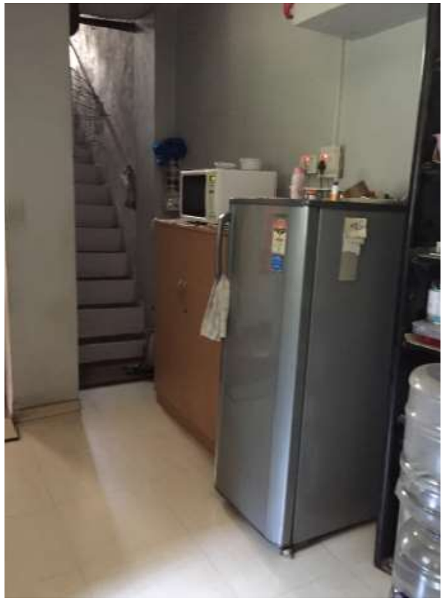


h

First floor

The highlighted part in Fig.5.83. is currently used by the occupants. Half of first floor is occupied, but not entirely by the Pangu family. Out of the three inhabited rooms, one is rented out to 5-6 college boys, the other room is used by the Pangu family to take afternoon naps or to have discussions and is more like a family room. The third room, is a new additional construction which is rented out as a classroom for taking tuitions. Apart from the internal staircase (Fig.5.82.(h)) near the washing area which leads to the family room on the first floor, there are two additional external metal staircases in the courtyard. These two staircases give direct access to the students (Fig.5.84.(b)) and the college boys (Fig.5.84.(a)) without entering the spaces occupied by the Pangu family. The staircases lead to a semi-open corridor space of about 1m depth (Fig.5.84.(c)) and acts as a transition space and a place where one could overlook the activities taking place in the courtyard below.

The room rented out to the college boys is just above the living space on the ground floor (Fig.5.84.(d)). The rectangular room has a couple of windows on the eye level, however, they are always kept shut. The only opening is the double door. The windows, which are more like ventilators are placed at about 2.3m height from the floor. There are 3 such ventilators that are the source of light and ventilation for this room. Since they are placed at a height, they are untouched and are never adjusted as per the user requirements.

The family room along the road is a combination of two rooms. This alteration was made to have more room space. The rectangular room has windows on both the elongated walls (Fig.5.86.(a)) (Fig.5.86.(b)). This room showcases a number of different types of openings

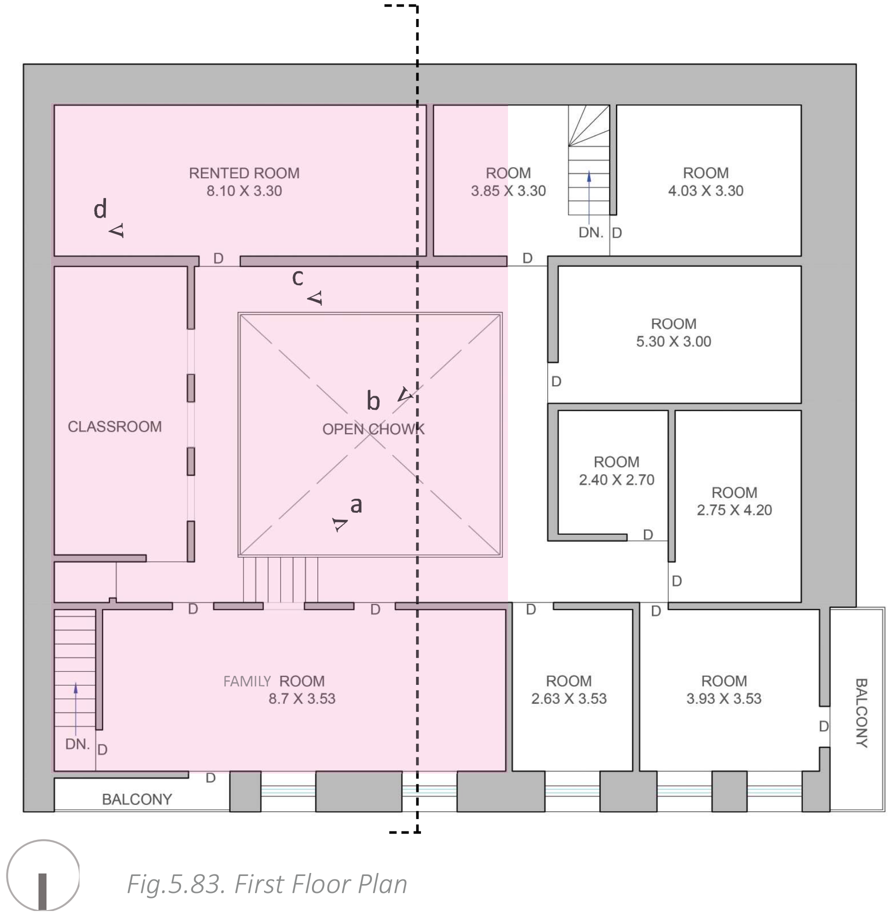


Fig.5.83. First Floor Plan

Fig.5.84.(a). External staircase leading to the new classroom
Fig.5.84.(b). External staircase leading to the boys room
Fig.5.84.(c). Semi-open corridor space
Fig.5.84.(d). Boys room

a

b

c

d

and they are described in brief as follows:

1. The double doors (Fig.5.86.(b)): There are two double doors. One that led to the internal staircase and the other that opened in to the corridor space.

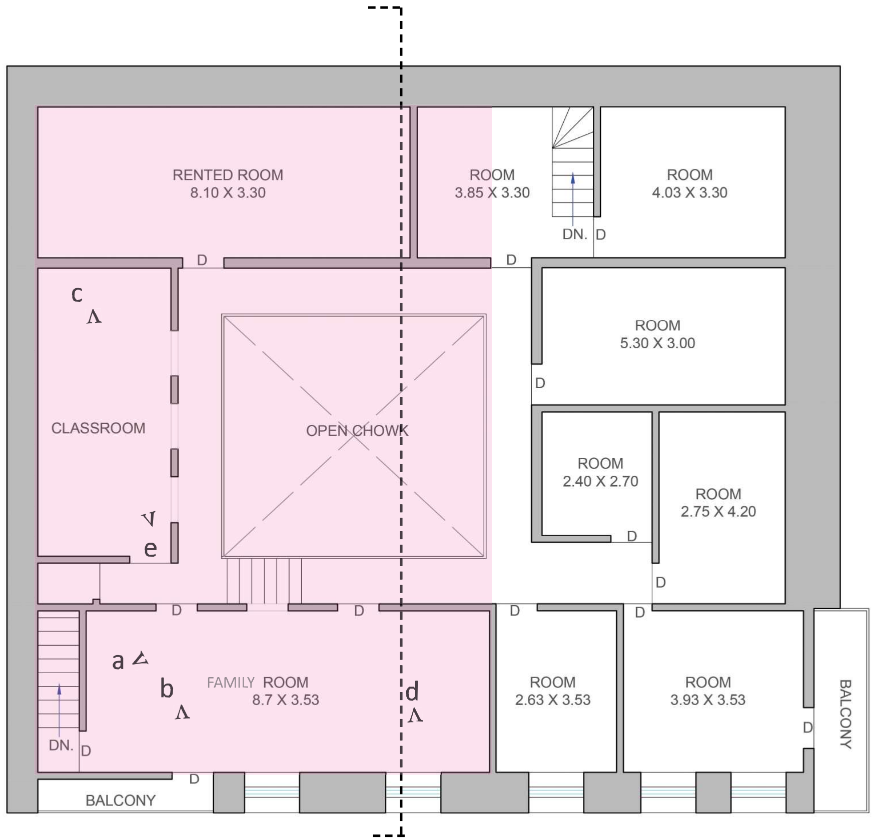
2. The full-height window (Fig.5.86.(d)): These windows are on the road side. They are three in a row and they are opened depending upon the occupancy and the activity taking place in the room.

3. The small window (Fig.5.86.(a)): The double shutter wooden frame windows are aligned on the corridor side. The two windows are opened as per the use of the space.

4. The light source (Fig.5.86.(a)): These are round holes at a height of about 2.5m. They are non-openable single glazed holes and act as the source of light.

Thus, depending on the use of space and the number of occupants, the natural light in the room and the thermal parameters of the room could be altered since there are number of adaptive opportunities available to the occupants to choose from.

The third occupied room is the new construction by the owners (Fig.5.86.(c)) (Fig.5.86.(e)). This new room is built on top of the existing kitchen space. Adjacent to this room, a common toilet is also constructed for the students to use. This additional room is made for renting out to obtain some extra income. With brick walls and metal roofing, this structure is supported with I-sections. Again, the windows are on elongated wall overlooking the courtyard. However, the windows in this new construction are single glazed sliding windows. This space is used from early morning till evening by students during school days and remains vacant during the school holidays.



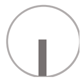


Fig.5.85. First Floor Plan

Fig.5.86.(a). Family room - Smaller windows on corridor side with light source.
Fig.5.86.(b). Family room - Double door - opens in to the corridor
Fig.5.86.(c). Family room - Longer window with light source
Fig.5.86.(d). New Classroom
Fig.5.86.(e). New Classroom

a

b

c

d

e

As observed, all the three rooms have their own characteristics and vary drastically in terms of the number occupants, occupancy pattern and the activities that happen in these spaces. However, one common link between these rooms is the narrow corridor overlooking the central courtyard. Apart from transition area, the constricted semi-open space is also used as a space to dry clothes.

Environmental analysis of the occupied spaces on the ground and first floor are discussed in the following chapter.

Fig.5.87. Section through Pangu Wada

Occupancy Pattern (Fig.5.88.)

The large house consists of around 18-20 rooms, mainly in the form of big halls. However, only 10 rooms are used throughout the year. These spaces are occupied by different occupants, namely, the Pangu family, the college boys who live in one big room on the first floor which is rented out to them and the children who visit every day to take tuitions except during summer vacations. The number of people residing in the *wada* is around 10-11 that include three family members of the Pangu family with their one full time house help and rest are the college boys who live on the first floor as paying guest (tuition boys are not included). Since, in the previous two case studies, the occupancy pattern of a family is considered, same is considered for this case as well.

On a daily basis, the Pangu family mostly uses the ground level. Since, the house is divided between the brothers, half the living room is used by the family who resides here. Furthermore, this half living room is divided in to two by a sliding wooden partition. The living space next to the entrance, is mainly used by Mr. Pangu for socializing and to read and acts as semi-public space. The other half of the living room which is next to *deo ghar* (prayer room) and kitchen, is occupied by the daughter 95% of the time. Since, she is bed ridden, most of the daily activities of the other house members (especially the mother and the house help) revolves around her. The television is also kept in this part of the living room. The sliding door is kept open most of the times and is only shut for private routines. This part of the living room is also used for sleeping by the daughter and the maid at night. The kitchen is used for preparing meals of the day and also to have meals, since it is also the dining area. The bedroom is used at night by Mr. and Mrs. Pangu to sleep. Apart from this the bedroom is hardly occupied

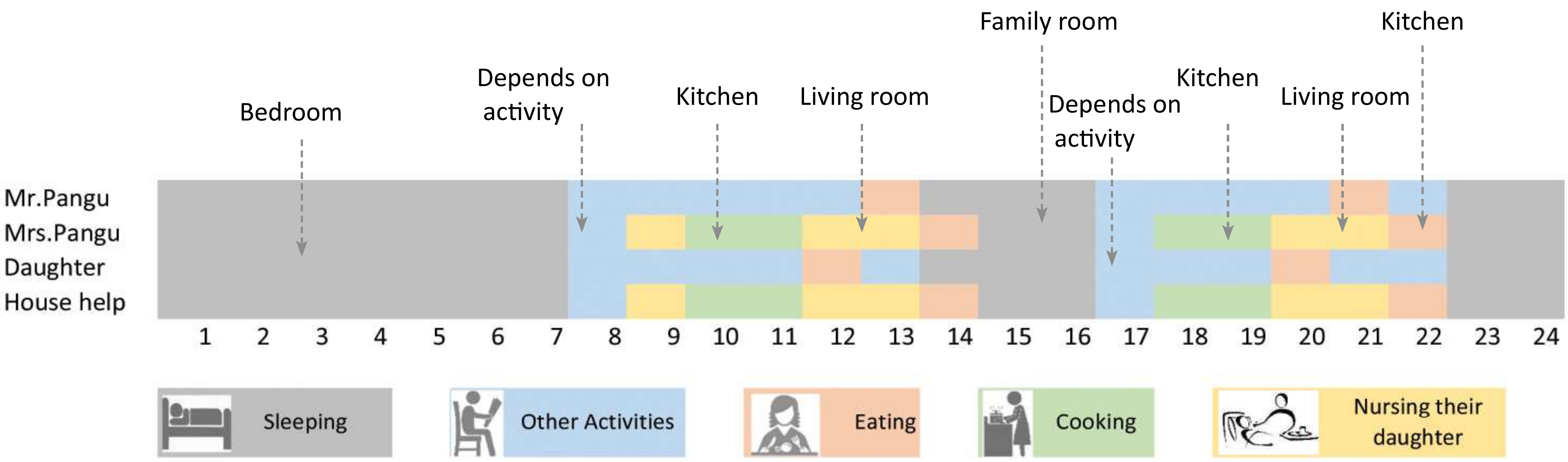


Fig.5.88. Average Daily Occupancy Pattern

throughout the day. The other room used by the people of this house is the family room on the first floor. During the day, this room is used for drying clothes and in the afternoon it is used by Mr. Pangu to take naps (Fig.5.89.).

One of the tag in the occupancy chart is of 'other activity' and no specific area is pointed out. That is because, it all depends on the activity. For example: if it is reading newspaper then it takes place anywhere in the house or chatting with someone also takes place anywhere in the house.

Also, the Pangu family seldom leave their residence and find the courtyard as a breather. Hence, instead of going out into the congested market area, they prefer indoors.

The space available to a family of three in this *wada* is beyond sufficient as compared to the restricted space of Mr. Chavan's unit in the *chawl*. Therefore, the excess room space and lower occupancy also becomes one of the reasons for comfortable living conditions in this typology.

Fig.5.89. Siesta time - Mr.Pangu

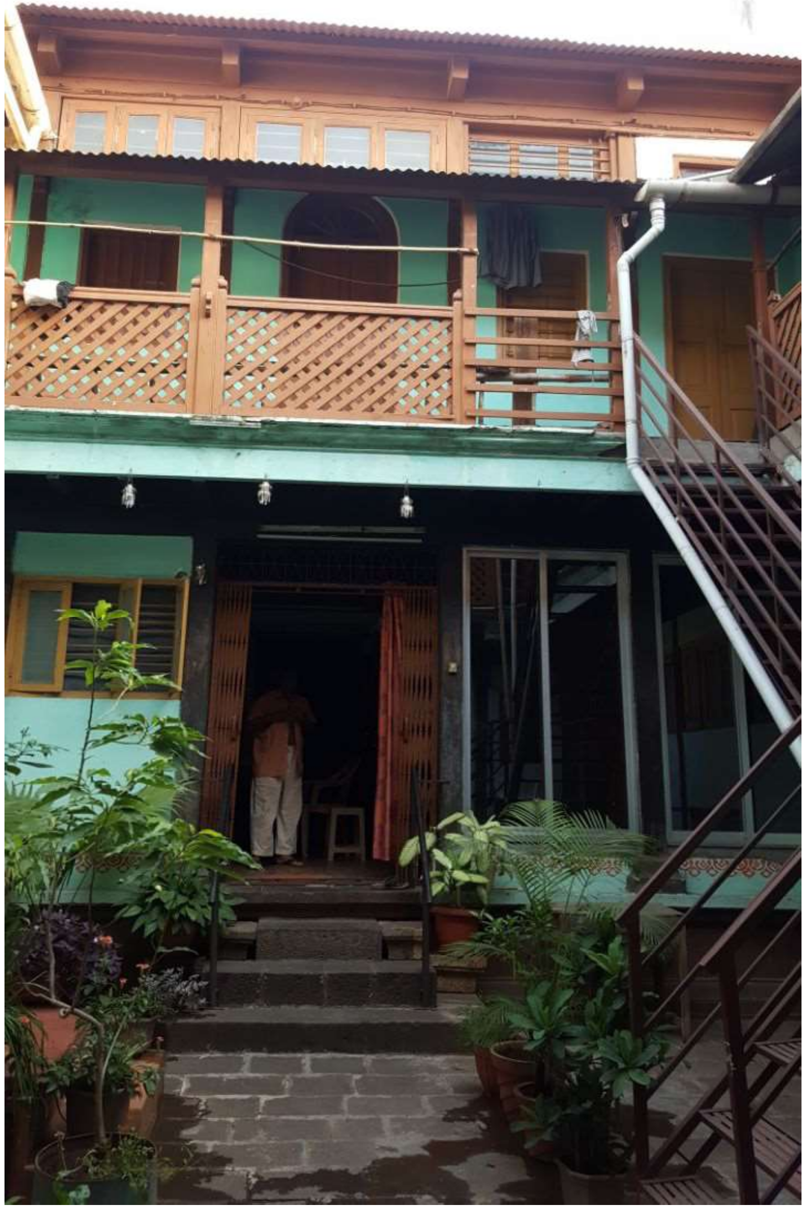


Fig.5.90. Different types of windows at different levels.

THE HOT-DRY WINDOW

Wadas and *chawls* exhibit a very similar form. Both the typologies have enclosed spaces aligned along a central courtyard. The courtyard in this case also serves the same purpose. Additionally, it plays a significant role with respect to routine cultures such as worshipping the 'tulsi' plant everyday as per the Hindu customs, which also has medicinal properties. Apart from worshipping the *'tulsi'* plant, the courtyard of this *wada* is not used as extensively, since the overall occupancy of the place is relatively low. However, the members of the Pangu family, have fond memories of the open *chowk (courtyard)* being used by their relatives and guests to play games, to chat late during night time, to celebrate festivals such as Diwali and so on. Now, with two additional metal staircases, the open-to-sky courtyard mostly acts as a transition space.

The external walls are about 900mm thick stone walls and the walls on the internal side are 230mm thick. It is assumed by the owner that the thick outer walls were for safety. The external walls do not have any openings except the wall facing the main road. All the other windows open in to the courtyard on both the floors. It was observed that the windows facing the external side were full-height windows while the windows overlooking the courtyard were smaller. It is presumed that the smaller windows opening in to courtyard provided privacy. The internal space was not visible from the courtyard due to smaller window size and also because the structure was placed on a plinth of about 700mm. The small windows and the main door were always kept open throughout the day. The main door was closed at night time for security. Similar to *chawls*, the combination of windows and courtyard help in providing indoor thermal and visual comfort for its user. But, unlike *chawls*, with around 18-20 rooms, the type of window in the *wada* changes with every space with respect to the function of the space (Fig.5.90.). Thus, for the purpose of study, three types of windows/openings are identified and they are as follows:

The small window:

The double shutter teak wood window in the living area, kitchen as well as the family room (first floor) opens in to the courtyard (Fig.5.91.(a) (b)). These are very simple wooden windows with metal grill for safety. Placed on a sill level of 800mm, the window in the living area also has mosquito net placed on the entire opening from the inside, which in a way restricts the accessibility to the window and natural light from entering the habitable space. The shutters of the lower level window have opaque glass panels while the one on the first floor are of solid wood. The users prefer this window over sliding window because when opened, they provide 100% clear opening as opposed to sliding windows. These double shuttered windows are always kept open on the ground floor in the living and kitchen area because these spaces are used by the occupants most of the time (Fig.5.92.(b) (c)). On the other hand, the windows on the first floor in the family room are kept shut (Fig.5.92.(a)). They are opened only when the space is used by the occupants. Although these windows provide cross-ventilation and are smaller, which is perfect as per the climatic conditions of the region (hot-dry), the occupants

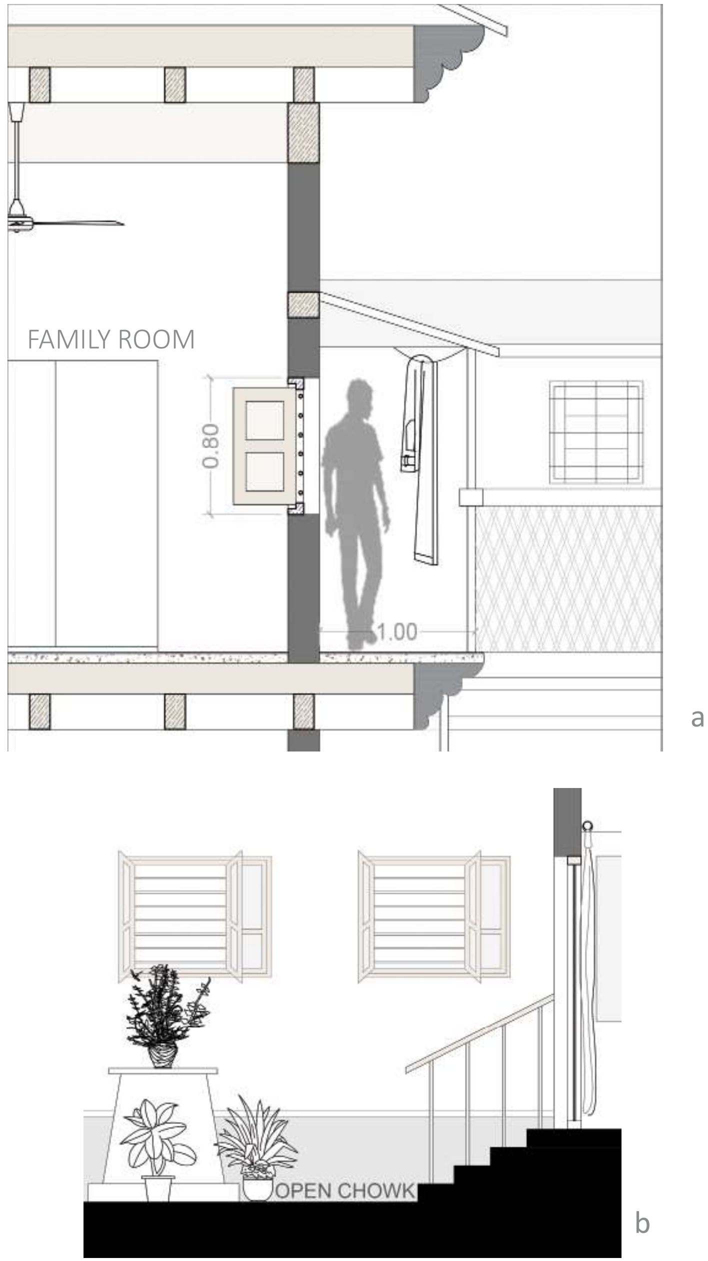


Fig.5.91.(a). Small Window - Section through family room (1st floor)
Fig.5.91.(b). Small Window - Elevation - kitchen window (Ground)

were not satisfied with the size of it. If given a choice, they preferred larger windows which they believe, would allow more natural light and fresh air in to the living spaces, something that they don't receive due to the present window size.

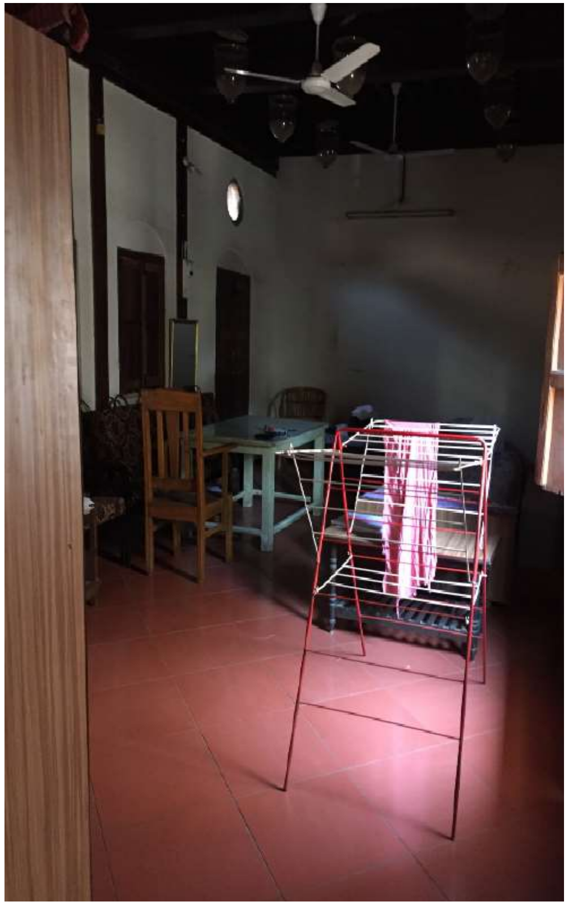


Fig.5.92.(a). Small window in the family room on 1st floor

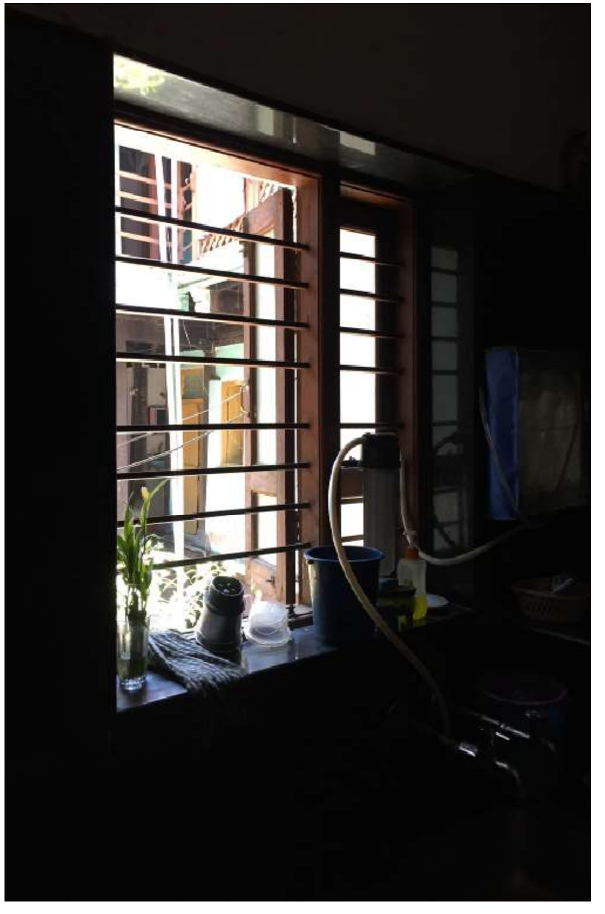


Fig.5.92.(b). Small window in the kitchen on ground floor

Fig.5.92.(c). Small window in the living space on ground floor

The full-height window (Fig.5.93.):

This window is located in the lower level bedroom area (Fig.5.94.(a) (b)), where a door has been converted into a full-height window. Apart from this, three full-height windows are also present on the first floor family room (Fig.5.94.(c) (d)). These windows are placed on the 0.9m thick external walls on both the floors. Every window in this form varies a bit in design, however are identical in size. Placed on the inner side, the converted bedroom window on the ground floor (Fig.5.94.(a)), also has a ventilator on top along with an exhaust fan. It has metal safety grills from the outside and a simple wooden lattice railing from the inside.

One of the window in the family room on the first floor, comprises of four teak wood openable shutters, two on top and two on bottom (Fig.5.93) (Fig.5.94.(d)). These shutters open on the inside as compared to the other window in same line that opens on the outside (Fig.5.94.(c)). Four openable shutters provide the user with the flexibility of choosing the percentage of window they want to open to feel comfortable. There are no metal safety grills for these windows but only a half-height simple lattice work that acts as a railing.

The light source (Fig.5.93.):

The circular windows are placed on the 0.9m thick external walls as well as on the 0.23m thick internal walls on both the floors. They are placed on top of the main window (Fig.5.94.(c)), but not above every window. It is presumed that these might be secondary sources to acquire indirect natural light into the room while preventing the solar radiation from entering the habitable spaces. They are non-openable windows and are present in the big family room on the first floor. They are not

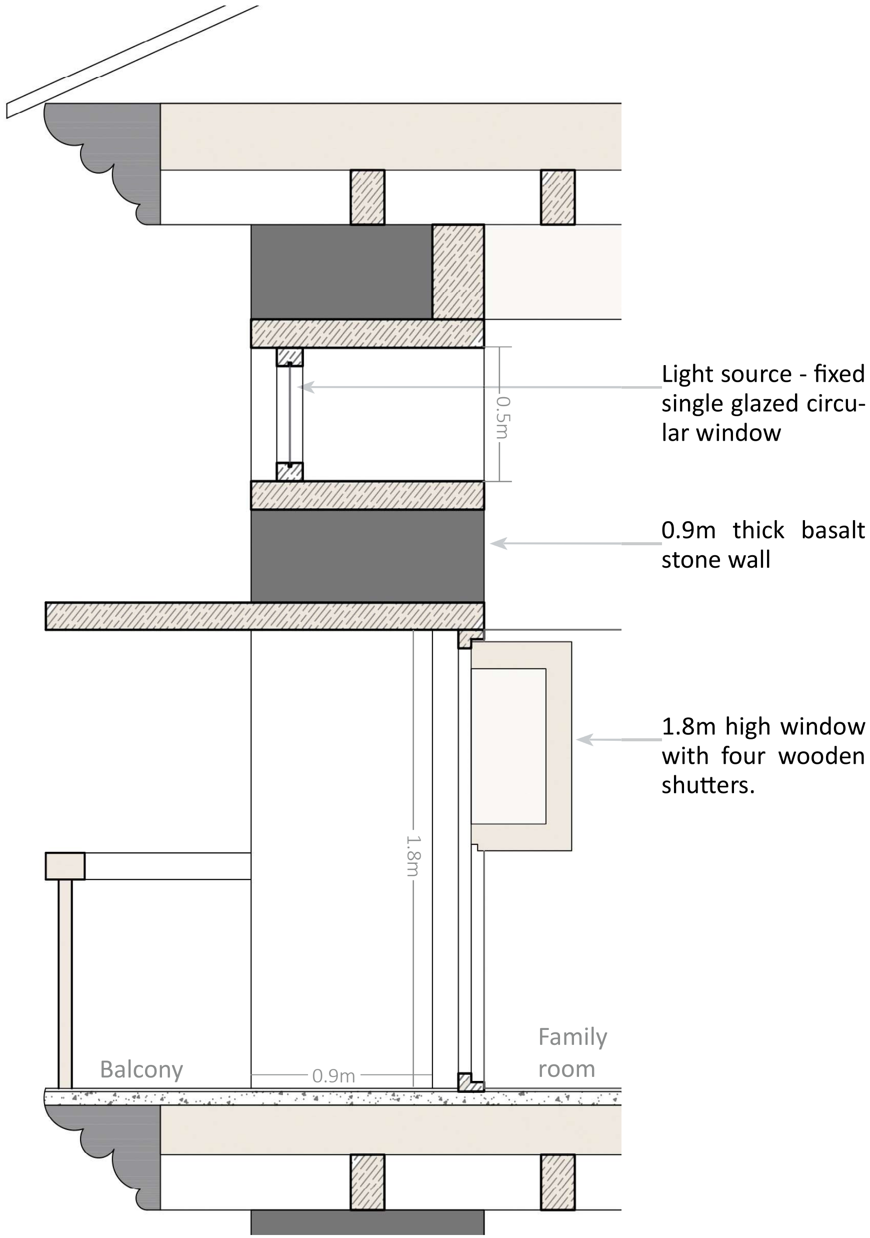


Fig.5.93. The long window and the light source

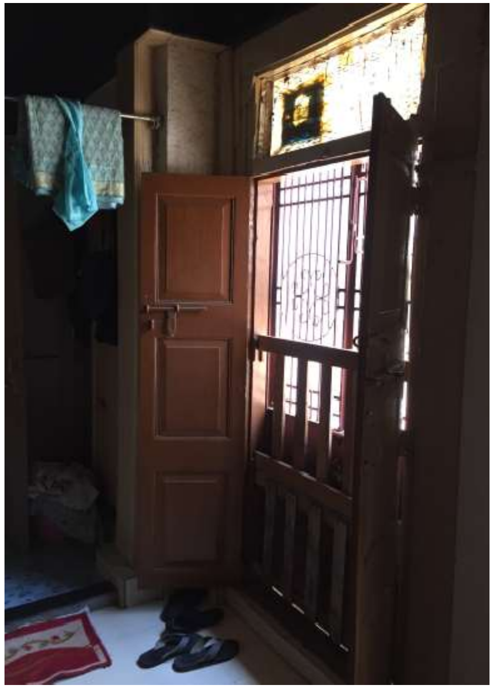


Fig.5.94.(a). Long window - Ground floor bedroom

Fig.5.94.(c). Long window in the family room on 1st floor

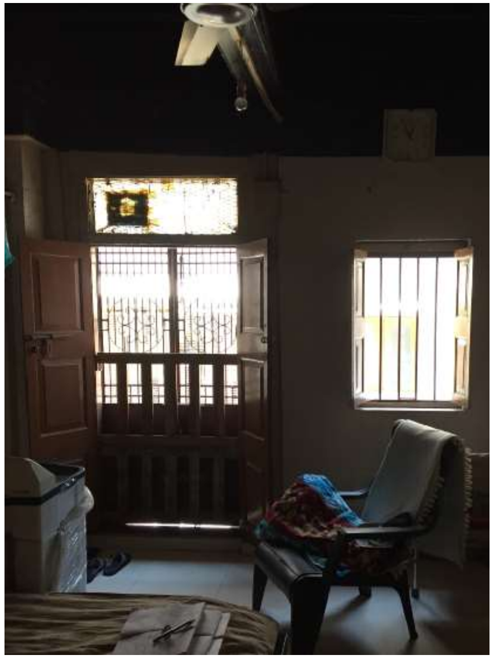


Fig.5.94.(b). Long window - Ground floor bedroom

Fig.5.94.(d). Long window in the family room on 1st floor

easily accessible since they are placed on a height and also they cannot be operated by the user since they are fixed (Fig.5.93). Hence, these holes of light remain untouched and they light up the room to some extent, irrespective of the occupancy level of the room.

With respect to the spatial configuration and window design, some of the comments from an interview with the occupants are as follows:

Q: How does the building perform during different seasons (summer, winter and monsoon?

A: Warm in winter and cool in summer. Very pleasant in all the seasons. The most used space in the wada has always been the 'chowk' (central courtyard). Even today it is used by the occupants for chatting at night, used by the children to play cricket, badminton and hide seek. It is a social space in the house and is liked by every member of the family.

Q: What do you think about the windows in the house? Would you like to change them or modify them? Why?

A: Some windows of the house like the kitchen window have been modified. The smaller windows in the house are not liked by the family members because of the inadequate light and wind/breeze.

Q: Are there any alterations made to the existing windows? If 'yes', then what? Why were they made?

A: The kitchen windows were made bigger to receive more light. One extra window was added at one of the staircase landings in order to get more light and breeze. Mosquito nets have been installed. Traditional windows are replaced by bigger sliding windows in one part of the living area to receive more light and breeze.

Q: What role do you think the windows play in maintaining indoor comfort?

A: They provide fresh air and natural light.

Q: How important are the windows in terms of pollution, external noise, privacy? How do the existing windows help?

A: Privacy is not an issue as such because the design of the wada is introvert. Being located centrally in a busy market area, we face lot of dust problem due to which the windows facing the road are kept shut most of the time.

Conclusion:

Unlike the apartment window, there are very less number of layers to the *wada* windows. It can be said that a hierarchy of simplicity can be observed, the apartment window being very complex, a bit simplistic window design for *chawls* and the *wadas* being the simplest. Since, most of the windows are inward looking, the users do not experience any issue with respect to privacy and safety. Hence, there are no curtains, blinds, safety grills to the windows (except at one or two places).

Apart from substantial thermal mass from the thick external walls, windows also contribute in creating a micro-climate along with the central courtyard and helps in maintaining comfortable indoor environments. Inspite of having comfortable indoor environment (as per fieldwork records), the occupants complained of inadequate natural light and ventilation. According to the observations made during the fieldwork, it is strongly believed that the changes in the internal layout of the *wada*, few windows that are shut permanently, changes in the type of occupancy and also changes in the surrounding context (new buildings and increase in density) were the main reasons that the Pangu family felt the need to change their existing windows.

Fig.5.95. Long window in the family room on 1st floor - One shutter is left open for the drying of clothes

OVERALL CONCLUSION

All the window types from the three typologies studied exhibit unique styles and methods incorporated by the occupants according to their needs while some were not altered at all. All the windows are operated in one way or the other to suit the user. The least modification, was observed in the *wada* windows whereas maximum modification was observed in the apartment windows. Considering the time when the *wada and chawl* were built about 125yrs ago and 90 years ago respectively and the time apartment was built, about 14 years ago, these modifications should have been the other way round in the present scenario. The old windows should have changed according to the changes in climate and the occupants whereas the new windows should have been designed in such a way that least changes would need to be implemented. Thus, the findings from the three case studies points out the need to change our perception of designing a window and not just provide a hole into a solid building mass. This study also points out at the need for learning from the vernacular buildings to design better windows that are climatically responsive.

Thus, to understand the role of windows from the three typologies from the fieldwork, their environmental performance is documented and discussed in detail in the following chapter, which also forms the basis of the computational simulation.

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Fig.5.24. A timeline of highrises built in Mumbai shows the construc-tion boom of recent years.Available from https://www.citylab.com/equity/2015/06/the-long-shadow-of-mumbais-mushrooming-highrises/393911/. [Accessed 03 February 2019].

Fig.5.25. Panorama Tower Location. Available from https://www.google.com/maps/place/Mumbai,+Maharashtra,+India/@19.1390084,72.8378256,575m/data=!3m1!1e3!4m5!3m4!1s0x3be7c6306644edc1:0x5da4ed8f8d648c69!8m2!3d19.0759837!4d72.8776559. [Accessed 05 February 2019].

Fig.5.27. Panorama Tower Location. Available from

https://www.google.com/maps/place/Mumbai,+Maharashtra,+India/@19.1390084,72.8378256,575m/data=!3m1!1e3!4m5!3m4!1s0x3be7c6306644edc1:0x5da4ed8f8d648c69!8m2!3d19.0759837!4d72.8776559. [Accessed 05 February 2019].

Fig.5.46. Location of Ahmed Sailor Chawl, Parel - Mumbai. Available from https://www.google.com/maps/search/ahmed+sailor+chawl/@19.009399,72.8423349,686m/data=!3m1!1e3. [Accessed 07 February 2019].

Fig.5.70. Kolhapur Location. Available from https://www.google.com/maps/place/Kolhapur,+Maharashtra/@16.643628,73.8335435,10.5z/data=!4m5!3m4!1s0x3bc1000cdec07a29:0xece8ea642952e42f!8m2!3d16.7049873!4d74.2432527!5m1!1e4. [Accessed 12 April 2019].

Fig.5.71. Maharashtra regional classification.
Available from https://www.google.com/maps/place/Maharashtra/@18.7719548,72.2765713,6z/data=!3m1!4b1!4m5!3m4!1s0x3bcfc41e9c9cd6f9:0x1b2f22924be04fb6!8m2!3d19.7514798!4d75.7138884 [Accessed 12 April 2019].

Fig.5.74. Shahu Palace, Kolhapur. Available from https://www.google.com/maps/place/New+Palace+(Kolhapur)/@16.7194229,74.2295095,749m/data=!3m1!1e3!4m5!3m4!1s0x3bc10062e28a31af:0x2d9cc5cd17874ec0!8m2!3d16.7194178!4d74.2316982 [Accessed 12 April 2019].

Fig.5.75.(a). Wada Location - Shivaji Peth, Kolhapur. Available from https://www.google.com/maps/place/C+Ward,+Kolhapur,+Maharashtra/@16.691901,74.2164417,1502m/data=!3m2!1e3!4b1!4m5!3m4!1s0x3bc10009e851948b:0x66ee1e8fb88c1a19!8m2!3d16.696152!4d74.2232888. [Accessed 12 April 2019].

Fig.5.75.(b). Location - Pangu wada, Kolhapur. Available from https://www.google.com/maps/place/C+Ward,+Kolhapur,+Maharashtra/@16.6939511,74.2200428,310m/data=!3m1!1e3!4m5!3m4!1s0x3bc10009e851948b:0x66ee1e8fb88c1a19!8m2!3d16.696152!4d74.2232888. [Accessed 12 April 2019].

CHAPTER 6

FIELDWORK & SURVEY

FIELDWORK

The previous chapter gave a detailed insight into the three different housing typologies belonging to different periods. Historical background for each of the dwelling units was presented along with location and weather conditions of these places. Additionally, the layouts of each typology were explained in detail with the help of architectural drawings and photographs. The occupancy patterns were drawn based on the information collected from the occupants as well as through observations made during the site visits. The most important section of the former chapter was the detailed analyses of the windows in these dwellings. Each window was unique as they represented the period they were built in, their users, their needs, their culture and the requirements with respect to the quality of spaces they lived in. It was very interesting to see how these openings were responsible for the characteristics they developed with the indoor as well as the outdoor environment, with private, semi-private and public spaces along with a routine that they had formed with the occupants. Thus, it was established that windows played a significant role in developing a social fabric, be it on a public or private level or both. Having said that, this chapter further presents and discusses the environmental role of the documented windows. It focuses on the indoor environmental quality of studied spaces and hence aims at drawing a relation between the window, the user and attainment of their comfort.

The environmental fieldwork was carried out since it helped in critically reviewing the performance of the indoor and outdoor spaces. The sequence of fieldwork study is as follows:

1.Contemporary Window of an Apartment, Andheri – Mumbai

a. Spot Measurements
b. Aftab Luminance
c. Continuous Measurements
d. Conclusion

2.Hot-Humid Window of a *Chawl*, Parel – Mumbai

a. Spot Measurements
b. Aftab Luminance
c. Continuous Measurements
d. Conclusion

3.Hot-Dry Window of a *Wada*, Shivaji Peth – Kolhapur

a. Spot Measurements
b. Aftab Luminance
c. Continuous Measurements
d. Conclusion

4.Overall conclusion

The environmental factors that were measured under spot measurement (Table.6.1.) and the tools (Table.6.2.) used for measuring them are shown in the adjacent tables.

The spot measurements were carried out in the immediate area surrounding the dwellings as well as in the indoors, which allowed the evaluation of how the users perceived (physiologically and physically) the environment around them. These measurements were taken for a single day when the data loggers where installed. The

Environmental factors		**Heat Loss Mechanism**
Air Temperature	°C	Convection
Relative Humidity	%	Evaporation
Wind velocity	m/s	Convection, Evaporation
Illuminance	Lux	

Table.6.1. Measured environmental factors

Instruments Used	Designed for the measurement	Image
Vane Anemometer + Thermohygrometer	Air flow velocity (m/s) Temperature (°C) Relative Humidity (%)	
Lux Meter	Light Intensity	
Infrared Thermometer	Non-contact surface temperature	

Table.6.2. Instruments to measure environmental factors

instruments mentioned in table 6.2 were used to take the measurements which were then reviewed and critically interpreted. The readings aided in identifying the micro-climates and the complexity created by various factors such as building geometry, building materials, vegetation and so on. They also helped in detecting the environmental problems that could be addressed and resolved by giving design solutions which can then be calibrated using simulation tools.

Apart from spot measurements, the quality and quantity of natural light were analysed through an iPhone application known as Aftab Luminance. This application created HDR images that resembled realistic luminance values. The images were further calibrated by adjusting the scale to evaluate and compare.

Furthermore, continuous measurements were taken for an elongated period of time to monitor the temperature and humidity levels inside the dwelling along with the outdoor weather conditions. The readings obtained, helped in monitoring the climatic changes outdoors as well as the environmental changes taking place indoors. The figures obtained from these devices were plotted in graphs for further analysis that helped in identifying the reason for the pattern created by the readings and linking them to the other findings from the fieldwork.

The next section gives a detailed description and analysis of the environmental fieldwork carried out at the three sites, extensively in the summer months.

Fig.6.1. Fieldwork at Wada, Kolhapur

The Contemporary Window from an Apartment

Andheri (Mumbai)

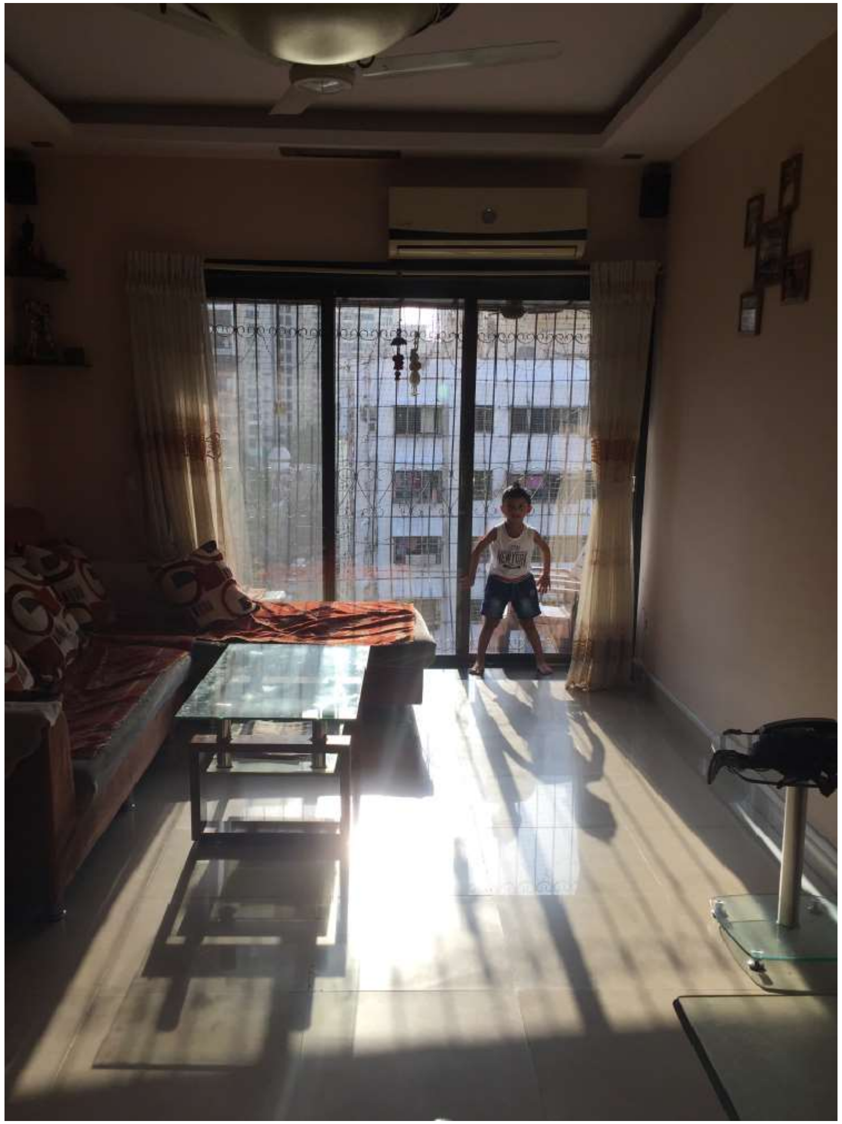

Fig.6.2. Apartment-modified window

SPOT MEASUREMENTS:

The spot measurements for the apartment in Andheri were taken on a partly sunny evening on 11th April 2018, between 17:00 and 18:00. To understand if the indoor and the outdoor environment are in sync with each other, the weather conditions for the particular time period for that day were also taken into consideration from a weather database. Total 21 points were marked in the entire apartment. The readings were taken in living cum dining room, both the bedrooms, both baths, kitchen as well as balcony or the semi-open cantilevered area.

Climatic data for the date and time period the measurements were gathered, are taken from a weather database and the recorded data is as follows:

a. Air Temperature: 31°C

b. Humidity: 64%

c. Wind Speed: 4.6m/s (Direction: West)

d. Sky Conditions: Partly Sunny

Weather Data from www.wunderground.com

i) <u>Air Temperature</u> (Fig.6.3.): It was observed that the air temperature in the living/dining area was the highest, about 34.8°C. This value gradually decreased in the rear bedroom and kitchen area. The bedroom facing the projection recorded the lowest temperature, in the range of 32.3°C – 31.0°C. The same temperature difference was observed in the semi-open space as well. The temperature in the projected area in front of the living space was higher as compared to the temperature in the same space in front of the bedroom.

The following reasons were believed to be responsible for the

Fig.6.3. Spot measurement - Air temperature

temperature difference in the semi-open space and the living and bedroom spaces:

a. Windows: The modified living room window was full height, that allowed more direct solar radiation in to the living space (Fig.6.4.). Since, the living room is west facing, the evening sun penetrated directly in to the area, making it very warm. While on the other hand, the bedroom window has a sill level of about 450mm which partly obstructed the direct solar radiation to enter the immediate space (Fig.6.5.)

b. Obstructions: The semi-open space adjacent to the living area did not have any obstructions as such, hence it allowed direct solar radiation to enter the living space. Whereas, the washing line with clothes drying, obstructed direct solar radiation from entering the bedroom space (Fig.6.5.).

c. Time: The first point of spot measurement was taken at 17:10 in the semi-open space adjacent to the living space while the last measurement taken was at 18:00 in the semi-open space adjacent to the bedroom. Thus, with the setting sun the temperature also dropped.

Therefore, it is believed that the combination of the above three factors is most likely the reason for a temperature difference of approximately 4.5°C.

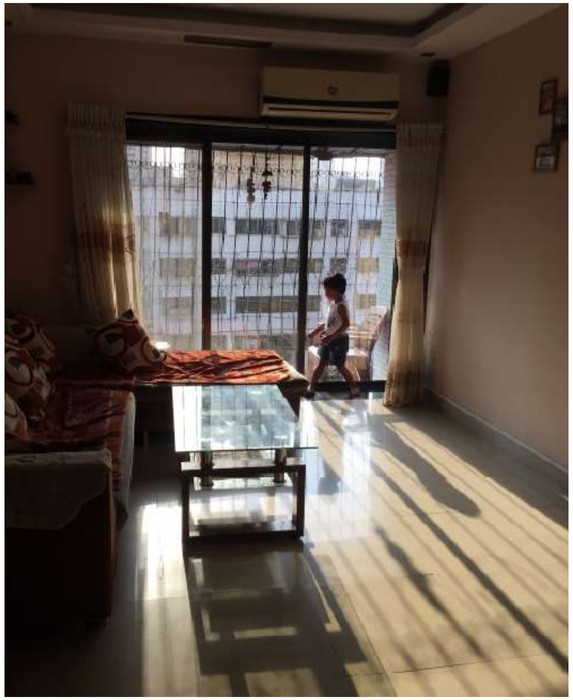

Fig.6.4. Full-height living room window

Fig.6.5. Front bedroom window

ii) **Humidity** (Fig.6.6): It was observed that the humidity levels in the west portion of the apartment was lower as compared to the east side of the apartment. As expected the semi-open space showed lowest humidity levels followed by bedroom, living room and kitchen. The rear bedroom showed highest humidity levels. It was also observed that the humidity levels next to windows, for example in living room, front bedroom, kitchen area, showed lower humidity levels as compared to the internal spaces away from the openings.

Fig.6.6. Spot measurement - - Humidity

Fig.6.7. Spot measurement - Wind velocity

iii) **Wind Velocity** (Fig.6.7.): In spite of being on the 7th floor, apart from the semi-open space/balcony and the immediate indoor space, there was no air movement felt in the apartment. No cross ventilation as such and hence the indoor air quality seemed stagnant and muggy.

iv) <u>Illuminance</u> (Fig.6.8.): It can be seen from Fig.6.8. that the illuminance level of spaces next to the windows were higher and decreased as one moved more into the indoors. Since the readings were taken in the evening and the apartment is west facing, the amount of light entering the living space and the west bedroom was the highest. As compared to the living room, the west bedroom received comparatively lower natural light. Having said that, according CIBSE the recommended lighting design criteria for the different spaces are as follows:

Building zone or space	Recommended illuminance (lux)
Entrances	200
Corridors	100 for daytime, 20 for night time
Stairs, stairwells, and lift lobbies	100 on the treads
Bathrooms and toilets	100 for toilets, 150 for bathrooms
Bedroom	100
Living room and kitchens	200
External lighting	10 for pathways and car parks, 20-30 for care homes with transition between interior and exterior areas

Table.6.3. CIBSE recommended lighting levels

The illuminance levels in the apartment was very unbalanced. If each space is analysed, the following observations can be made:

1. In the rear bedroom, the minimum value recorded was 18 lux and maximum was 56 lux (near the window). Similarly, minimum value recorded was 52 lux in the dining area. These were comparatively less illuminate spaces.

2. However, the least illuminated area was the passage between

Fig.6.8. Spot measurement - Illuminance

the kitchen and bath where the minimum value recorded was 13 lux.

3. The west bedroom receives a bit more than sufficient light. The maximum noted reading was 740 lux, while according to CIBSE the required luminance level for bedroom is only 100 lux (Table.6.3.)

4. The amount of light received in the living space, especially near the windows was high, the maximum reading recorded was 1890 lux. Whereas, the recommended lighting level is 200 lux.

AFTAB LUMINANCE

Furthermore, the HDR (High Dynamic Range) images were captured from an iPhone application known as Aftab Luminance. The application gives additional information regarding the quality of light in the indoors or outdoors. This exercise allowed analysing the level of brightness, sparkles, glare and dull spaces in the studied apartment, which further helped in highlighting the problematic spaces with respect to light distribution.

The images were taken in the living room (Fig. 6.9.(a),(b)), the front bedroom (Fig.6.9.(c),(d)) and the rear bedroom (Fig.6.9.(e),(f)). All the images were taken at the time when the spot measurements were recorded. Further, a consistent scale was set for every image that enabled in understanding the lighting condition of the spaces, during the same time in different rooms of the apartment. The results corresponded with the realistic luminance value and supported the illuminance readings obtained during spot measurements.

As per the spot measurements, maximum illuminance levels were recorded in the living room as also seen in the images (Fig.6.9.(a)) (Fig.6.9.(b)). Similarly, the bedrooms recorded lower values. Also, the living room (Fig.6.9.(a)) and the front bedroom (Fig.6.9.(c)), both are west facing. However, with a smaller window in the bedroom with washing line in the window and full-height window in the living room with no obstruction, the difference in the light levels is quite evident from the images as well as the spot measurements.

Fig.6.9.(a). Living/Dining area

Fig.6.9.(b). HDR - Living/Dining area

Fig.6.9.(c). Front bedroom

Fig.6.9.(d). HDR - front bedroom

Fig.6.9.(e).Rear bedroom

Fig.6.9.(f). HDR - rear bedroom

CONTINUOUS MEASUREMENTS

Apart from spot measurements and Aftab images, continuous measurements were taken, for which 8 Tinytag Plus 2 - TGP - 4500 - Gemini Data Loggers were used. These instruments have built-in sensors that monitor temperature from -25°C to +85°C and relative humidity from 0 to 100%.

The instruments were placed in the apartment on 10th April 2018 at 11:15 and were removed from the apartment on 27th June 2018 at 17:15. The logging interval for each data logger was set at 15 minutes time interval. Three data loggers were placed in the apartment in three different locations (Fig.6.10), for the following reasons:

a. Balcony: To acquire the outdoor climatic condition, so that it can be compared and analysed with the indoor thermal variations.

b. Living room: This area was used extensively by the Oza family during the day, throughout the year. It was used for relaxing, for having meals, for watching television, for reading, for socializing and so on. Also, the window of this room was modified to a great extent by the user to meet their requirements of a bigger space and to obtain more light and ventilation (See Chapter 5, p 113-117). Last but not the least, this room had an air conditioning unit which was extensively used by the occupants throughout the year. Hence, with so many rationales the living/dining area became an important space to be analysed.

c. Kitchen: This was the only room in the apartment that did not have air conditioning and purely depended on natural ventilation for thermal comfort and daylight for visual comfort.

Four graphs were plotted and studied and for all the graphs, a comfort

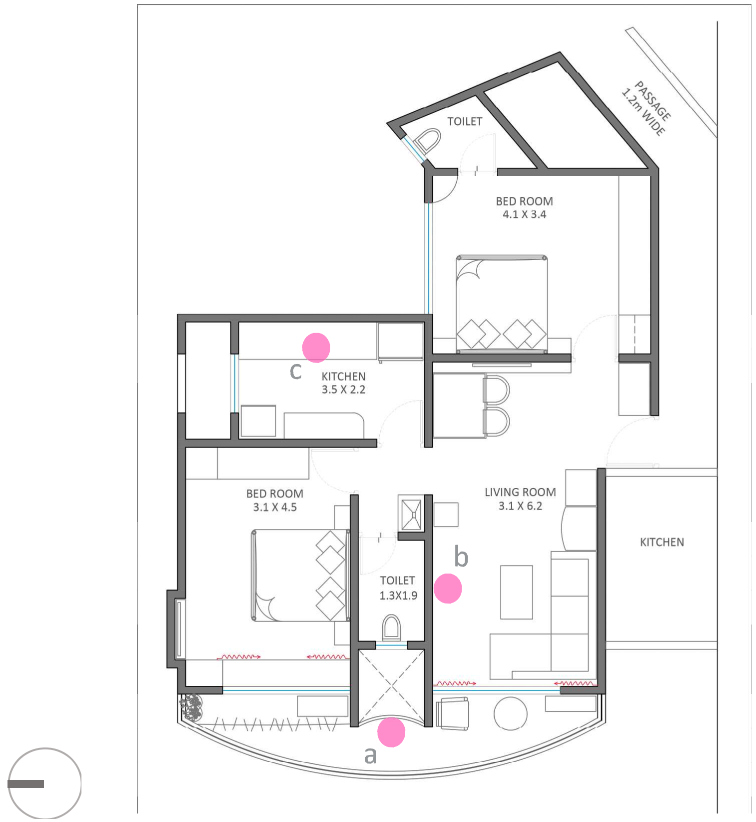

Fig.6.10. Location of data loggers

band was derived from ASHRAE 55, which is a comfort regulating tool developed by CBE (Centre for the Built Environment). The interpretation of the graphs is explained further.

i. **Graph 01 (Fig.6.11.):** It is a simple graph showing the monitored temperature and relative humidity in the balcony area (outdoors). This graph clearly shows the change in the outdoor climatic conditions. As one can observe, the fluctuations in the temperature and humidity increases drastically after 6th June. The temperature drops and the humidity level is almost 100%, this marks the onset of monsoon in Mumbai.

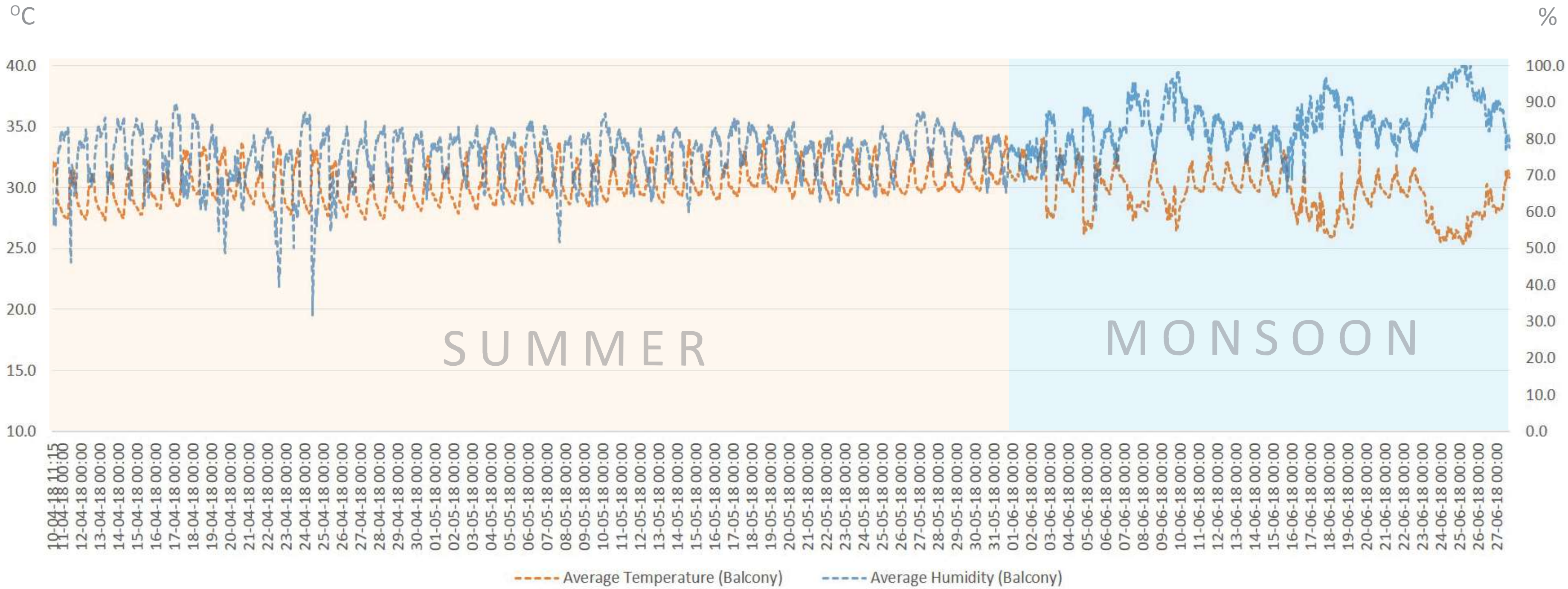

Fig.6.11. Graph 01 - Balcony (outdoor) temperature & humidity

ii. **Graph 02 (Fig.6.12.):** For this graph, average living room monitored temperature, balcony and kitchen temperatures are plotted.

The outdoor temperature (balcony) fluctuates during day and night time. The maximum day time temperature recorded is 34.3°C, whereas the minimum night time temperature recorded is 25.3°C. The difference in the day and night time outdoor temperature is about 9°C. The maximum monitored temperature in kitchen is recorded at 35.3°C and the minimum DBT (dry bulb temperature) recorded is 28.8°C. Thus, the difference in maximum and minimum kitchen DBT is 6.5°C. Lastly, maximum living/dining area monitored temperature recorded is 32.2°C and the minimum recorded is 26.5°C, which makes the difference in the temperature of 5.7°C.

Thus, it can be concluded that, fluctuation in the daytime and night time temperature is less in the living/dining area as compared to the outdoor space. The reason for which might be the extensive use of the air conditioning unit that regulates the indoor temperature as per the user requirement irrespective of the outdoor climatic conditions. The graph also indicates that both, the kitchen as well as the living/dining area temperatures are not in the comfort band. As per the recorded readings the average temperature of the balcony is 30.0°C, living area is 30.7°C and the kitchen area is 31.7°C. This shows that even after using air conditioning, the average indoor temperature was higher than the external temperature.

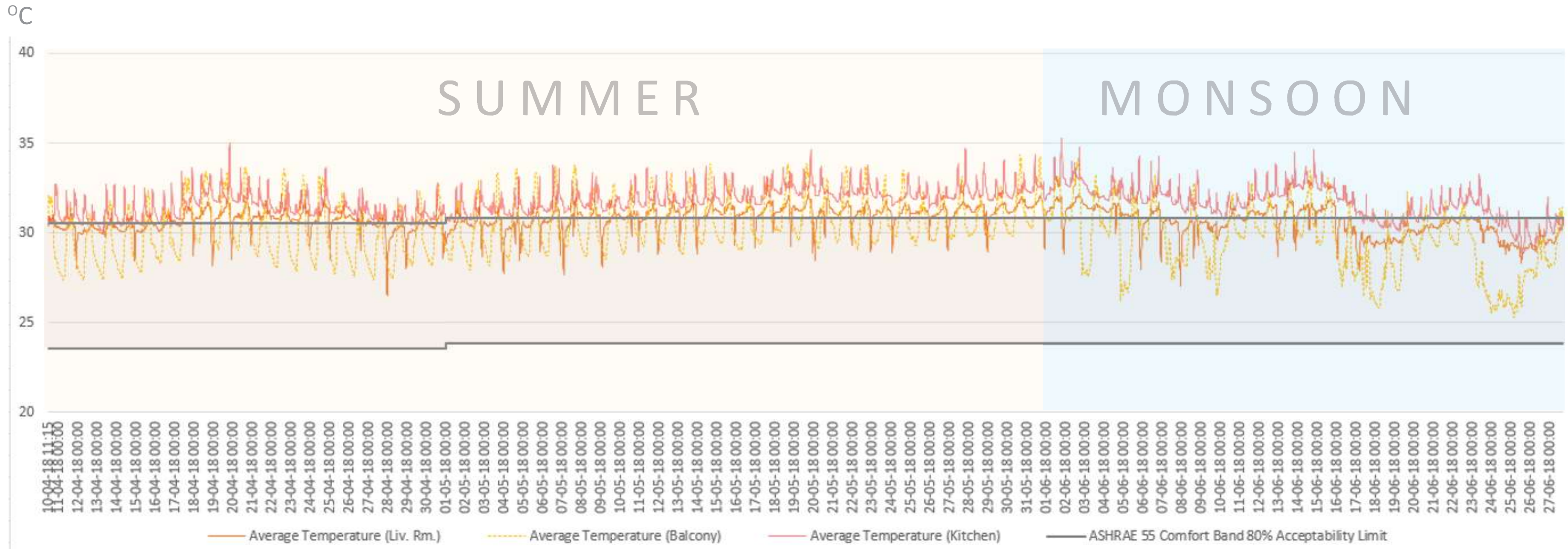

Fig.6.12. Graph 02 - Temperature - All spaces combined

iii. **Graph 03 (Fig.6.13.):** For this graph, average temperature and relative humidity for living room balcony are plotted.

A contradiction in the outdoor humidity levels and living room humidity levels can be seen very clearly i.e. when the outdoor humidity increases indoor humidity drops. The lowest humidity level recorded in the living room is 34.9% whereas the highest recorded is 88.7%. This makes the difference between them to be of 53.8%, which is quite high. It should also be noted that while the indoor DBT decreases the indoor humidity level increases.

Although the spot measurements for humidity (Fig.6.6.) shows that the indoor humidity levels are higher (since spot measurements were taken when the air conditioning was not in use), the continuous measurement however shows that the indoor humidity levels are below the outdoor humidity levels, majority of the times. Thus, it can be concluded that a significant drop in the indoor humidity levels of the living room indicates the extensive use of air conditioning which also acts as dehumidifier.

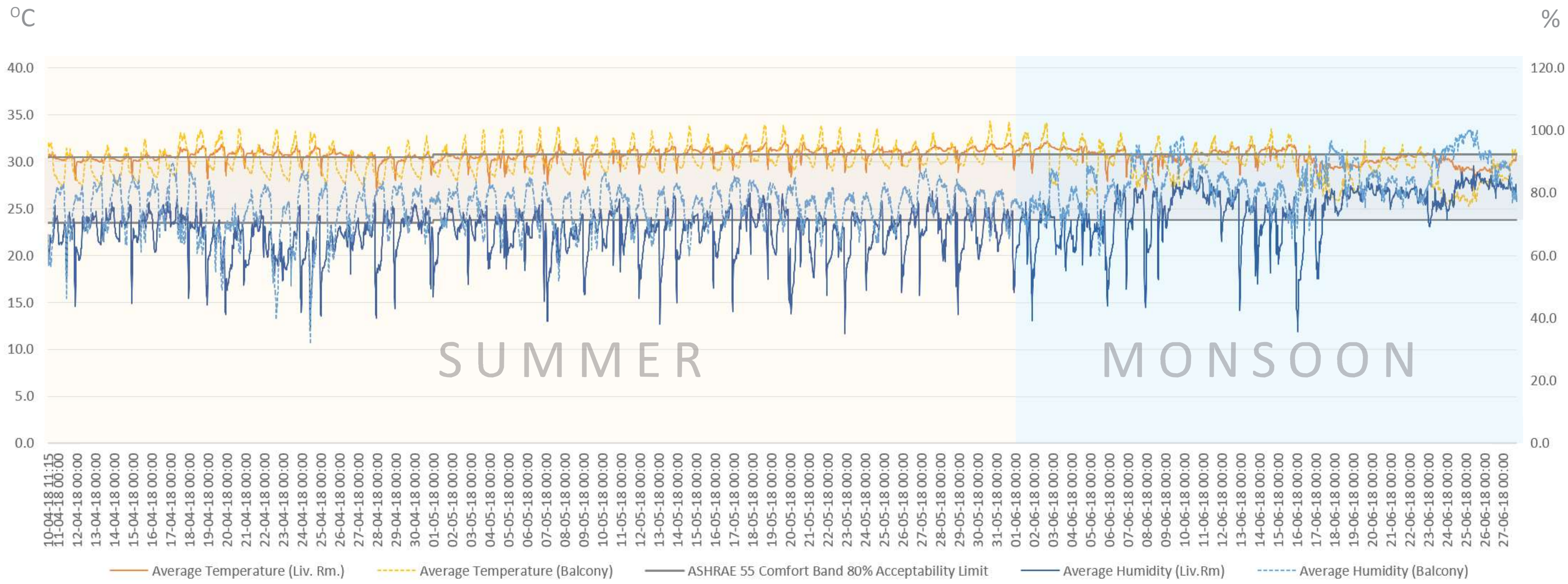

Fig.6.13. Graph 03 - Temperature & Humidity - Living & Outdoor space

iv. **Graph 04 (Fig.6.14.):** A zoomed-in graph, that analyses the thermal conditions for every monitored room together, is plotted for a period of 10 days, from 10th May till 20th May.

When the external temperature is higher the relative humidity drops. However, if the internal conditions are taken in to consideration, the humidity levels in the living room are comparatively lower and fall drastically along with the temperature at some places. This might be linked to the extensive use of mechanical cooling which also acts a de-humidifier. As stated earlier, the monitored temperature of the living space is more or less constant as compared to the kitchen, which is naturally ventilated.

CONCLUSION

a) The indoor temperatures are higher in comparison with the outdoor temperature.

b) The continuous measurements clearly show that as the outdoor temperature increases the temperature in the kitchen increases while in the living area it decreases which indicates constant use of air conditioning in the living area throughout the time period when the data loggers were placed in the apartment.

c) Even after using mechanical cooling the average living room temperature was only 1.7°C lower than the kitchen temperature. This also means that during day time when the air conditioning is used, it is least effective which can further be linked to the modified full-height window that receives excessive solar radiation.

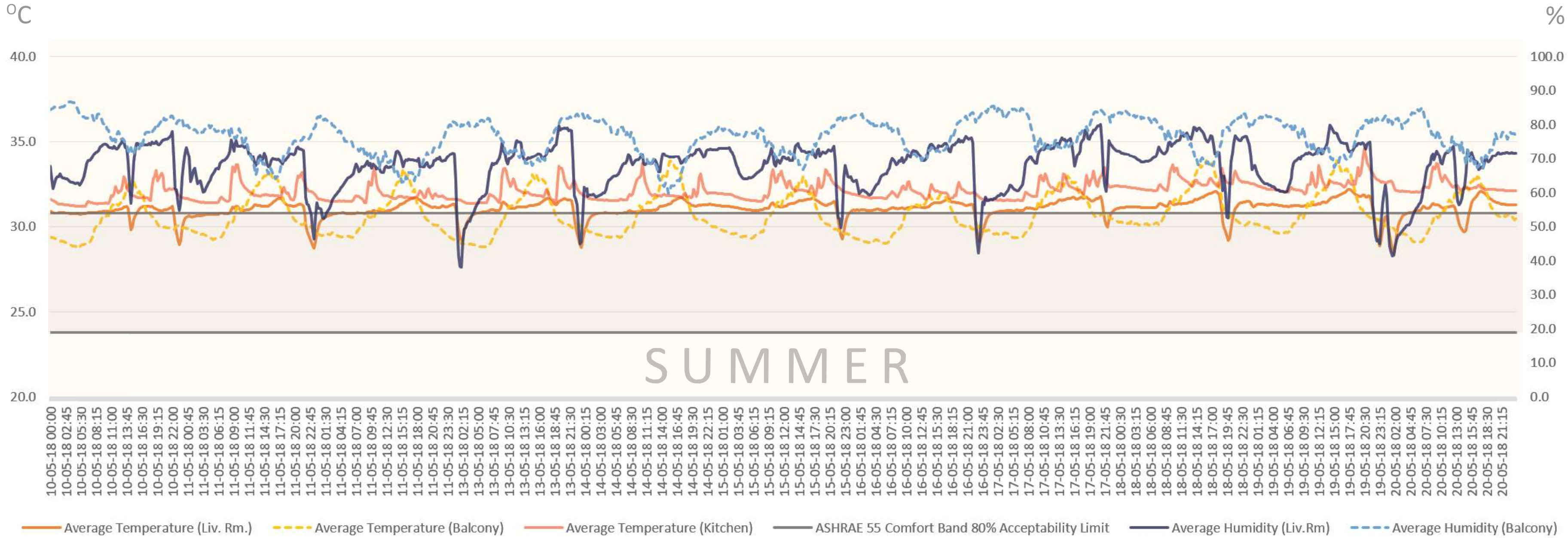

Fig.6.14. Graph 04 - Temperature & Humidity - All spaces (Zoomed in)

The Hot-Humid Window from the '*Chawls*'
Parel (Mumbai)

Fig.6.15. Chawl - window -door combo

SPOT MEASUREMENTS

The spot measurements for *chawl* in Parel were taken on a partly sunny day on 14th April 2018, when the summer season had already commenced in full form in Mumbai, which means by this time the city experienced high temperatures but not as high as the month of May. The readings were taken between 13:05 and 13:40, when the solar radiation is the highest. To understand if the indoor and the outdoor environment were in sync with each other, the weather condition for the particular period for that day was also noted from a weather database. Total 10 points were marked. Since the *chawl* unit was comparatively smaller only three points were taken indoors and the rest were taken in the outdoor area surrounding the building. Indoor readings were taken in the living room, loft space and kitchen. Whereas, the outdoor spaces included the kitchen garden, *verandah*, internal courtyard, shop and shop front and the main road.

Climatic data of the day and the period the measurements were taken were obtained from an online weather source. The recorded data is as follows:

- **a. Air Temperature: 32°C**
- **b. Humidity: 66%**
- **c. Wind Speed: 6.2m/s (Direction: West)**
- **d. Sky Conditions: Partly Sunny**

Weather Data from: www.wunderground.com

i) <u>Air Temperature</u> (Fig.6.16.): The maximum temperature recorded was 35.7°C in the outdoor area next to the main road. This was followed by the internal courtyard which had the next highest

Fig.6.16. Spot measurements - Air temperature

temperature of 32.3°C. The difference between both the outdoor temperatures was of 3.4°C respectively.

The temperature recorded in all the three areas of Mr. Chavan's unit was 32.5°C. Thus, as per the outdoor spot measurements, the indoor temperature was comparatively lower. However, if the courtyard and the unit temperatures are compared, they showed very similar temperature levels

Therefore, it can be said that:

a) The temperature difference between roadside and the courtyard ascertains the creation of a micro-climate in the courtyard.

b) Even though the indoors were not cooler, the constant indoor and outdoor temperature and similar temperature in all the indoor spaces suggest that the spaces were well-ventilated.

ii) <u>Humidity</u> (Fig.6.17.): The highest humidity levels were recorded in kitchen (71.3%). Apart from this, the loft also showed similar humidity levels (71.6%). The courtyard recorded 68.7% humidity whereas the outdoor roadside area recorded only 57% humidity.

Thus, as the loft is located above the kitchen space, similar higher humidity levels were experienced in the loft. Also, since the measurements were taken at noon, the time when lunch was prepared, the humidity levels recorded are higher. In spite of being open-to-sky, the humidity was higher in the central courtyard because of the following reasons:

a. Space remains shaded most of the times.

b. The courtyard is washed everyday.

Fig.6.17. Spot measurements - Humidity

c. Plus, the wet clothes from almost all the households are put up for drying in the courtyard.

iii) Wind velocity (Fig.6.18.): All the spaces, indoor and outdoor, experienced air movement. The kitchen garden and the *verandah*, both the spaces were immediately adjacent to Mr. Chavan's unit and recorded the highest wind velocity of 1.2m/s and 1.5m/s respectively. The maximum air movement inside the unit was noted in the living room at 0.8m/s.

Thus, the continuous flow of air indicates effective cross ventilation as well as stack ventilation taking place in the entire built form. The credit for continuous movement of air can be given to:

a. The door + window + ventilator combination along with rear window (See Chapter 05, p 127-129). This combination allowed excellent cross ventilation within the indoor spaces.

b. The form of the building: C-shaped building with open-to-sky central courtyard develops stack ventilation.

iv) Illuminance (Fig.6.19.): The outdoor illuminance levels were as high as 75600 lux while the inner courtyard recorded only 7800 lux. The illuminance level in the living, kitchen and loft were only 74, 40, and 20 lux respectively. However, as per CIBSE guide, the illuminance level for kitchen and living must be 200 lux, whereas bedroom should be 100 lux (See Chapter 06, p 181, Table.6.3).

Fig.6.18. Spot measurements - Wind velocity

Fig.6.19. Spot measurements - Illuminance

The reason for lower illuminance level in the courtyard space can be attributed to the shadow from the built form of the *chawl,* itself. Since, the studied unit is located on the ground floor, the day-light entering the indoor space was comparatively less. Apart from the location of the unit, the cantilevered projection outside the main door, also blocked natural light from entering the living space (See Chapter 05, p 127-128). Since, the double height of the kitchen space was now divided horizontally in to kitchen and loft space, this also led to the distribution of light coming from the rear window which now gets divided and becomes the source of natural light and ventilation for both kitchen and loft space.

AFTAB LUMINANCE

Furthermore, the HDR images obtained from Aftab Luminance application, gives a fair idea of the quality and quantity of light received in the indoor spaces and supports the illuminance readings obtained from the spot measurements. The images show the quality of light received in the living area (Fig.20.(a),(b)) which consists of door + window + ventilator combination. The second set of images shows the low quality of light received in the loft space through a small ventilator of the rear window (Fig.20.(c),(d)). Besides, it seems that the height and color of the space also affects the indoor quality of the light. A comparison can be drawn between the double height living space (Fig.6.20 (b)) and the loft (Fig.6.20 (d)) which is only 1.5m high. The difference in the quality of light due to the volume of the room can be clearly seen.

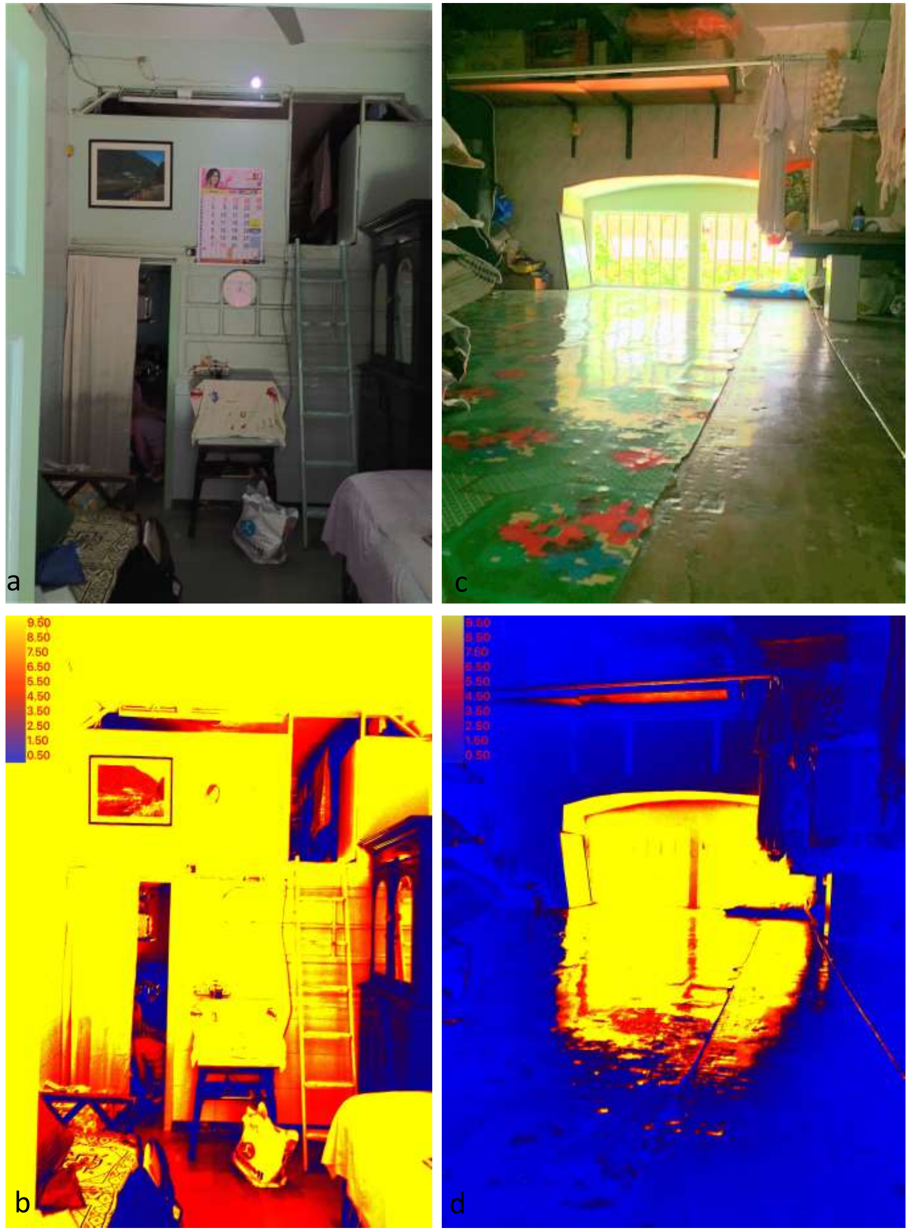

Fig.6.20.(a). Living area
Fig.6.20.(c). Loft
Fig.6.20.(b). HDR - Living area
Fig.6.20.(d). HDR - Loft

CONTINUOUS MEASUREMENTS

The continuous measurements were taken using three Gemini Data Loggers. The instruments were placed in Mr. Chavan's unit on 12th April 2018 at 13:00 and were removed from the unit on 27th June 2018 at 10:45. The logging interval for each data logger was set at 15 minutes' time interval. The data loggers were placed in the unit at three different locations for the given reasons:

a. **The *Verandah* or the front porch (Fig.6.21.(a))**: To acquire the outdoor climatic condition, so that it can be compared and analysed with the indoor thermal variations.

b. **Living room (Fig.6.21.(a)):** This multi-purpose space was used extensively by the Chavan family throughout the day, all through the year. The space was used for relaxing, for having meals, for watching television, sleeping, reading, socializing and so on. Also, the double height space has the documented window system which comprises of double door, window and ventilator combo. Hence, it was important to study the performance of the living space with this fenestration system.

c. **Loft (Fig.6.21.(b)):** The loft was occupied by a single person, majority of the time. Apart from central open area, all four walls of the loft had storage space against it. The 1.5m high loft space that was located above the kitchen area also consisted of two openings on the opposite ends. One, the entrance door to the loft while the other was a small ventilator which was a part of the kitchen window. It was necessary to log this space since it was interesting to note how it performed being on top of kitchen and also given the constricted volume of the space.

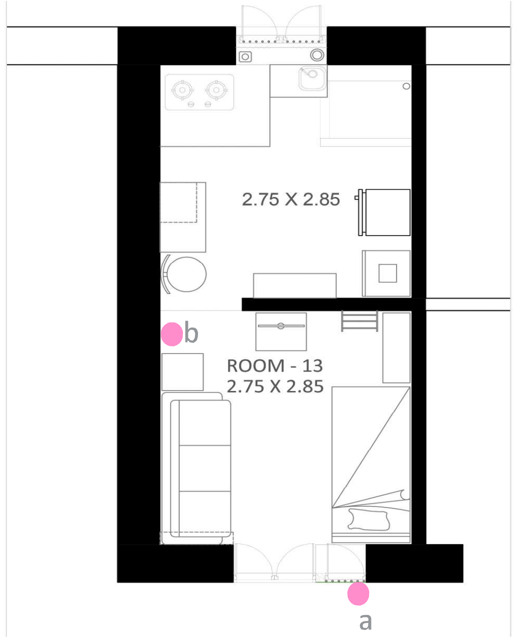

Fig.6.21.(a). Location of data logger - Lower level

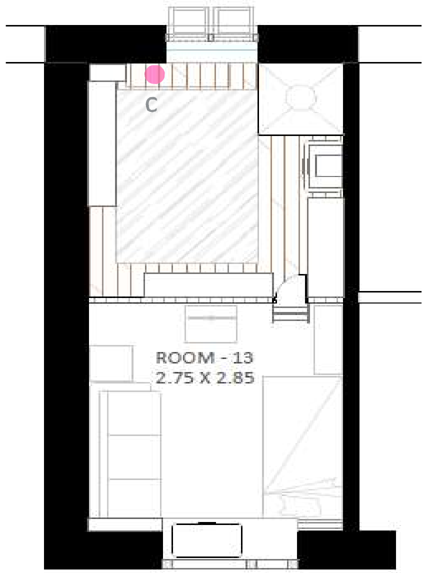

Fig.6.21.(b). Location of data logger - Upper level

Three graphs are studied with a comfort band derived from ASHRAE 55, which is a comfort regulating tool developed by CBE (Centre for the Built Environment). The interpretation of the graphs is explained below:

i. Graph 01 (Fig.6.22.): The plotted graph shows only the temperatures from the verandah, living area and loft. It can be seen that the indoor DBTs are not in comfort band throughout summer. However, with the onset of monsoon, the indoor monitored temperature enters the comfort band. It should also be noted that the indoor temperature is in sync with the outdoor thermal conditions. Since, no air conditioning was present in this house, no major fluctuation in temperature is observed. Lastly, the indoor monitored temperature seems to be more stable as compared to the outdoor temperature. Also, in spite of full occupancy throughout the day and being a tiny place with lot of furniture and appliances, most of the times the indoor thermal condition is about 1 to 2 degrees cooler as compared to outdoor temperature.

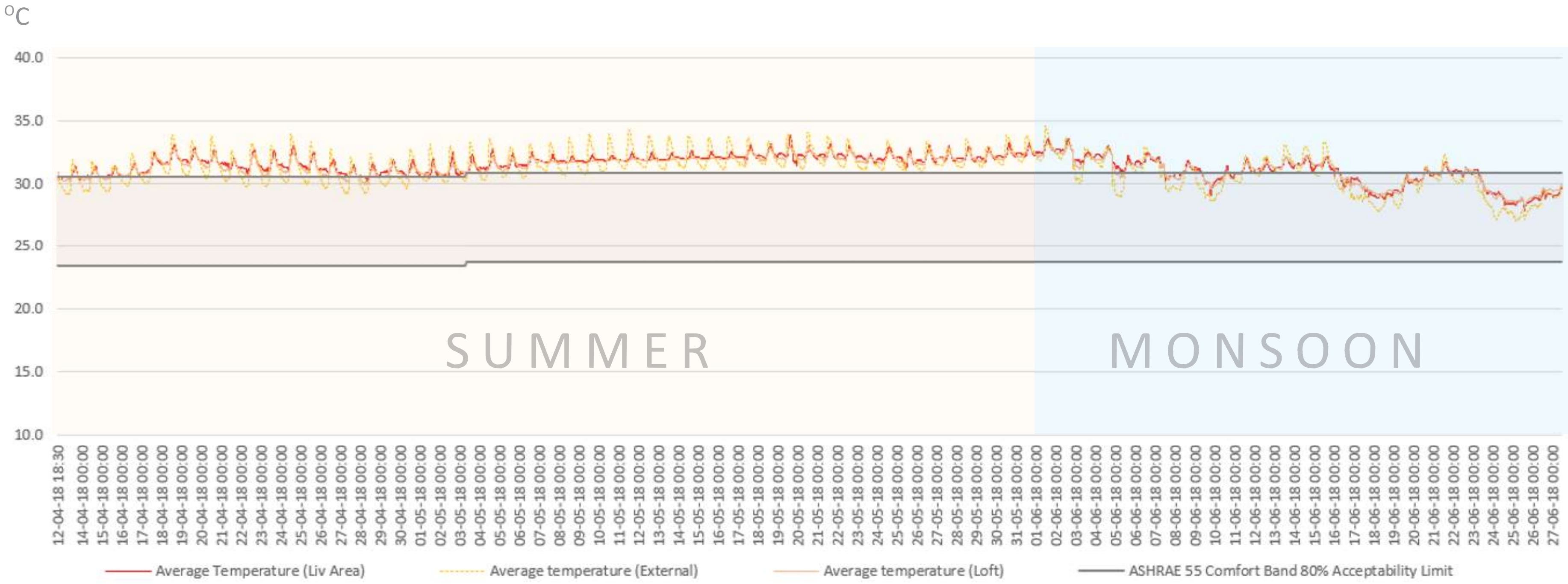

Fig.6.22. Graph 01 - Temperature - All spaces

ii. Graph 02 (Fig.6.23.): Temperature and relative humidity for living space and loft are plotted for this graph, to analyse the thermal conditions in these two space. It is also to compare and understand if the loft space is affected by its volume, by the size of its openings or by the fact that it is located above kitchen. The graph shows that the humidity levels in the living area and in the loft act in conjunction with each other. Also, the graph demonstrates that the temperature of the living area is slightly higher than that of the loft, almost throughout the logging period. Hence, although the loft space is above the kitchen with the height barely 1.5m, these factors do not affect the thermal conditions of this space. The temperature in the loft is stable, although not in the comfort band, especially in the summer months.

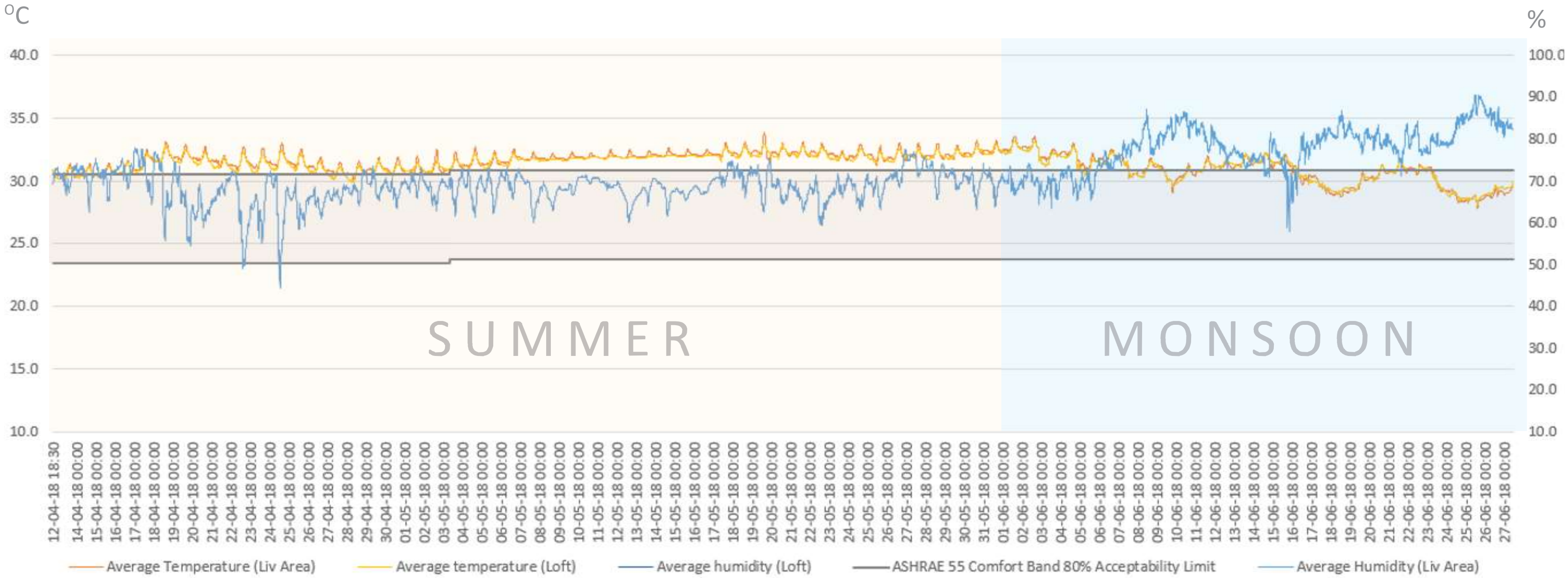

Fig.6.23. Graph 02 - Temperature & Humidity - Living & Loft

iii. Graph 03 (Fig.6.24.): Temperature and humidity of the living area and *verandah* are plotted for this graph. The purpose of this graph is to analyse the indoor thermal conditions as compared to the outdoor climatic variations. The graph shows that both temperature and humidity follow similar fluctuations. However, the indoor monitored temperature does not show as drastic changes in the temperature as the outside temperature. It can be said that the indoor thermal conditions remain comparatively steady which is assumed to be achieved by efficient use of the window + door + ventilator combination that provides the occupants with various adaptive options in which the combination could be used.

CONCLUSION

Therefore, in conclusion it can be said that since there is no air conditioning present in the house, the indoor thermal conditions change according to the outdoor climatic condition. The lower indoor temperature also indicates an effective cross-ventilation system taking place in the house throughout the data logging period, especially in the summer months. In this case the form of the building and the openings that provide cross ventilation play a significant role in providing occupant comfort.

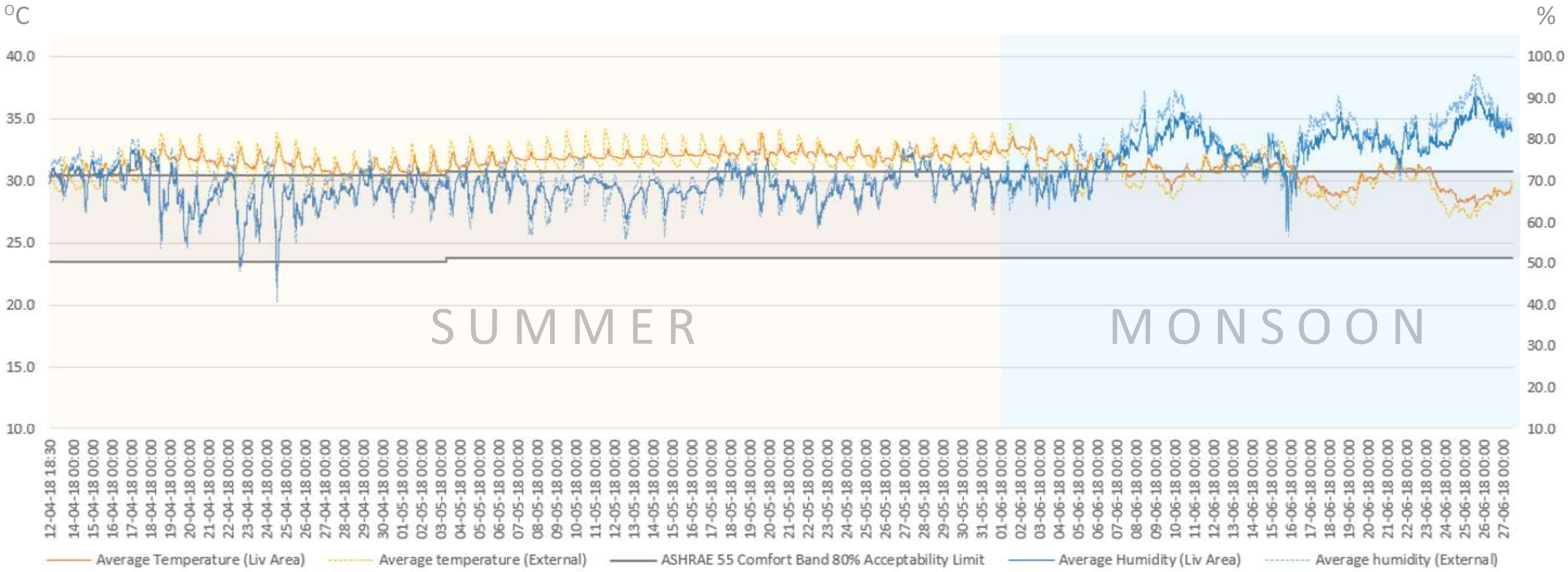

Fig.6.24. Graph 03 - Temperature & Humidity - External & Living

The Hot-Dry Window from a '*Wada*'
Shivaji Peth (Kolhapur)

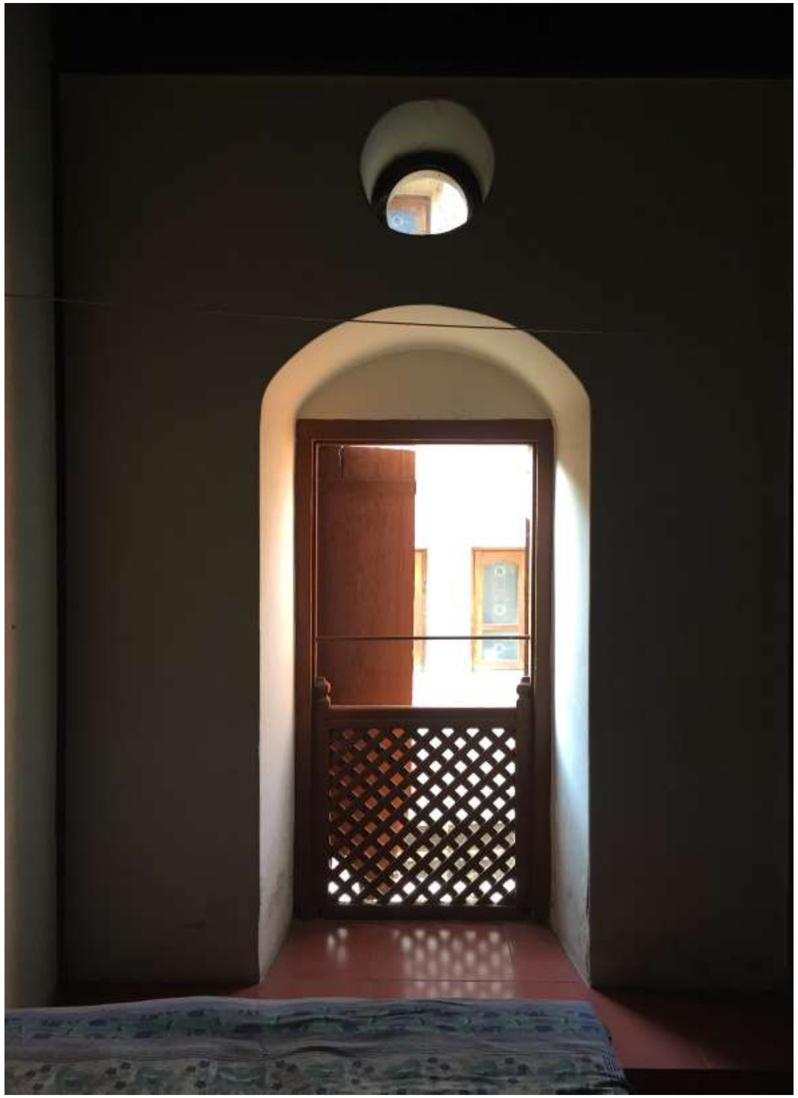

Fig.6.25. Wada - full-height window

SPOT MEASUREMENTS:

The spot measurements for the Pangu *wada* in Kolhapur were taken on a sunny day on the 26th April 2018, when the summer season is almost at its peak. The readings were taken between 11:30 and 12:42. Total 13 points were marked. Since the *wada* is comparatively very big, majority of the points were taken in the *wada* itself which comprised of open, semi-open and enclosed spaces, plus measurements were also recorded on the upper floor areas of the house. Apart from the narrow road in front of the house, all the other measurements were taken inside the house that included spaces such as the main entrance, courtyard, living space on the lower level. While on the upper level - family room, the semi-open corridor and boys room was chosen for taking spot measurements.

To understand if the indoor and the outdoor environment were in sync with each other, climatic data for the date and time the measurements were taken, were obtained from a weather database and the recorded data was as follows:

e. **Air Temperature: 33°C**

f. **Humidity: 11%**

g. **Wind Speed: 3.0m/s (Direction: West-North-West)**

h. **Sky Conditions: Sunny**

Weather Data from: *www.wunderground.com*

i) <u>Air temperature</u> (Fig.6.26.(a)(b)): The highest temperature recorded was in the courtyard at 35°C. While the temperature recorded in the narrow road adjacent to the house was 1.5°C cooler. Both the spaces were open to the sky and were not obstructed by any surrounding built form. However, it is assumed that being surrounded by walls on four sides and since all the windows opened in to the courtyard, it acted like an exhaust, which could be the reason for higher courtyard temperature.

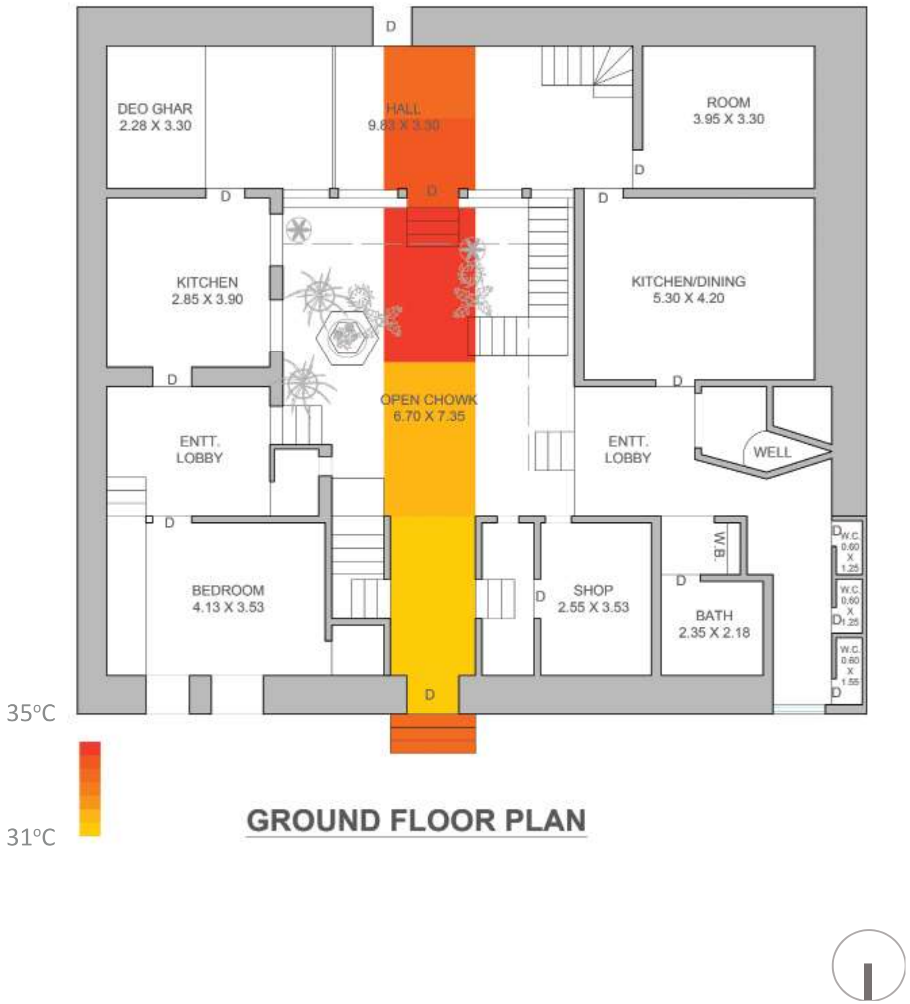

Fig.6.26.(a). Spot measurement - Air temperature - Lower level

The living space that is adjacent to the courtyard also experienced higher indoor temperature of 34°C. The lowest temperature on the lower floor was recorded at the main entrance at 31.3°C, which marked a temperature difference of 3.7°C. The reason for the higher indoor temperature at the lower level was believed to be because of the lack of cross ventilation. Hence, unlike the continuous air movement that was observed in the *chawl,* there was no air movement in the *wada.*

The lowest temperature noted on the upper level was 32.6°C and was recorded in the family room which have windows on opposite sides that facilitated cross-ventilation. Only two windows were opened when the unoccupied room was opened for taking the spot measurements. It is likely that if more windows are kept open out of the six windows, the temperature in this room could reduce considerably. It was also observed that, apart from cross ventilation, since the upper level rooms were unoccupied when the spot measurements were taken, the indoor temperature was lower as compared to the living room on the ground floor. The semi-open corridor space logged similar values as obtained from the weather database. No major fluctuations in the temperature were observed in the *wada* as such.

ii) **<u>Humidity</u> (Fig.6.27.(a),(b)):** Kolhapur, being a hot and dry region, the humidity levels during summer are very low. On the ground floor, apart from the narrow road, the lowest humidity recorded in the living room was 28%, which was expected, since the temperature in this space was higher. However, with high temperature, the courtyard recorded higher humidity levels (40%), which was 12% higher than the above internal humidity level and the reason could be because of the numerous potted plants that occupy this particular space and because the courtyard is washed everyday.

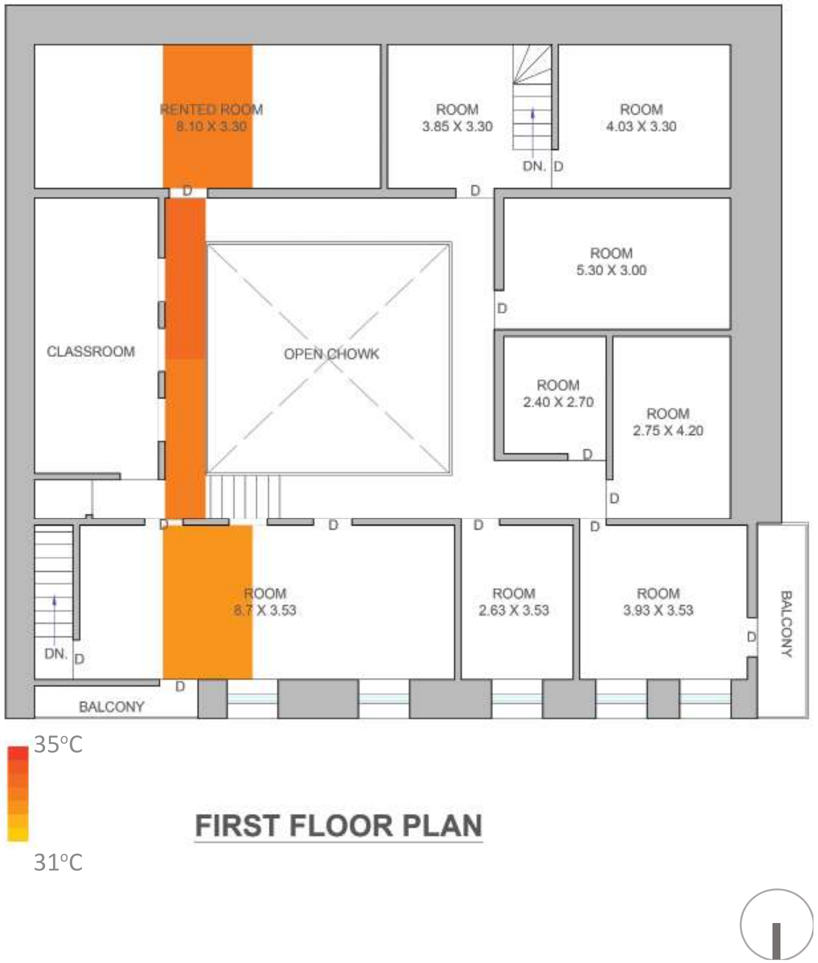

Fig.6.26.(b). Spot measurement - Air temperature - Upper level

On the upper floor, the semi-open spaces recorded lower humidity levels. Whereas, the unoccupied boys room logged highest humidity at 43%. Following are believed to be the reasons for higher humidity levels in the boys' room:

1. Clothes were put for drying on washing line inside the room with windows shut.
2. Negligible ventilation from the ventilators and closed windows.
3. Since there were no windows on lower level, the room did not receive any solar radiation.

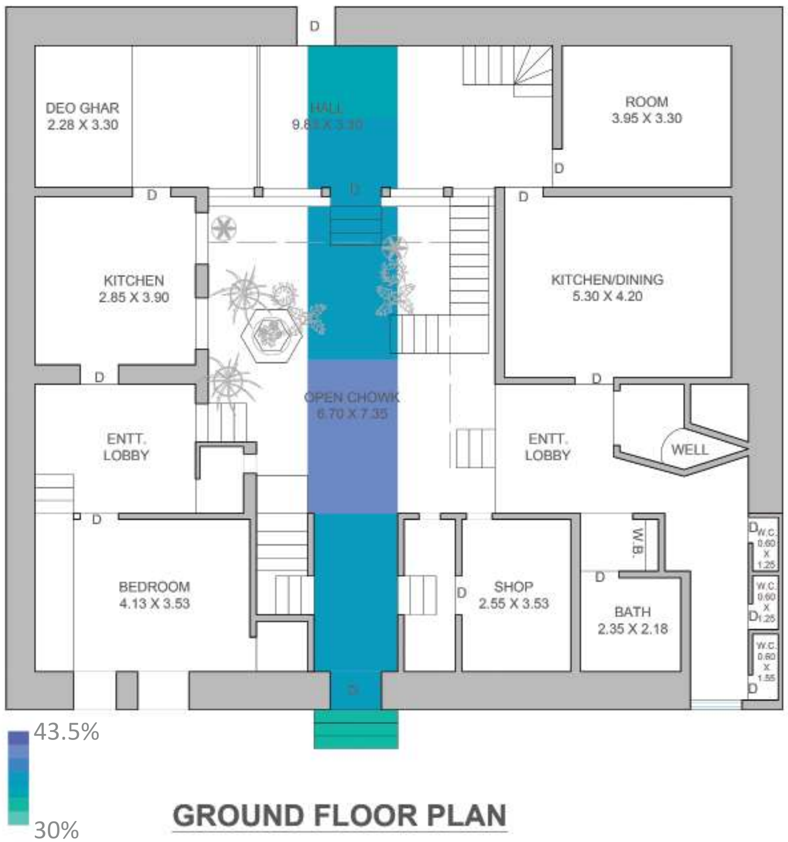

Fig.6.27.(a). Spot measurement - Humidity - Lower level

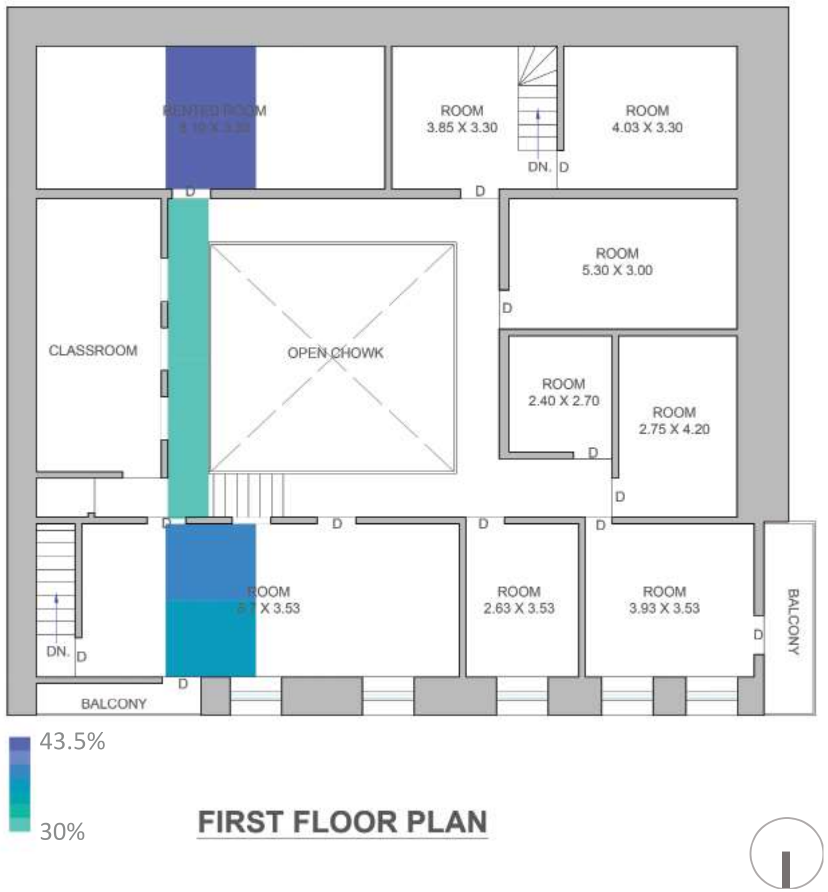

Fig.6.27.(b). Spot measurement - Humidity - Upper level

iii) **Wind velocity** **(Fig.6.28.(a),(b)):** Although *wada* and *chawl* have similar form, unlike *chawl*, there was no wind movement felt neither in the indoor nor in the outdoor spaces of the *wada*. The main reason for this difference in air movement could be linked to the lack of provision or rather lack of effective use of cross ventilation in the house. Although there is a courtyard but with no windows present or used on two sides of the room in the *wada*, the cross ventilation strategy does not work here.

The other reason for it could also be due to its location. The current growth in the rise of buildings surrounding the *wada* makes it sit in an extremely congested area (See Chap 05 p:146-147) which in turn does not allow any air movement.

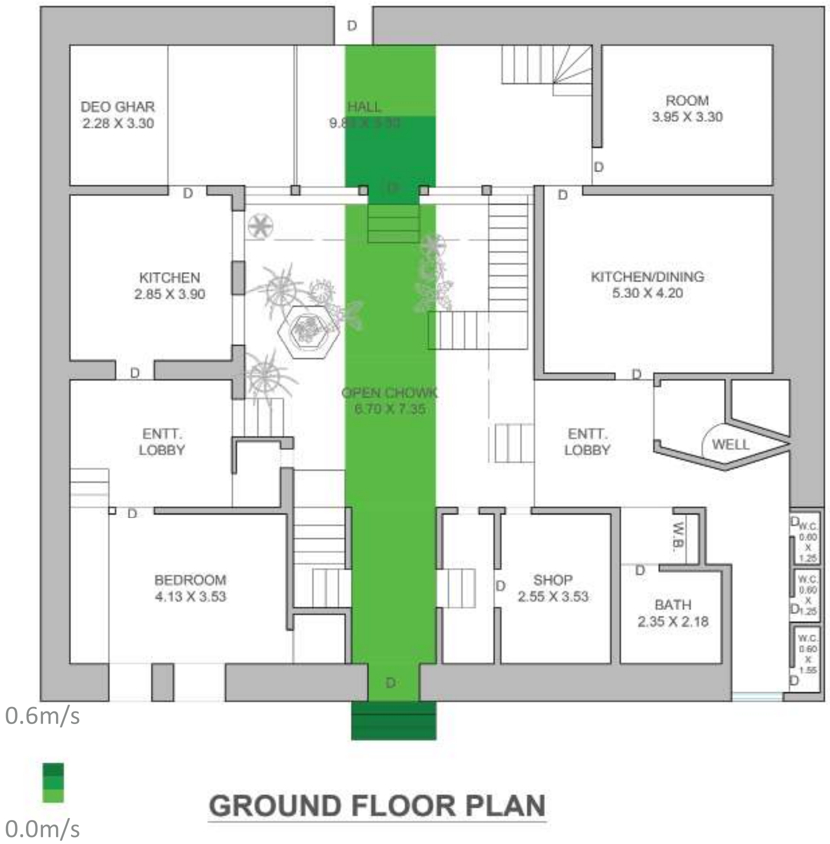

Fig.6.28.(a). Spot measurement - Wind velocity - Lower level

Fig.6.28.(b). Spot measurement - Wind velocity - Upper level

iv) **Illuminance (Fig.6.29.(a),(b)):** It has been observed that although abundant natural light is available in India, the indoor spaces are most of the times poorly lit. In *wada* as well, the maximum illuminance level recorded was 98800 lux on the road and 95500 lux in the courtyard. However, the illuminance levels in the indoor spaces drastically reduces to a minimum of 27 lux in the living room and 46 lux and 49 lux in the rooms on the upper level respectively. The reason for this being, no windows on the external periphery and smaller windows that open in the courtyard. Inadequate natural light in the interiors was one of the reasons why the Pangu family wanted to replace the existing windows.

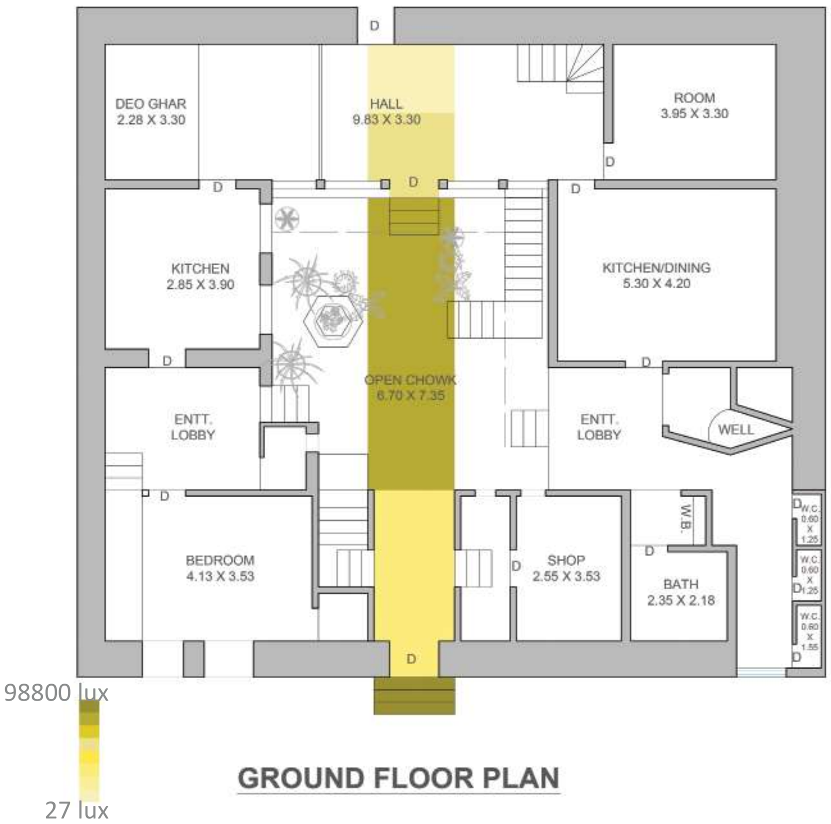

Fig.6.29.(a). Spot measurement - Illuminance - Lower level

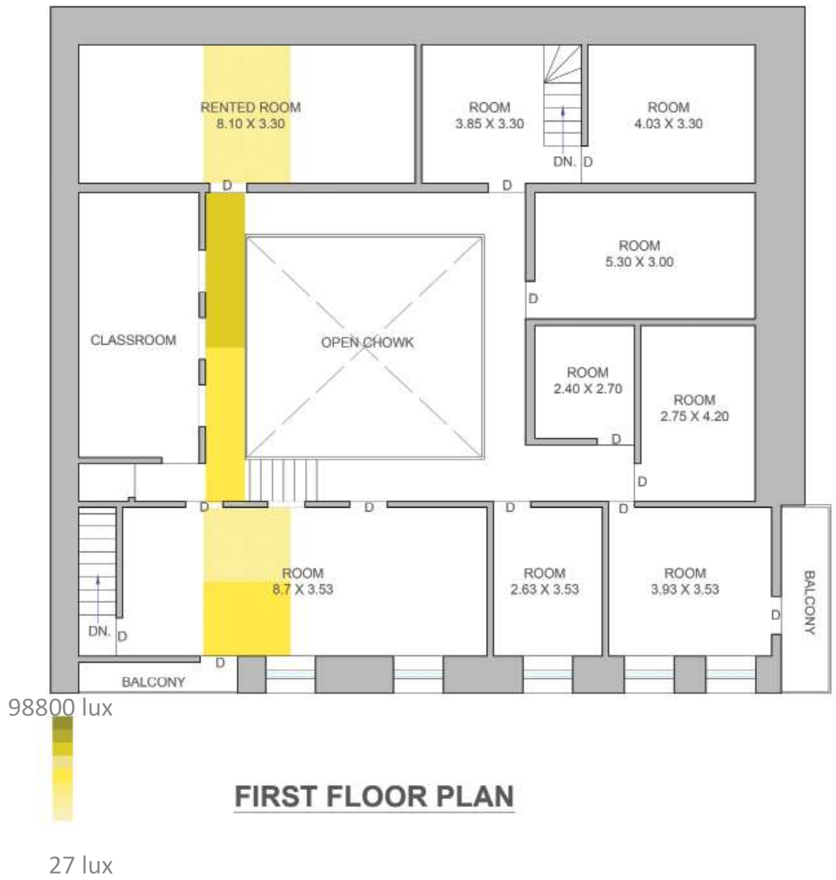

Fig.6.29.(b). Spot measurement - Illuminance - Upper level

AFTAB LUMINANCE

The poor quality of light can further be observed through the HDR images taken from Aftab, an iPhone application. The application provided supporting information regarding the quality of light in the *wada* and highlighted the problematic spaces with respect to light distribution that also supported the illuminance reading obtained during the spot measurements.

With no artificial light on, the images are taken in the kitchen (Fig.6.30.(a),(b)) on the lower level, which is one of the maximum used space, the family room on first level (Fig.6.31.(a), (b)) and the boys room on the first level (Fig.6.32.(a),(b)). These images were taken during the spot measurements and a uniform scale was set for every image that enabled in understanding the lighting condition of the spaces in different rooms of the *wada.*

If the images from all three spaces are compared, it shows how the light gets reflected due to light colours in the kitchen space. Whereas, the family room (Fig.6.31.(a),(b)) and boys room (Fig.6.32.(a),(b)) on the upper floor with dark coloured ceiling, does not reflect any light and both the spaces appear quite poorly lit. The only source of light in the boys' room is through the top ventilators, this light, as can be seen, does not reach the floor or the living space. Thus, overall the indoor areas do not receive adequate natural light and the occupants are left with using artificial lights even during the day time.

Fig.6.30.(a). Kitchen

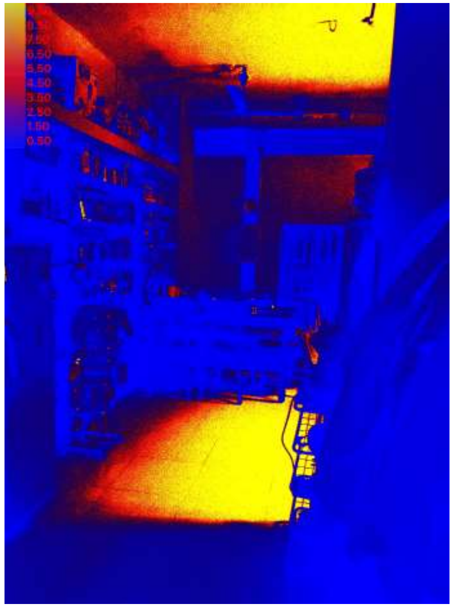

Fig.6.30.(b). HDR - Kitchen

Fig.6.31.(a). Family room

Fig.6.31.(b). HDR - Family room

Fig.6.32.(a). Boys room

Fig.6.32.(b). HDR - Boys room

CONTINUOUS MEASUREMENTS

Continuous measurements were taken using five Gemini Data Loggers. The instruments were placed in the Pangu *wada* on 25th April 2018 at 17:30 and were removed from the unit on 21st June 2018 at 07:45. The logging interval for each data logger was set at 15 minutes' time interval. The data loggers were placed on the lower (Fig.6.33.(a)) as well as upper (Fig.6.33.(b)) floor rooms. They were placed in the following places for the given reasons:

a. **The courtyard:** This data logger was placed to acquire the outdoor temperature and humidity levels, so that the readings could be compared and analysed with the indoor thermal variations.

b. **Living Area:** This lower level room was extensively used by the occupants as compared to the other areas. The main door which opened in to the central courtyard and provided entry to the indoor spaces was kept open throughout the day. This space was used for reading, relaxing, for socializing and so on. Hence, being the most habitable space of the entire house, it was important to study the performance of the living area.

c. **Kitchen:** After living room, this lower level room was used almost throughout the day, since this space was not only used for cooking but also for having meals. Apart from this, it also acted as a transition space to go the bathroom, bedroom and even the upper level rooms. The occupants had changed the kitchen windows, wherein the size of the windows was increased. Hence, the analysis this space was essential too.

d. **Family room:** Although this space was occasionally occupied,

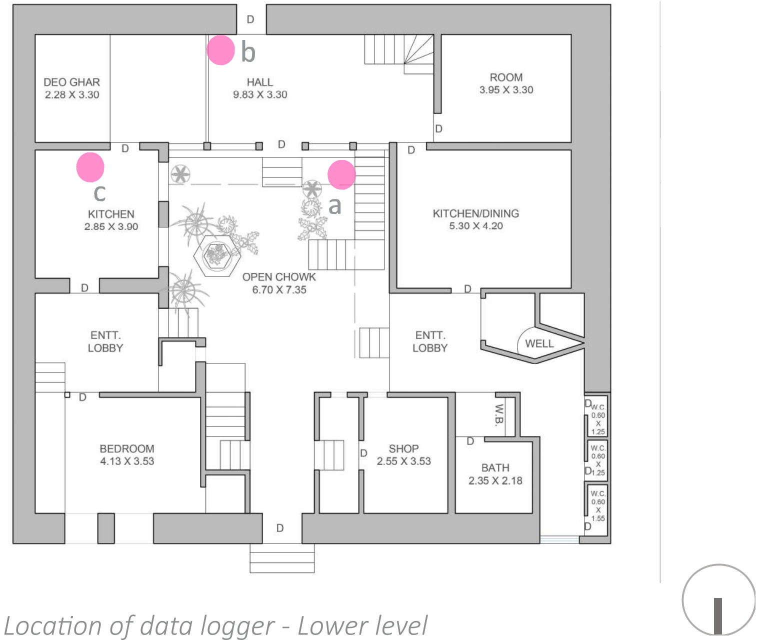

Fig.6.33.(a). Location of data logger - Lower level

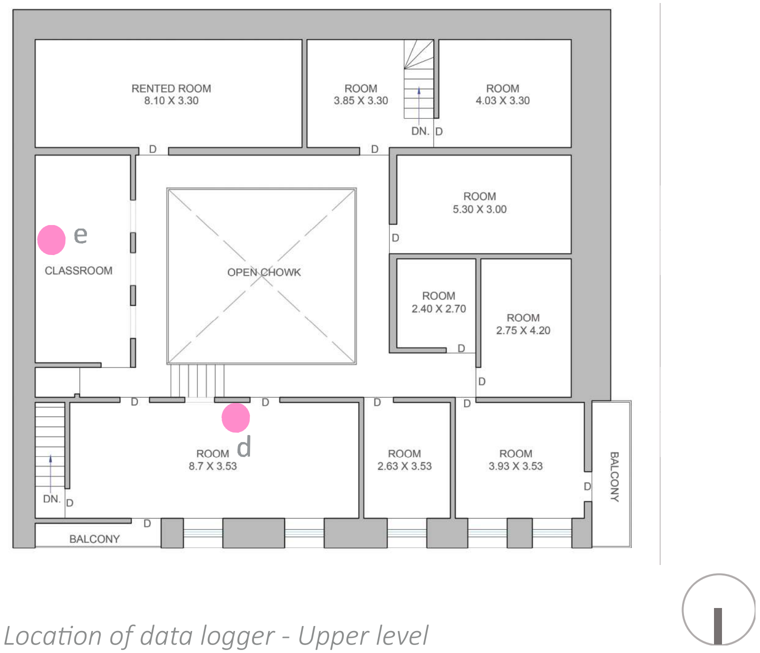

Fig.6.33.(b). Location of data logger - Upper level

the importance of this space was mainly due to the presence of windows of different design and sizes on two opposite elongated sides of the room. This place was used to dry clothes, to take afternoon naps and during family gatherings.

e. Classroom: It was essential to log the temperature of this room because it was a new construction where new building techniques and modern materials were used, such as brick walls, metal roof, sliding windows and so on. Hence, it was necessary to analyse the performance of this space and compare the same with the other spaces on the same floor.

Three graphs are studied and their analysis is explained further:

i) Graph 01 (Fig.6.34.): The temperature from the courtyard, living room and kitchen areas of the *wada* are plotted in this graph and analysed. It can be observed that there is a huge difference between the external daytime and night time temperatures, about 6^{o}-7^{o}C difference. Therefore, although the daytime temperatures are high, the atmosphere during the night is pleasant in Kolhapur. Having said that, the indoor monitored temperature of living area and the kitchen space does not fluctuate as drastically as the outdoor temperature.

Overall, the indoor thermal conditions are comfortable. During summers, the temperature in the afternoon touches 33^{o}C making it uncomfortable for the occupants, while the night time temperature is pleasant and is completely in the comfort band.

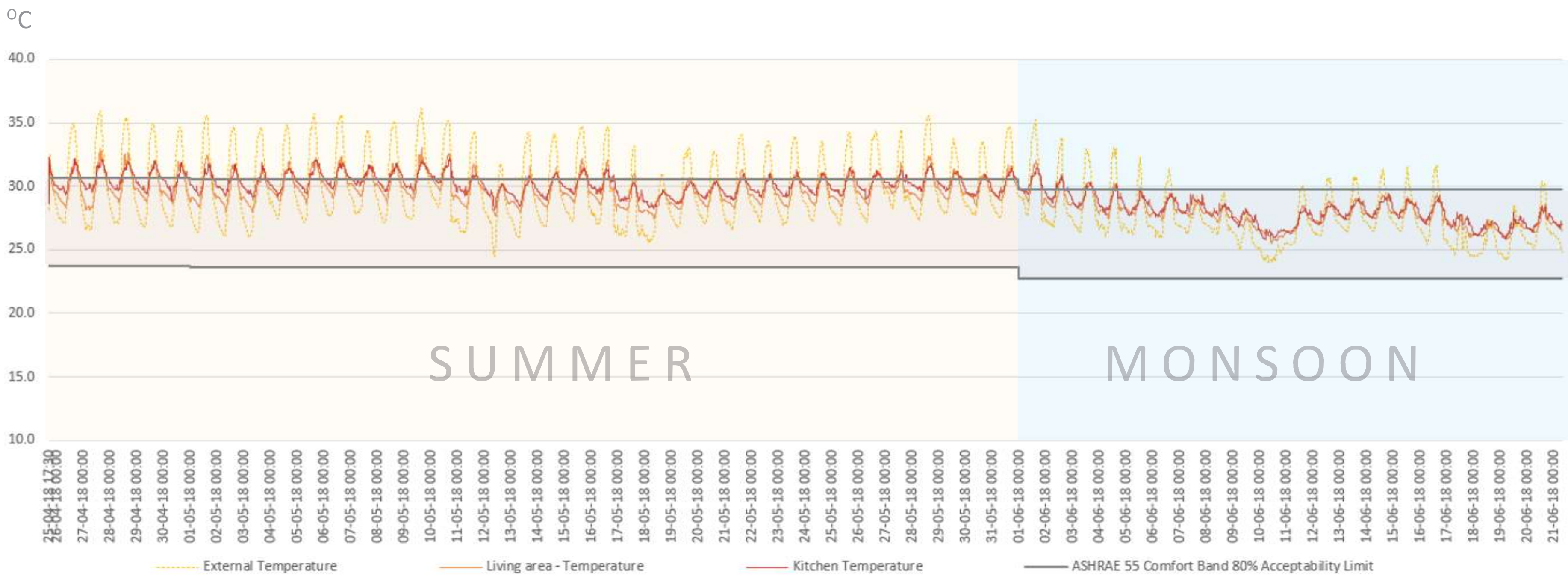

Fig.6.34. Graph 01 - Temperature - External, Living & Kitchen

During the monsoons, the daytime as well as the night time temperatures are completely in the comfort band. Therefore it is evident that, comparatively smaller openings work well for the indoor spaces of the house in terms of thermal comfort.

ii) Graph 02 (Fig.6.35.): Temperature and humidity of the living area and courtyard were plotted together in a graph. As stated earlier, the DBT of the living room is always in the comfort band during the night and the highest temperature recorded is during afternoons. The monitored temperature of the living room is in the comfort band during the monsoons. Furthermore, the indoor temperature does not fluctuate as drastically as the outdoor temperature. Also, the variations in the indoor and the outdoor humidity levels is almost the same except during the night time when the indoor humidity is slightly lower than the outdoor level, which can be linked to the lower occupancy level.

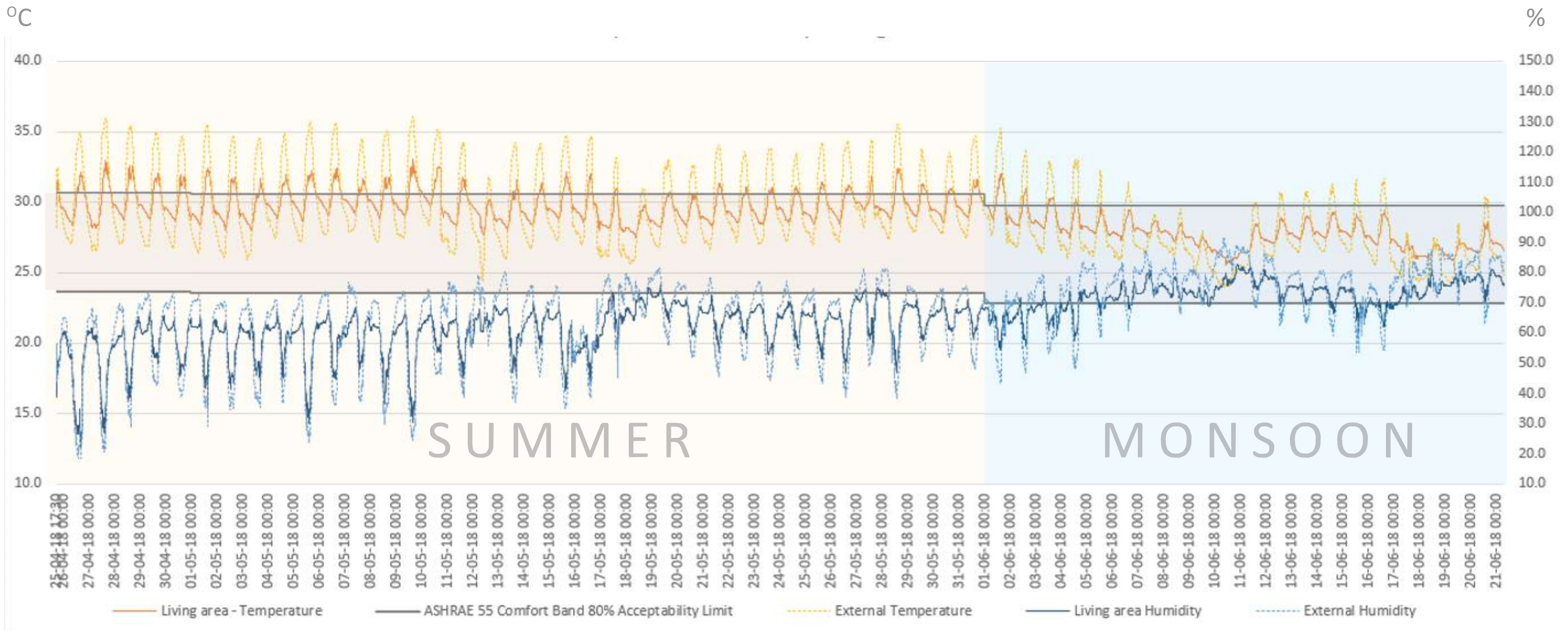

Fig.6.35. Graph 02 - Temperature & Humidity - Living Room & Kitchen

iii) Graph 03 (Fig.6.36.): This graph demonstrates the logged temperature of the family room (old construction) and the classroom (new construction), which are located on the upper level. Both the spaces had minimum occupancy level, during the time the data loggers were placed in these spaces. The monitored temperature of the classroom is strikingly higher than the family room temperature. The maximum temperature recorded in the classroom is 46.5°C during this time the outdoor temperature recorded is 32.6°C, whereas the temperature in the family room at the same time is logged at 33°C. Thus, the difference between temperature between both the rooms at the same time is of 13.5°C. It is evident that the old building performed better as compared to the new construction. The difference between the old and the new building was:

a. The construction material for walls was brick in the new construction and stone in the old one.

b. The material for roof used in the new building were metal sheets and for old building manglore (clay) tiles were used.

c. The windows in the new construction were single glazed sliding window whose effective aperture area was only 50% of the total construction area of the window. While the windows of the family room were double shutter teak wood windows with effective aperture area of 100% (See chapter 05, p 157)

Thus, the above mentioned points are the primary reasons for the higher temperature levels in classroom.

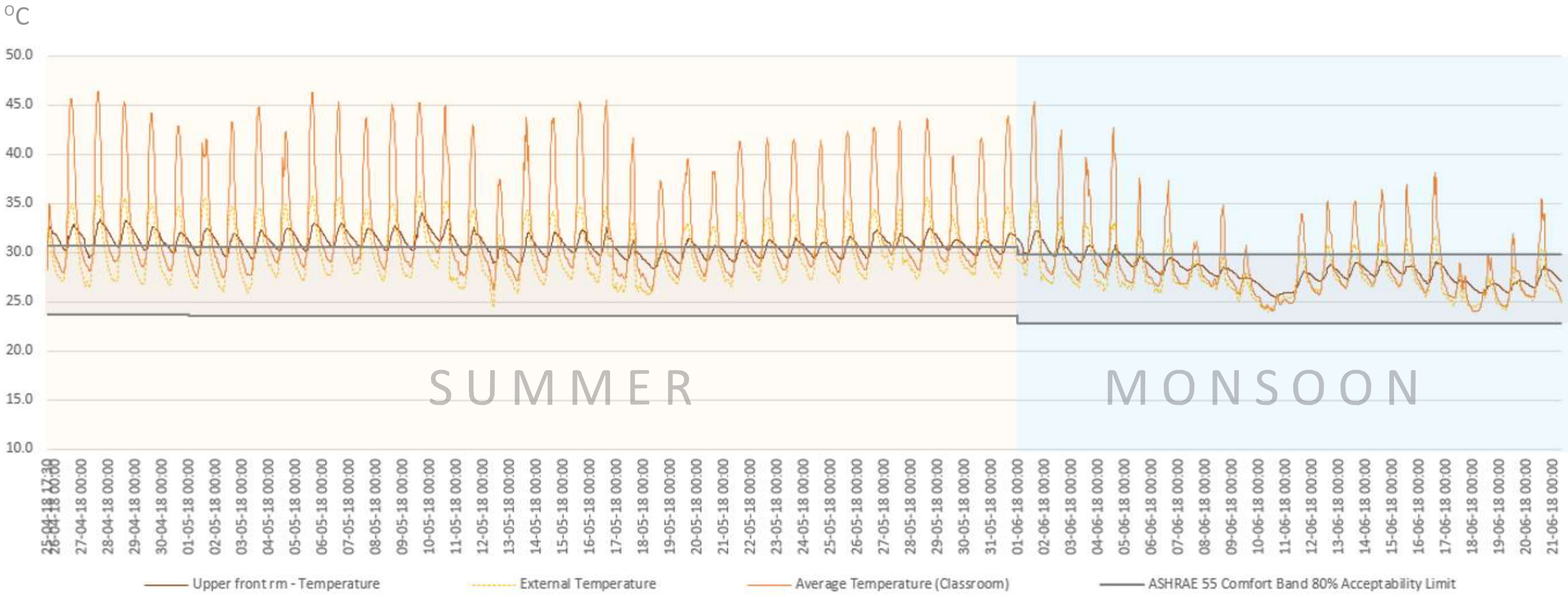

Fig.6.36. Graph 03 - Temperature - Family room & New Classroom with External Temperature

CONCLUSION

Although chawl is said to be derived from wada, the later does not function as well in terms of thermal and visual comfort as compared to the chawls. The indoor spaces felt hotter, artificial lights were used in the living and kitchen area and there was no air movement as such. Therefore, just having a central courtyard does not make an indoor space environmentally comfortable. The spot measurement demonstrated the importance of adaptive windows. If the windows in the rented boys room (Fig.6.39.) were not placed so high, they could have had the opportunity to adjust them which would have aided in reducing the indoor temperature. It was also observed that, even though there were ample windows present in the house, some were kept shut most of the times and were hardly used (Fig.6.37., 6.38., 6.40., 6.41., 6.42.). Thus, apart from the form of the building, having openings that can be easily used by the occupants to adjust the aperture area, makes a lot difference in their comfort level, psychologically as well as physiologically.

Fig.6.37. Upper Rooms

Fig.6.38. Lower level -Bedroom

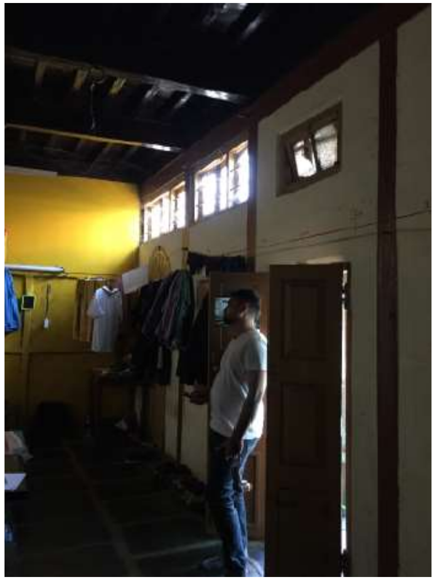

Fig.6.39. Boy's Room

Fig.6.40. Boy's Room

Fig.6.41. Family room

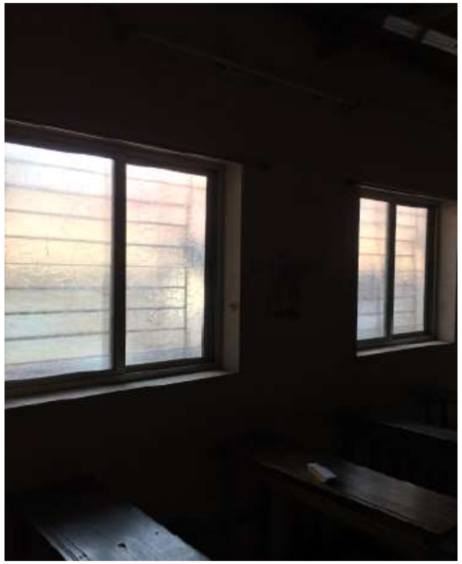

Fig.6.42. Class room

OVERALL CONCLUSION

If we observe the environmental performance of all the three typologies, it is quite evident that the windows play a very crucial role in setting the indoor thermal and visual environment of a space. The observations can be summarized as follows:

1. **The Apartment:** The west facing windows in the living room and the adjacent bedroom brought in lot of light and radiation in the respective spaces, especially the full height living room window. The many added layers to the window such as curtains, mosquito nets, washing line just outside the window, had an impact on the indoor environmental conditions. Even after modifying the window as per their liking, Mr.Oza's family ended up using air conditioning extensively and the use of it was quite evident in the monitored data obtained. In an interview with Mr.Oza, he mentions the use of mechanical cooling throughout the year. Hence, although the window is modified, it is perhaps not modified in a way that would improve the indoor environment, rather it made it worse.

2. **The *Chawl*:** This household probably performed the best out of the three documented typologies. In spite of being a tiny cramped up space with full occupancy, Mr. Chavan's house performed extremely well and was in sync with the outdoor weather variations. With a central courtyard form of the building and a fantastic window + door + ventilator system that ensured cross-ventilation, allowed enough air movement inside the house, thus making it comparatively a comfortable space to live in. Not having an air conditioning till date nor having any interest to buy one in the near future nor any interest in changing the current window design, shows the level of satisfaction of Mr. Chavan's family with the space they live in.

3. **The *Wada*:** The oldest building studied, this *wada* had similar features as the *chawl.* However, environmental performance wise it was observed that the house had the potential to perform much better especially when it came to natural light and ventilation. The fieldwork demonstrated that all the windows were not used to their full potential, since they provided with many alternatives for the occupants to use and to adjust their indoor environment. The most under performing space was the living area with inadequate natural light and zero air movement. This extensively used space lacked cross-ventilation, which would have completely changed the indoor climate for the living space. Apart from this the rented room of the upper floor had the potential to be bright and airy if all the window were used efficiently. Therefore, it can be said that, although, overall the *wada* performs well, the indoor environmental conditions had potential to be improved further with full and proper use of the available windows already present in the house.

Thus, the conclusion drawn from the fieldwork, becomes the base of the computational analysis performed in the following chapter. The window systems from the three typologies are analysed further to lay an emphasis on the important role that windows play in providing indoor environmental comfort along with other architectural elements.

SURVEY

In addition to the fieldwork that comprised of data collection in the form of drawings, photographs and environmental measurements such as spot measurements, continuous measurements and HDR images, two forms of surveys were performed. These surveys were essential in understanding what the occupants living in the apartments felt about their spaces. Building Use Study (BUS) questionnaire and a questionnaire designed specifically to understand the importance of windows in the daily routines of the occupants were distributed amongst 22 occupants from big and small cities.

1. Findings from BUS (Building Use Studies) Survey:

Developed in the 1980s in London, Building Use Studies (BUS) is a methodology that is used for evaluating occupant satisfaction through qualitative/quantitative feedback process (UKGBC, 2013). The purpose of this study is to understand the user perception of buildings so that further adjustments are made for future projects. The post-occupancy evaluation method has two categories for which two different sets of questionnaires are made available:

a. Housing units

b. Non-domestic buildings with permanent inhabitants.

The 45-questions feedback form aims at extracting information from the users on aspects such as (Leaman, 2011):

a.	Personal control	b.	Lighting
c.	Thermal Comfort	d.	Ventilation
e.	Noise	f.	Design, space and needs.

The 2 – page questionnaire that was used to obtain occupants perception of their spaces consisted of questions based on the following:

a. Background: Consisted of questions such as gender, age, name, number of people living in house, the type of house, ownership status and so on.

b. About the residence in general: This section was based on the layout of the house, location, the space, storage spaces and overall appearance.

c. Needs: It was aimed at understanding if the users were happy with the facilities that were provided to them. They were expected to give examples of what worked for them and if any additional facilities were required.

d. Special circumstances: It was to know if the needs of the occupants were met in case of special circumstances

e. Comfort: The most important part of the questionnaire, this section helped in obtaining information regarding comfort conditions during summers and winters that included questions based on tem -perature, air quality and overall conditions during summer and winter months along with comments on ventilation, cooling and heating.

f. Noise: This part investigated the effect of noise from different sources such as people between rooms, neighbours and from outside.

g. Lighting: The quality of natural as well as artificial light is questioned in this section.

h. Personal Control: To know how much personal control did the users have on heating, cooling, ventilation, lighting and noise.

i. Other sections that are included in this form tends to understand the health of the inhabitants, how they felt about the overall design and about the environmental design features and so on.

This questionnaire was distributed amongst 22 individuals living in Mumbai (city), Ratnagiri (city) and Alibag (town), all of which belong to hot and humid climate. Majority of the surveyed occupants live in an apartment system. Some of the prominent findings from this survey are discussed below:

Condition in Summer:

Summer conditions in hot and humid cities like Mumbai are most of the times uncomfortable, this was observed during the fieldwork as well as the survey. The results showed that the indoor thermal conditions during the summer months were not comfortable, with humidity being one of the main reasons (Fig.6.44). Majority of the surveyed individuals felt, the air became very humid during summers (Fig.6.43). Plus, they also felt that the internal temperature became too hot and thus experienced uncomfortable conditions during summers (Fig.6.45) (Fig.6.46). Such discomfort in most cases subsequently leads to the use of mechanical cooling to dehumidify the indoors and bring down the temperature.

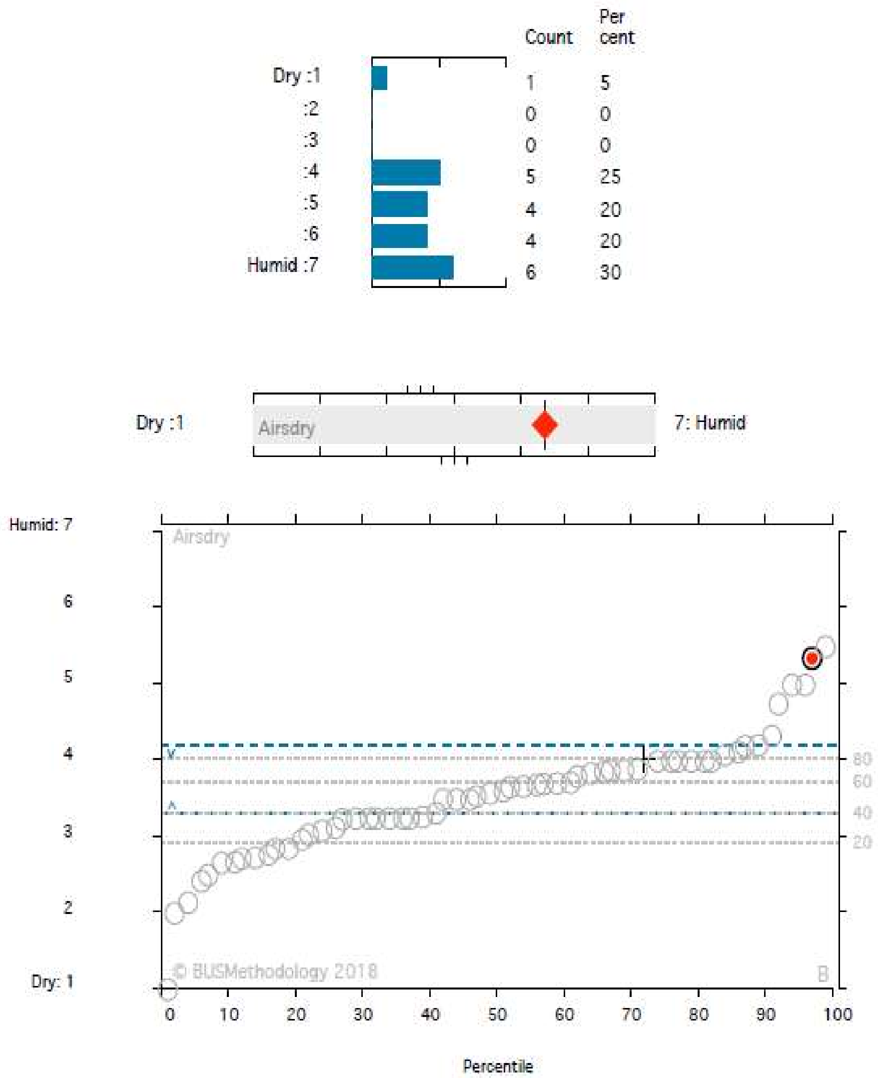

Fig.6.43. Air in Summer (BUS Methodology)

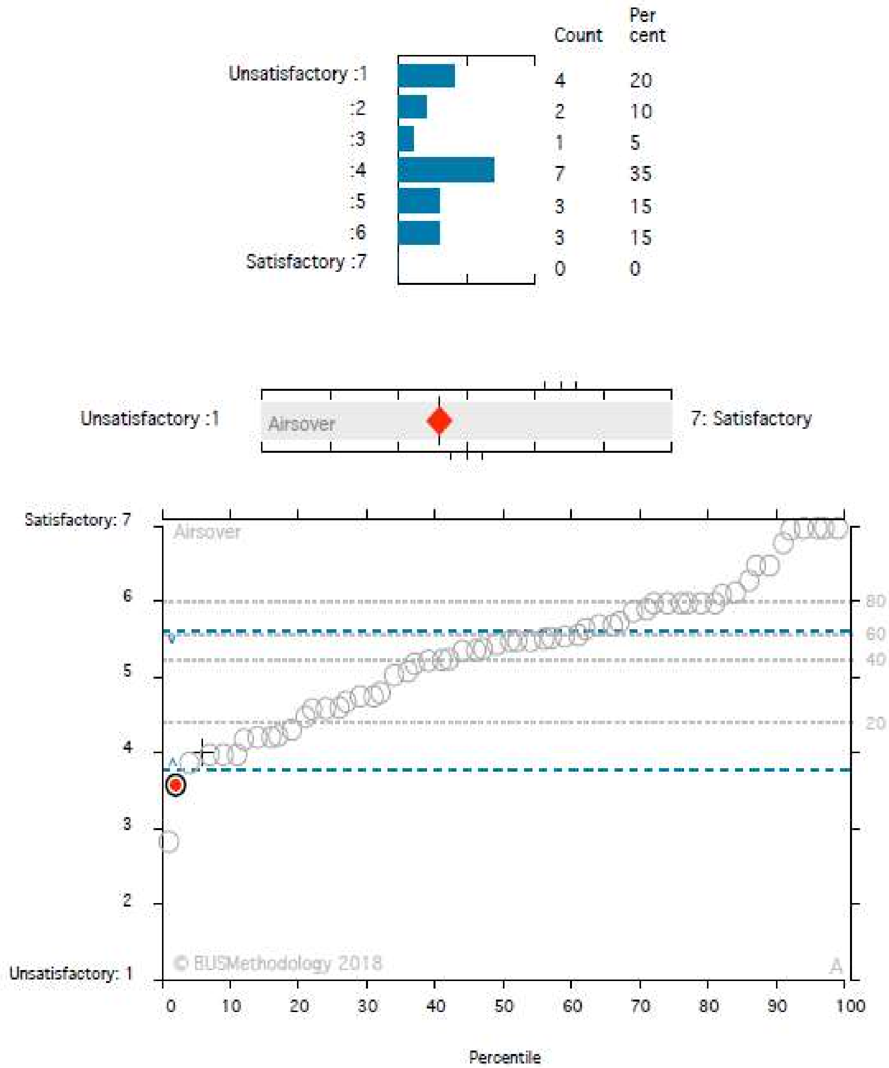

Fig.6.44. Air in Summer - Overall (BUS Methodology)

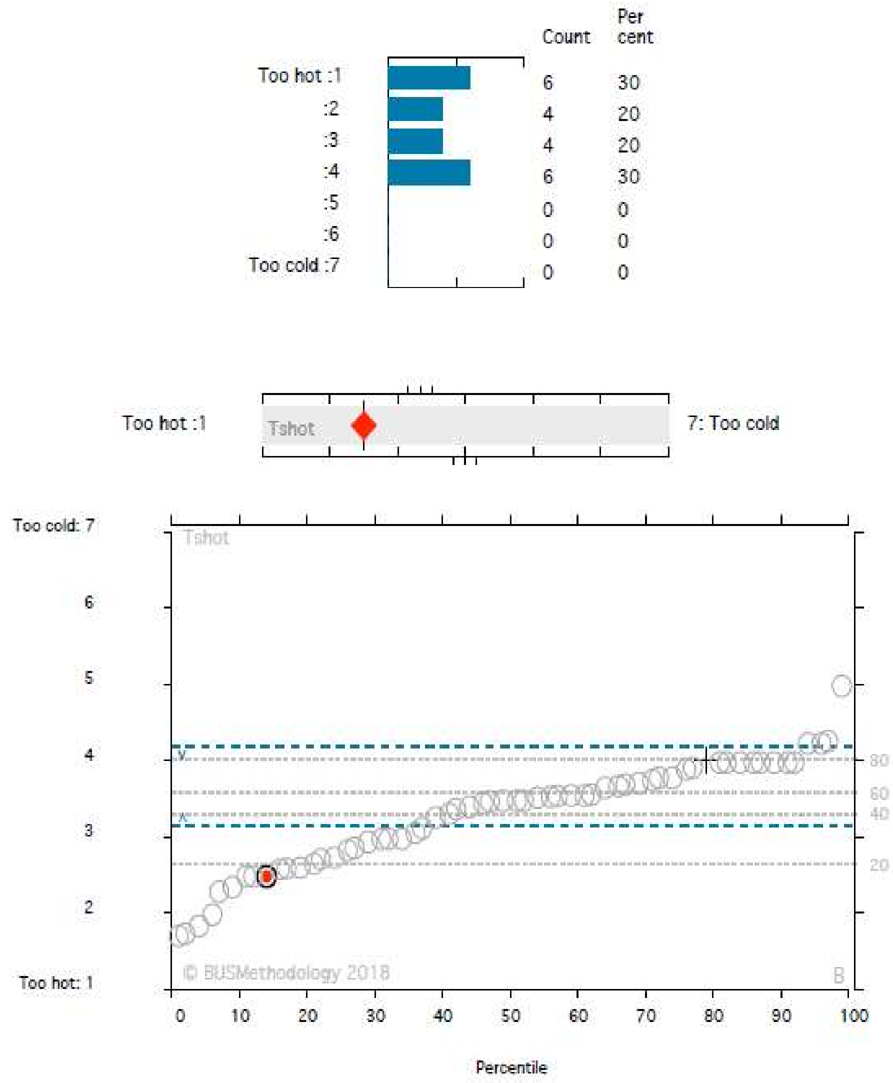

Fig.6.45. Temperature in Summer (BUS Methodology)

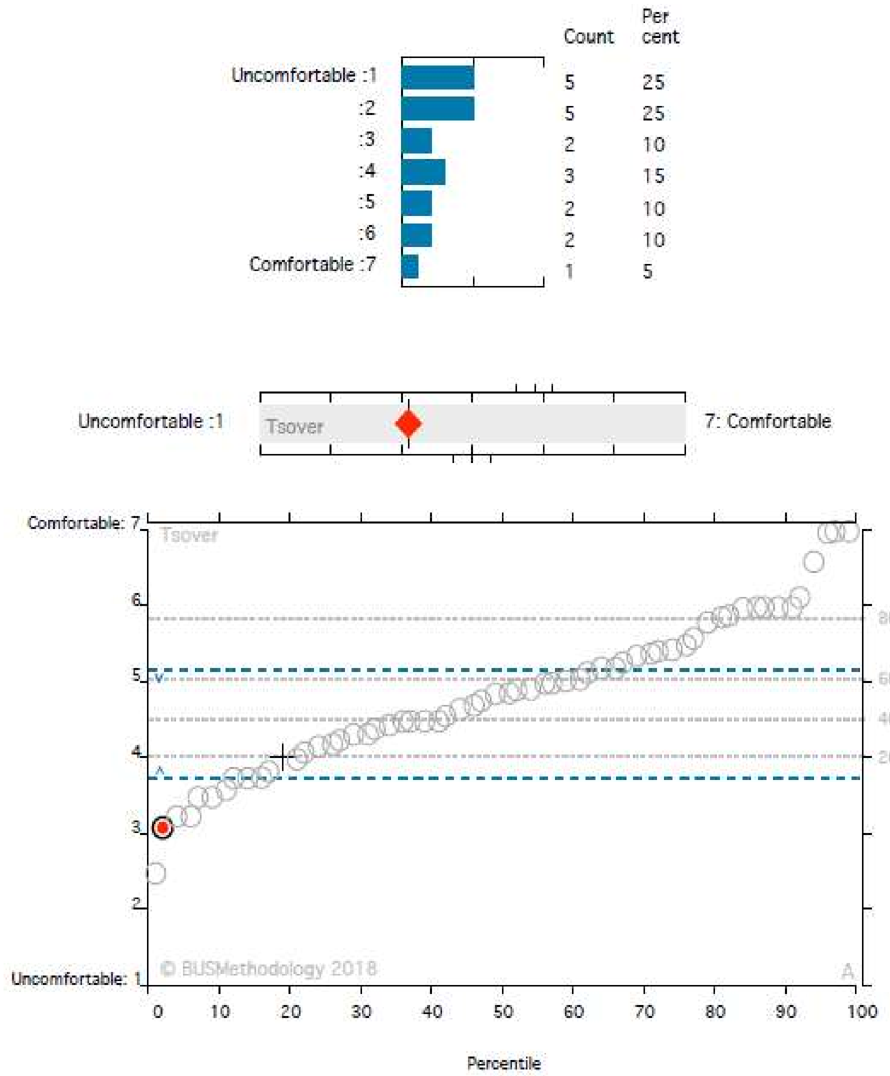

Fig.6.46. Temperature in Summer - Overall (BUS Methodology)

Noise Control:

In order to allow air circulation, when the windows were kept open, occupants experienced lot of outside noise especially from the traffic (Fig.6.48). They had no control (Fig.6.47) over the disturbance created by the outside noise except by shutting down all the openings such as doors and windows that minimized the noise level but led to the rise in the indoor temperature.

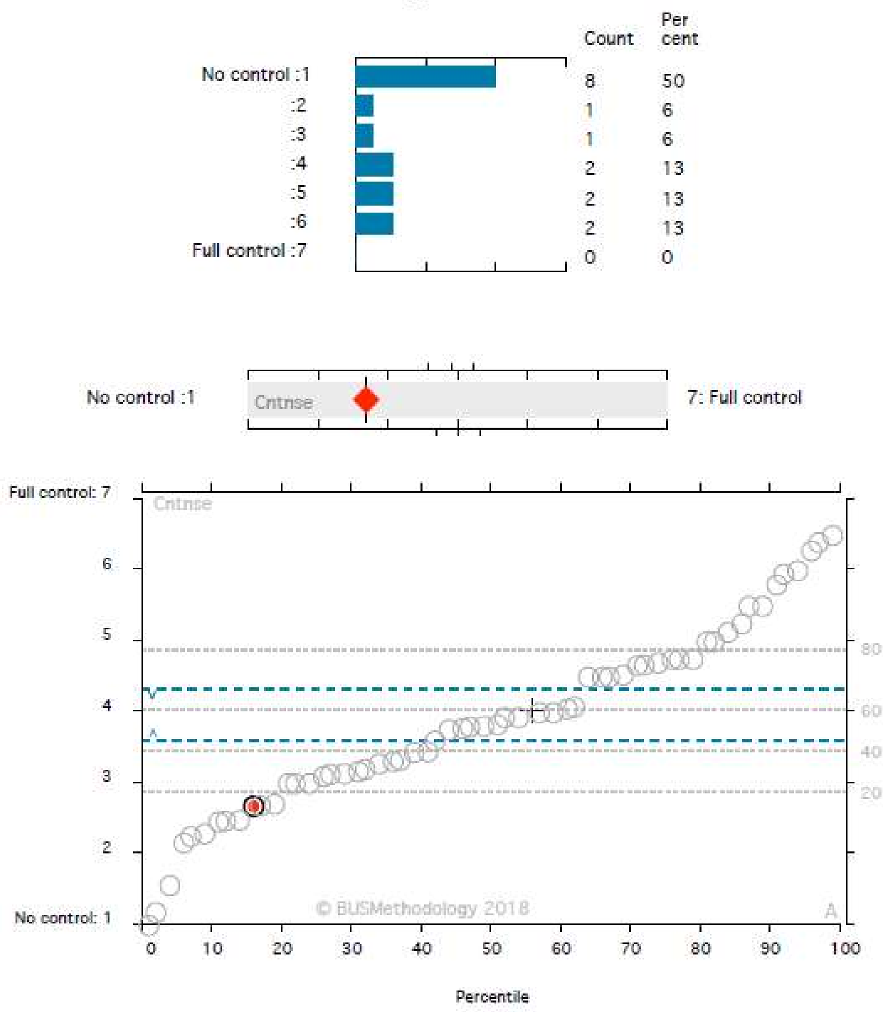

Fig.6.47. Noise Control (BUS Methodology)

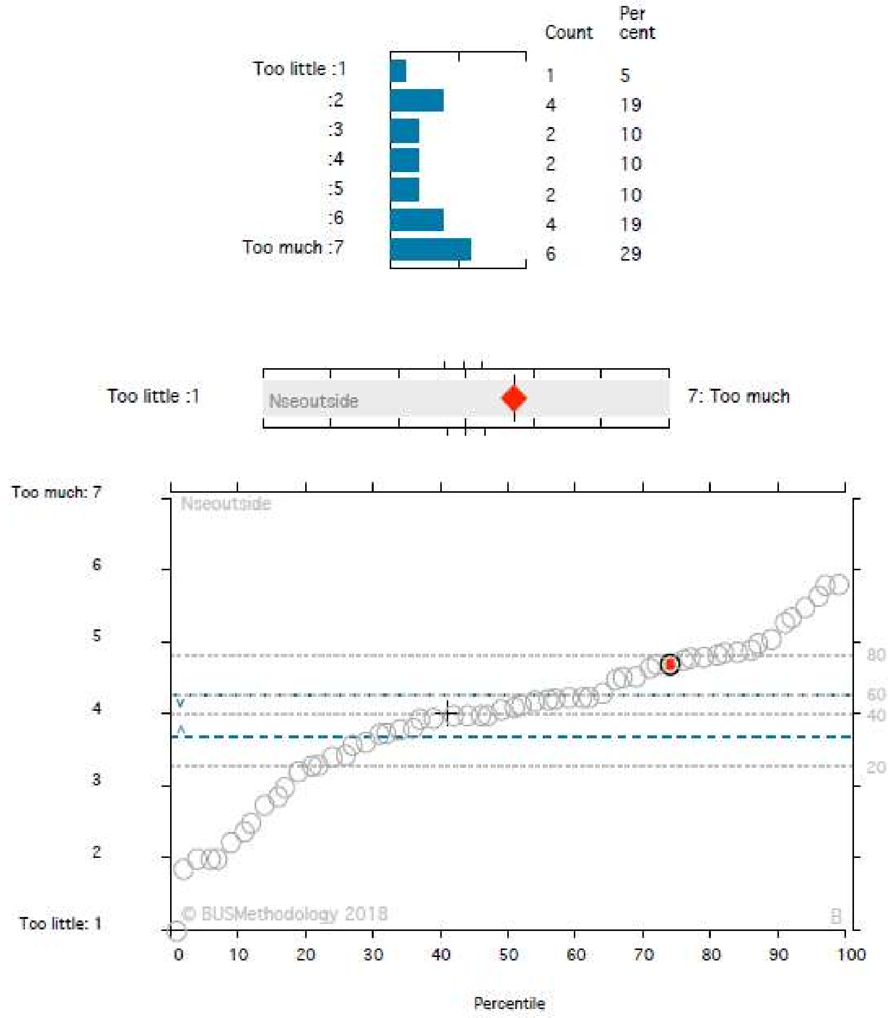

Fig.6.48. Noise from Outside (BUS Methodology)

Lighting – Natural Light:

The occupants felt that the natural light received in their living space was generally higher than their requirements (Fig.6.49). With bright sunny skies especially during the summer months and also most of the times during rest of the months except some rainy days, the excess natural light caused discomfort amongst the inhabitants.

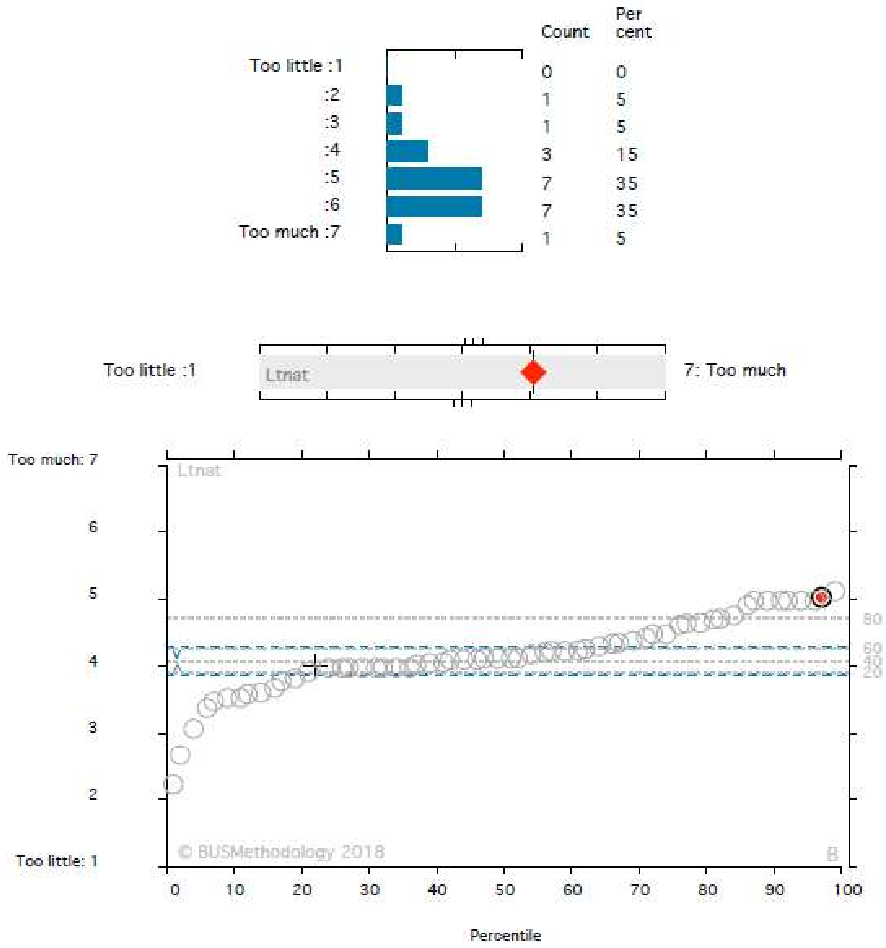

Fig.6.49. Natural Light (BUS Methodology)

Findings from 'Windows' Questionnaire:

The 19 – questions survey form was created keeping in mind the Indian context. It was distributed amongst 21 individuals from Mumbai, Alibag and Ratnagiri and was designed mainly to understand the role windows play in the daily routine of the occupants. Through this survey, it was anticipated that it would allow in understanding if 'windows' acted as an adaptive tool if they had the potential to create diversity, flexibility and social interaction along with providing thermal and visual comfort for its users. The topics covered under this questionnaire were as follows:

a. Importance of windows

b. Window and privacy

c. Window and insects/mosquitoes

d. Window and safety

e. Air conditioning and lighting

f. Window and social interaction

The following observations were made:

a. *Importance of window:*

Majority of the surveyed individuals felt that windows must be operable (Fig.6.50), especially for fresh air (ventilation), view out and sunshine (natural light). Amongst other advantages, the occupants also felt that windows played important role in knowing what is happening outside, for plants, in helping with time, as a storage space and also provided information on the changing climatic conditions (Fig.6.51). Although windows play various important roles in the daily lives of occupants, there are also some disadvantages of the same. The most common draw back of opening a window that was recorded through the survey was the problem of mosquitoes and insects. Outside noise (Fig.6.47.) (Fig.6.48), dust and privacy were also some of the major issues that the occupants faced when windows were kept open (Fig.6.52). Whereas, too much heat, glare and too much light were the least voted problem factors.

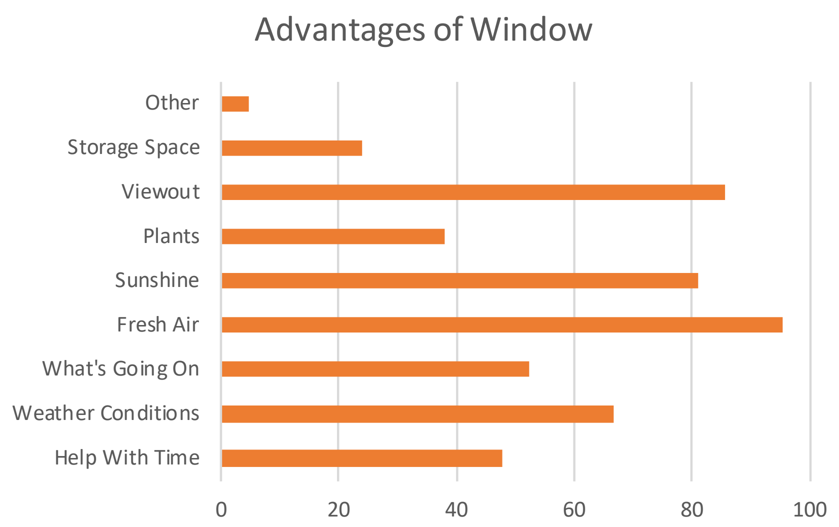

Fig.6.51. Advantages of Window

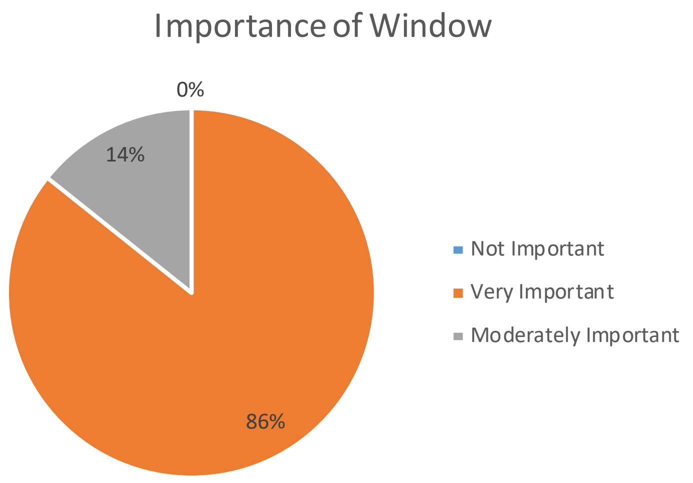

Fig.6.50. Importance of Window

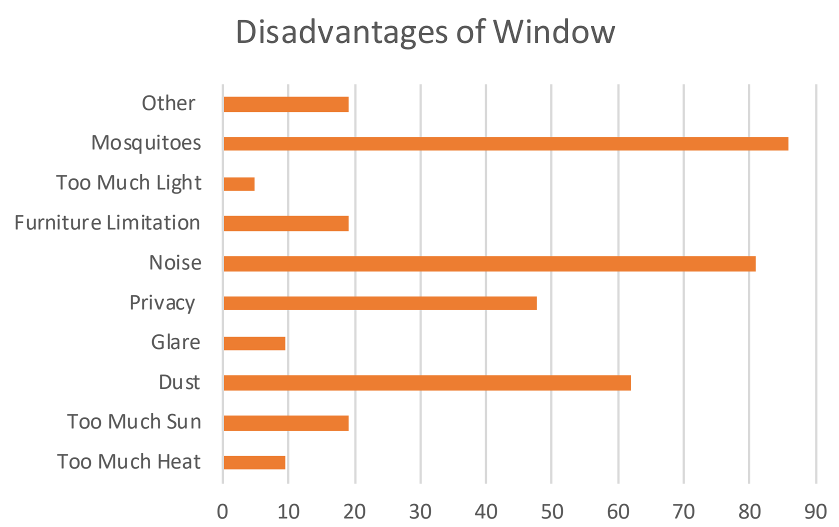

Fig.6.52. Disadvantages of Window

b. *Window and privacy:*

Privacy seemed to be important criteria for the occupants. Though, 57% of the surveyed occupants never faced any privacy related issue, 43% did have problems related to privacy, the main reason for which was close proximity of the neighbouring building and large windows. It was stated by majority of the occupants that this issue was tackled by using curtains or blinds (Fig.6.56).

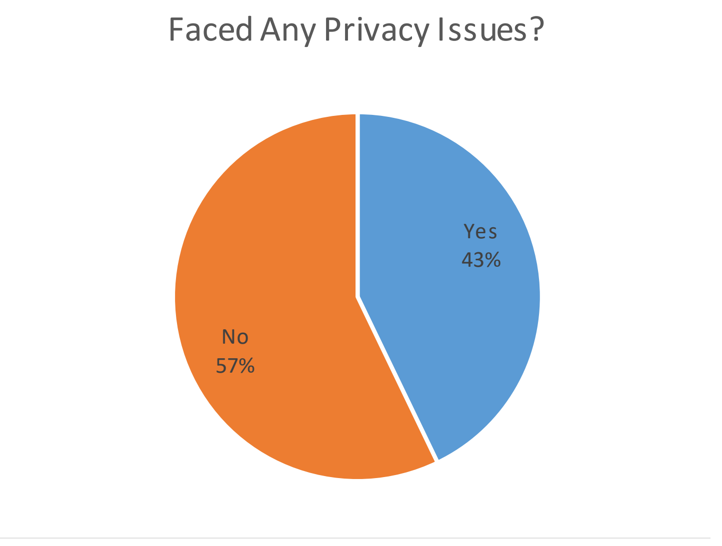

Fig.6.54. Faced Any Privacy Issues

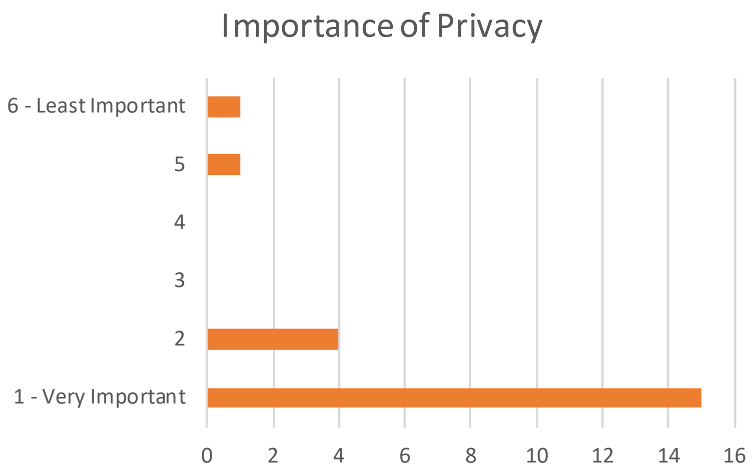

Fig.6.53. Importance of Privacy

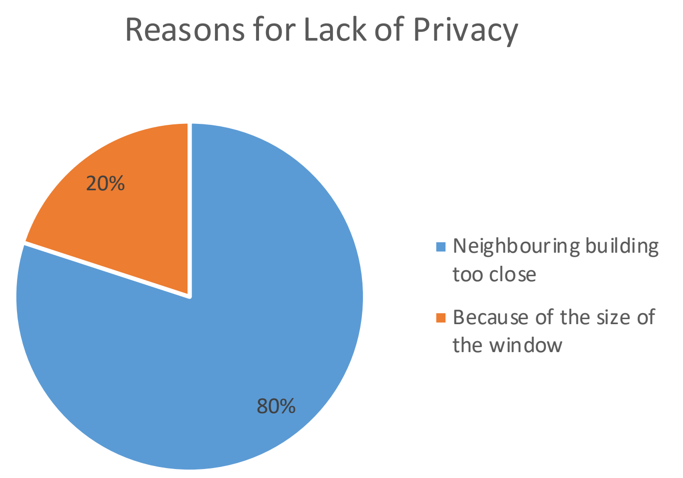

Fig.6.55. Reasons for Lack of Privacy

Fig.6.56. Curtains for Privacy

c. *Window and insects/mosquitoes:*

Keeping the windows open especially in the evenings caused a major issue of insects, specifically mosquitoes entering the house (Fig.6.57). Although, monsoons saw rise in the number of mosquitoes, the problem was persistent throughout the year (FIg.6.58). The solution applied by most of the occupants for this issue was by fixing a mosquito net on the window, by using mosquito repellents or by keeping the windows shut and using air conditioning.

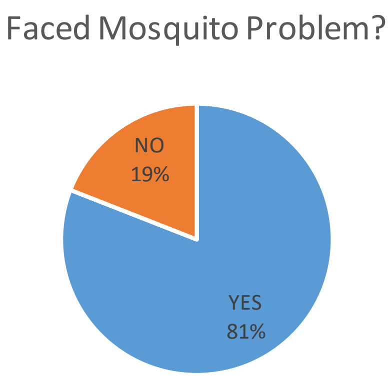

Fig.6.57. Mosquito Problem

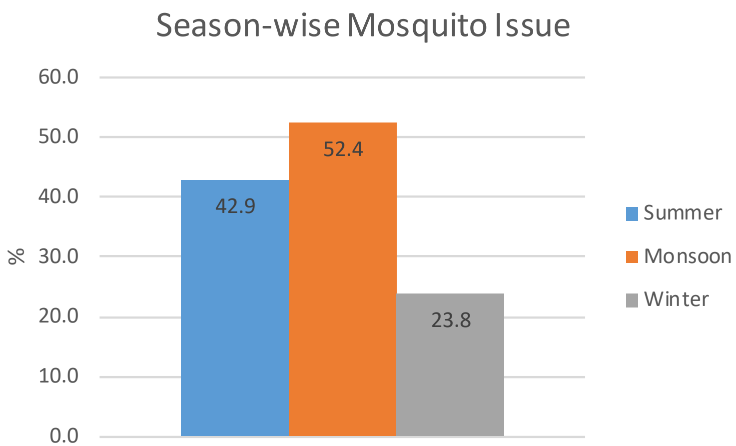

Fig.6.58. Season-wise Mosquito Issue

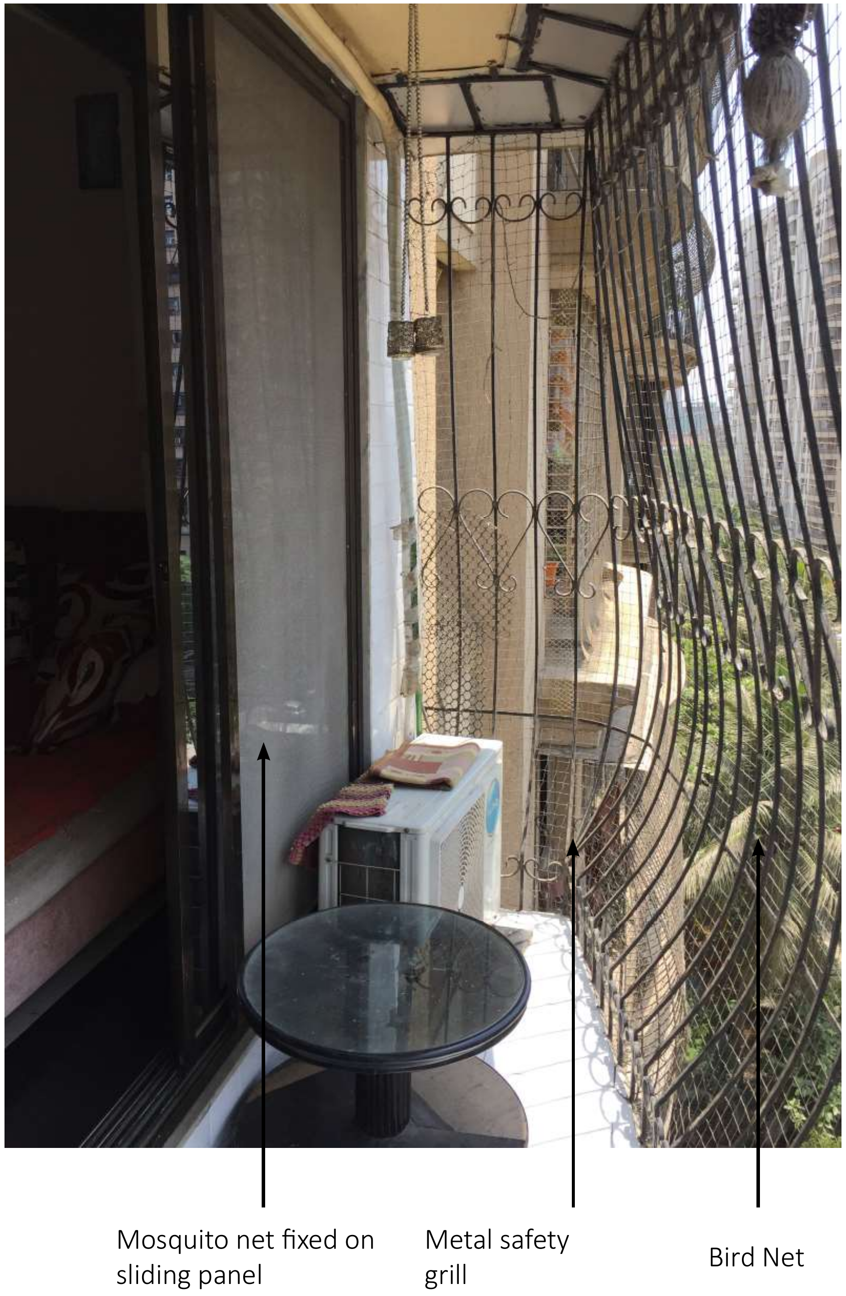

Fig.6.59. Mosquito Net & Bird Net

d. *Window and safety:*

While the occupants felt safety as an important aspect of any window design (Fig.6.60). They ensured that it was obtained by installing a metal safety grill on the outer side of the window (Fig.6.59) even on higher floors.

f. *Window and social interaction:*

The survey showed that the use of window for social interaction was very low and it was only used to call out to someone rather than for communication purpose (Fig.6.61). As a result, the present window system and the form of the buildings fail to create a sense of social connectedness amongst its occupants and hence becomes one of the main reasons for social isolation.

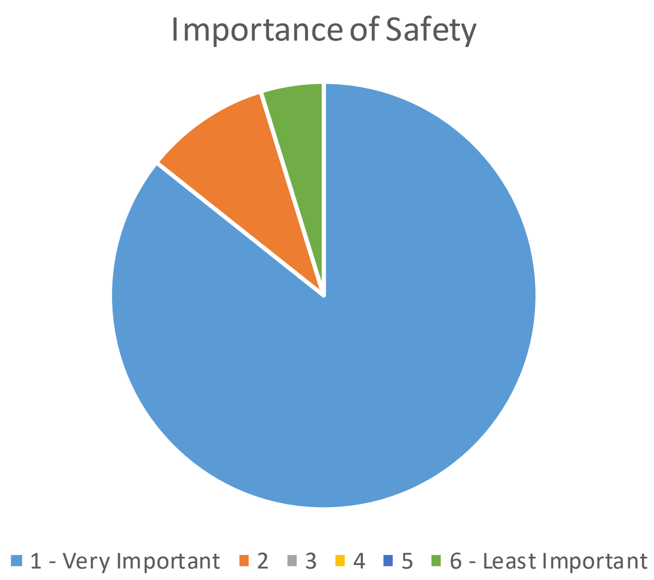

Fig.6.60. Importance of Safety

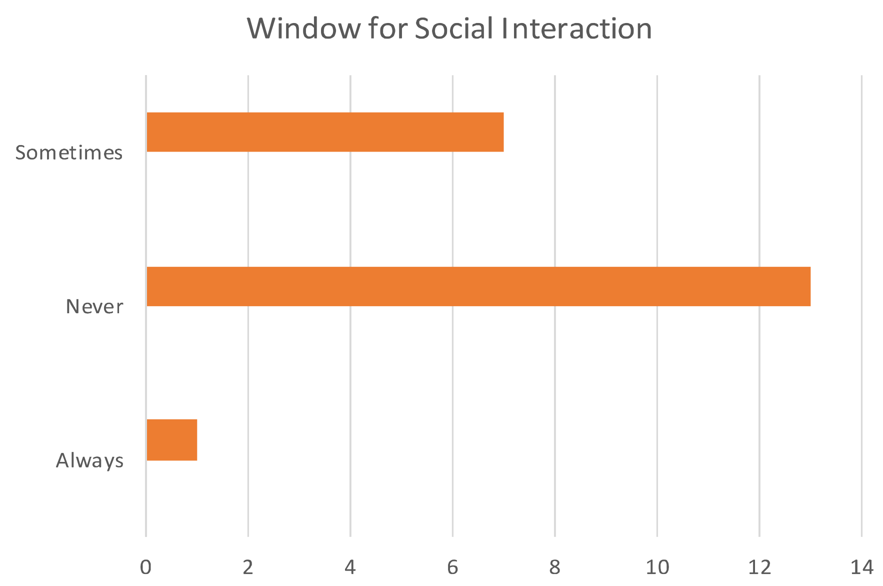

Fig.6.61. Window for Social Interaction

e. *Air conditioning:*

Although it is estimated that only 5% of the Indian households are equipped with air conditioning (Dzieza, 2017) (AFP, 2018), the survey pointed towards rapid growth in the use of mechanical cooling systems. It showed that the air conditioning was used extensively with majority of them having provision in both living room as well as bedroom (Fig.6.62) (Fig.6.63). The mechanical cooling was not used in the morning and evening hours, it was mainly used during the night. Full occupancy at night time and shutting of the windows during sunset to avoid mosquitoes entering the house, seems to be the major reason for the use of air conditioning at night time. While higher temperature and high solar radiations, seems to be the reason for the use of air conditioning in the afternoons (Fig.6.64).

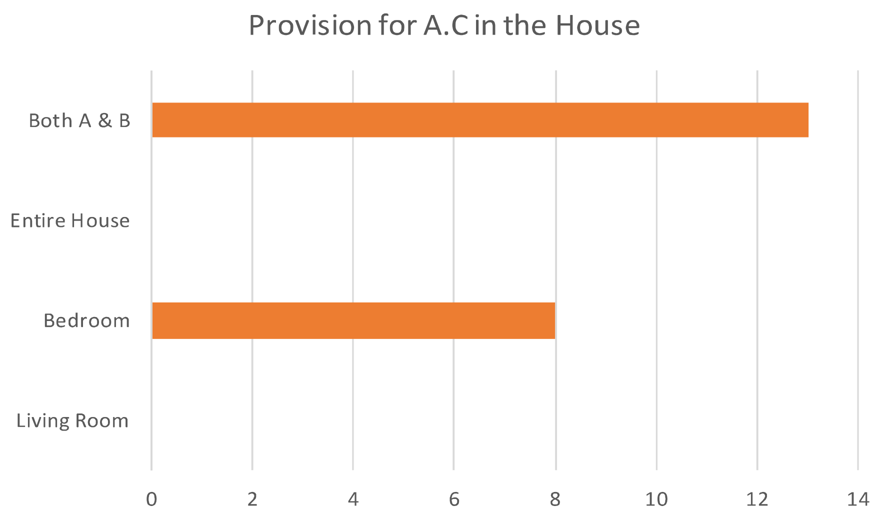

Fig.6.63. Provision for A.C. in the House

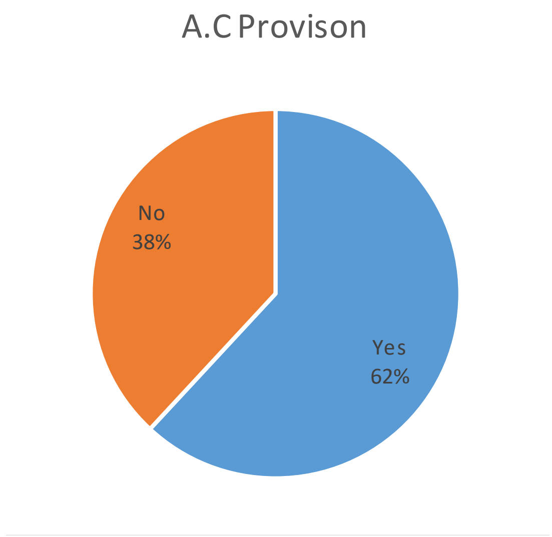

Fig.6.62. A.C. Provision

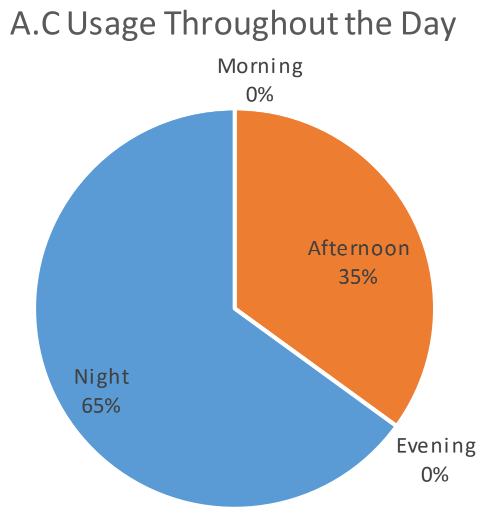

Fig.6.64. A.C. Usage Throughout the Day

Additional Comments

Some of the comments that were documented on the question, *'If you would like to change anything about your present window?',* are *as follows:*

a. Would like to have wooden frame shutter windows instead of aluminum sliding windows. Also, would like to add a ventilator above the main door in the living room for the purpose of cross ventilation.

b. Any amendments to the existing window that can help in reducing the noise levels, although happy with the full length of the window (would not want to change that).

c. Would like to reduce the height as it takes up the entire wall and limit the availability of usable space.

d. Would make balconies more spacious.

e. Would like to have lower windows with flower bed in front.

f. Would like to install bird and mosquito net to keep them out.

g. Would remove the window grill and use the cantilever space as a sit out space.

The above comments demonstrate, how every individual perceives window. Each occupant has their own requirements and definition of their window. Hence, this further strengthens the core belief of this research study of why windows cannot be monotonous.

Reflections

Looking at the outcomes from both the surveys, it can be said that windows play varied vital roles in the life of the occupants. However, there were also some discomforts due to windows. These issues were addressed by the occupants by adding various features such as curtains, safety grills and so on. Nonetheless, these solutions resulted in addition of more and more layers to the existing window which ultimately added to the total cost of the window.

The survey showed that people faced privacy issues and the main reason cited was close proximity to the neighbouring buildings. One must understand that the issue of privacy maybe partially due to the placement of windows but it is mainly due to high density that results in buildings being placed in close proximity with each other. Although, an appropriate solution to this would be to have sufficient distance between buildings, the installation of blinds or curtains by majority of the occupants helps them tackle this issue. But, the use of blinds or curtains prevents ventilation and also obstructs natural light from entering the indoor space. Likewise, another problem that the occupants faced was of outdoor noise from the traffic. Again, the main reason for this discomfort is partially the windows but the main reason was the rise in vehicular traffic. Thus, to cut off the outdoor noise, the occupants had to keep their windows shut and use air conditioning instead. However, a more appropriate way of reducing the traffic noise would be strict vehicular traffic rules such as 'no honking' or proper traffic lights. Although, solutions are available, such as use of curtains or better traffic rules, there is also a scope to incorporate design interventions. The use of jaalis or lattice system that provide privacy and also allows light and ventilation at the same time. Provision of balcony and urban interventions such as plantations are some other ideas that can be incorporated to reduce noise levels.

One of the prominent issue that is faced by nearly every occupant in India is of mosquitoes, almost throughout the year. The fixing of mosquito nets to the windows is now a norm and almost every developer provides these nets by default. This is an important concern and hence, rather than just putting up nets, it would be best to keep surroundings clean and to use pest control to eliminate the growth of mosquitoes over a period of time. Another similar problem that the occupants usually face is of dust. To prevent dust from entering the house, windows are kept shut most of the times. But again, the more appropriate solution for this would be to have dust-free surroundings and more plantations around the built spaces.

Furthermore, the occupants have pointed out excess natural light entering their living space. Again, for which the users end up putting curtains or tinted glazing which in turn restricts the air flow and encourages the use of air conditioning to achieve indoor comfort. An ideal way to deal with excess natural light would be through smart shading design such as cantilevers and calculated size of windows as per the orientation of the building and as per the room size.

Thus, the issues cited by the occupants and their solutions has added more layers to the existing window. These layers have been added to the existing window, as per the occupant requirements. The supplementary layers add more money to the base price of the window, and instead has led the occupants to opt for easy but expensive and environmentally harmful solutions such as the use of mechanical systems for cooling and lighting. It has also made the developers and designers less creative in terms of window designing. This, is precisely what this study tries to highlight – it is to understand the current window design trends, to document them and analyse them, to identify how they are being perceived and used by the occupants and figure out the issues associated with them and suggest solutions.

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CHAPTER 7

PERFORMANCE ANALYSIS

Various architectural elements such as walls, floors, roofs, windows have the ability to improve or worsen the indoor environment. Changes in material, dimensions, building techniques can shift the thermal properties of a built space tremendously. To study these changes, dynamic thermal simulations are performed. In this chapter, these simulations are carried out, particularly, to understand the impact of windows, specifically from the *'chawl'* and *'wada'* typology, on a typical contemporary window that belongs to the apartment block. All of the above-mentioned typologies are documented (See Chapter 05 and 06). The simulations are performed to understand the impact of change in wall, floor and ceiling construction method and material on the documented apartment and also the impact of the addition of external shading on indoor environment. A case by case record of the impact created after these changes are applied and presented in the form of graphs. These cases are compared and analysed to draw conclusions and also form supporting information for the concluding chapter.

Computational Simulation – TAS (Thermal Analysis Software)

The modelling software chosen for further study is Thermal Analysis Software (TAS) developed by Environmental Design Solutions Limited (EDSL). This software simulates the dynamic thermal performance of buildings, by taking into consideration, the effects of thermal mass and operative temperature. There are various modules in TAS, of which the TAS building designer is the main segment that executes dynamic simulations with integrated forced and natural airflow. The 3D modeller module allows to include CAD link to create building geometry for simulation. It has built-in construction libraries with their U-values which can be synthesized to create construction elements as per user requirement. TAS also allows linking of weather files from online weather sources which are then converted into a graphical format in TAS to give annual environmental variables such as temperature, humidity, wind velocity, cloud cover, sunshine and so on. Further, it provides ventilation, heating and air conditioning (HVAC) controls which can be coupled with the 3D geometry to be simulated (Saleh, 2018). It allows the user to add infiltration and ventilation rates along with calculated internal gains. Plus, the user also gets to add advanced inputs such as aperture types, window and ventilation schedules, shading types and so on. Thus, TAS provides with the opportunity to combine dynamic thermal calibrations of space while giving control over functions such as natural and mixed-mode ventilation rates and provides annual hourly outputs that can be customized as per the requirements.

Methodology for Analysis

Taking into consideration the above specifications of the software, Tas 9.4.4. was used in determining the thermal performance of an apartment block in Mumbai (Case study 01) (Fig.7.1). Out of the three field studies, an apartment, in the eighteen-floor tower was chosen for calibration because the tower represented the current building trend in the residential sector and hence served as a typical apartment building example throughout India.

The main aim to carry out thermal simulation was to further stress upon the role of windows in formulating the indoor environment. Thus, this analysis was performed to establish the adaptability that 'windows' provide. The fieldwork showcases three typologies belonging to the different eras that exhibit different style of construction, materials, technical details as well as different designs. The simulations were performed to determine the impact of the documented window designs along with the materials and construction techniques used, on a typical contemporary apartment block. As a result, eight cases were formulated based on the field study. The cases were tested and the results were plotted for typical summer days for the west-facing living-cum-dining area of the apartment.

Fig.7.1.Panorama Tower, Andheri-Mumbai

Fig.7.2. Panorama Tower - Plan

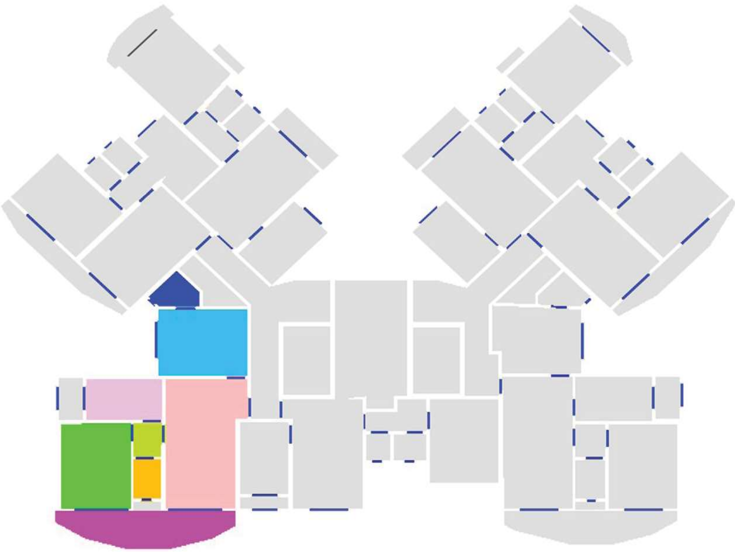


Fig.7.3. Panorama Tower – Plan in TAS

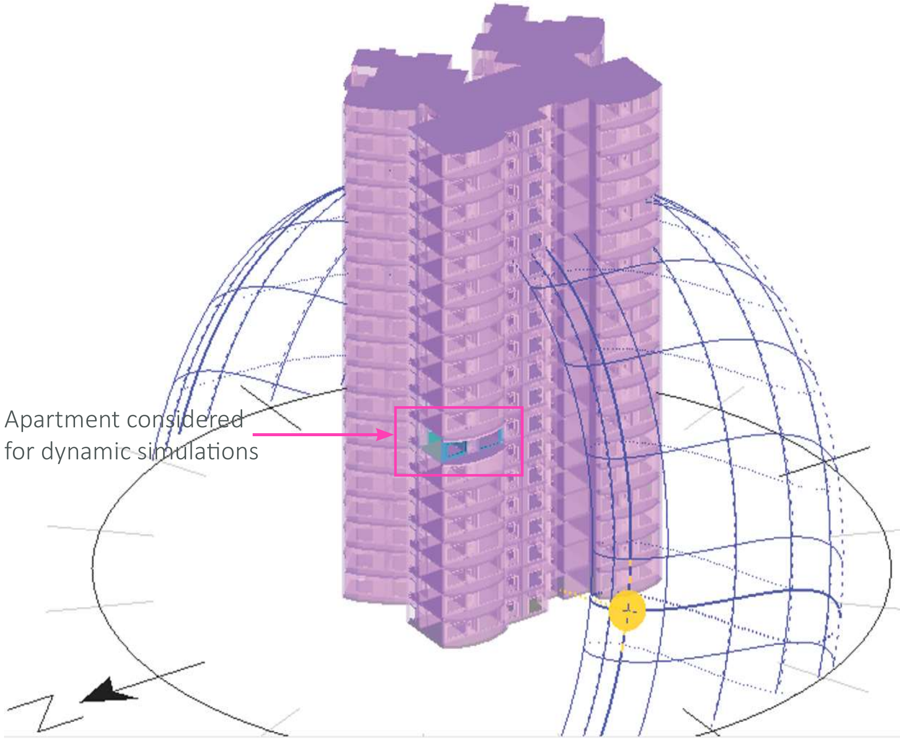


Fig.7.4. Panorama Tower – 3D in TAS

1. Case 01: Calibration is performed taking into account the exisiting contemporary apartment block where the windows, floor, walls and ceiling are considered as per the present condition alongwith the documented internal gains. (Typology 1).

The cases that are considered for simulation are as follows:

2. Case 02: The window of case 01 is replaced with the one used in *'chawl'* (typology 2).

3. Case 03: The wall thickness and material of case 01 are replaced with the one used in 'chawl' (typology 2).

4. Case 04: The floor and ceiling of case 03 are replaced with the one used in *'chawl'* (typology 2).

5. Case 05: The window of case 01 is replaced with the one used in *'wada'* (typology 3).

6. Case 06: The wall thickness and material of case 05 are replaced with the one used in *'wada'* (typology 3).

7. Case 07: The floor and ceiling of case 06 is replaced with the one used in *'wada'* (typology 3)

8. Case 08: A simulation is performed, were the existing walls, ceiling and floor are replaced with exposed RCC along with window + door + ventilator combination that allows night-time ventilation.

An additional simulation is performed keeping the window design and material configuration same as case 08 with an addition of external shading system.

Assumptions

Some common components were considered for all the eight cases and they are as follows:

I. **3D modeller:** As shown in Fig.7.4, a 3D model of the tower was created and the apartment to be simulated was zoned. Other parameters such as building elements like walls, floors and ceilings, windows and shades changed as per the cases and are discussed further in detail in each case.

II. **Internal Conditions:** Factors such as infiltration rates, ventilation, lighting gain, sensible and latent occupancy and equipment gains were derived based on the fieldwork analysis (Refer Chapter 05 and 06) These values were the same for all the cases and are as follows:

Infiltration rate: It is assumed that the building is not air-tight and air trickles through the gaps, such as cracks, leakage in doors or windows and so on. As per CIBSE Guide A, the infiltration rate considered for rooms in dwellings is 0.2ach.

Ventilation: To provide fresh air to the inhabitants and to remove concentrations of harmful pollutants from a space, hourly values for ventilation were calculated using the formula:

$$\text{Air changes/hour} = \frac{(l/s) * \text{no. of occupants} * 3.6}{\text{volume of room}}$$

Where,

(l/s) is the amount of inflow of air per unit time. This value is considered 10l/s for each occupant.

The hourly weekend and weekday values are given below (Table.7.1), that were derived by taking into consideration the occupancy pattern. These ventilation rates were considered only for the calibrated case.

	Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Ventilation rate (ach)	Weekday	0	0	0	0	0	0	1.9	1.9	1.2	0.6	0.6	0.6	1.2	1.2	0	0	2.5	1.9	1.9	3.1	1.9	1.9	1.9	0
	Weekend	0	0	0	0	0	0	1.9	1.9	1.9	0.6	0.6	0.6	1.9	1.9	0	0	1.2	0.6	0.6	1.2	1.2	1.9	1.9	0

Table.7.1. Table of hourly ventilation values

Lighting Gains (Table.7.2): The internal heat gains from the lighting fixtures were calculated based on the number of fixtures in the living room and their consumption pattern. The hourly values of lighting gains for weekday and weekend table are as follows:

	Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Lighting Gain (W/m^2)	Weekday	0	0	0	0	0	0	2.1	2.1	4.9	4.9	4.2	4.2	2.1	2.1	0	0	2.1	2.9	3.75	4.6	4.6	4.6	3.75	0
	Weekend	0	0	0	0	0	0	2.1	2.1	4.9	4.9	4.2	4.2	2.1	2.1	0	0	2.1	2.9	3.75	4.6	4.6	4.6	3.75	0

Table.7.2. Table of hourly lighting gains

Occupancy Gains (Table.7.3): Depending upon the activity of the occupants that was recorded during the fieldwork, sensible and latent occupancy gains were derived from CIBSE Guide A and are as follows:

	Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Sensible Occupancy Gain (W/m^2)	Weekday	0	0	0	0	0	0	5.8	5.8	11.7	11.7	2.9	2.9	5.8	5.8	0	0	11.7	9.8	9.8	11.9	8.8	9.2	9.2	0
	Weekend	0	0	0	0	0	0	5.8	5.8	9.8	9.8	2.9	2.9	5.8	5.8	0	0	5.8	3.1	3.1	5.8	5.8	9.2	9.2	0
Latent Occupancy Gain (W/m^2)	Weekday	0	0	0	0	0	0	4.6	4.8	11.3	11.3	2.3	1.9	4.2	3.8	0	0	7.5	11.3	11.3	7.9	5.6	6.5	6.5	0
	Weekend	0	0	0	0	0	0	5.4	4.4	6.4	6.4	2.3	1.8	4.2	3.75	0	0	3.75	2.3	2.3	3.75	3.75	6.5	6.5	0

Table.7.3. Table of hourly sensible and latent occupancy gains

Equipment Gains (Table.7.4): Since, equipments do not add moisture into the environment, only sensible equipment gain is generated. The values of the same are derived from CIBSE Guide A and are follows:

	Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Sensible Equipment Gain (W/m^2)	Weekday	0	0	0	0	0	0	0.9	3	3	0.4	0.4	2.75	2.75	2.75	2.75	0.4	0.4	0.4	2.75	3	3	2.75	2.75	0
	Weekend	0	0	0	0	0	0	0.9	3	3	0.4	0.4	2.75	2.75	2.75	2.75	0.4	0.4	0.4	2.75	3	3	2.75	2.75	0

Table.7.4. Table of hourly sensible equipment gain

IV. The BUS survey, questionnaires, interviews with the occupants considerably pointed at the uncomfortable thermal conditions experienced by the users specifically in the summer months. Hence, the results for all the cases were drawn for five typical summer days of the year. For simulation purpose, the comfort band was calculated using CBE Thermal Comfort Tool for ASHRAE 55, that calculates the lower and upper limit of the thermal comfort ranges (Tyler et al., 2017). Table.7.5. below shows the days considered and the comfort band limits of the same:

	Summer
Days	10th May – 15th May (Day : 130-135)
Comfort Band (80% acceptability limit was considered)	23.8°C – 30.8°C

Table.7.5. Days of Analysis and Comfort Band

Case 01:

The existing modern apartment block where the windows, floor, walls and ceiling are considered as per existing design (Fig.7.5 – 7.7). (Typology 1).

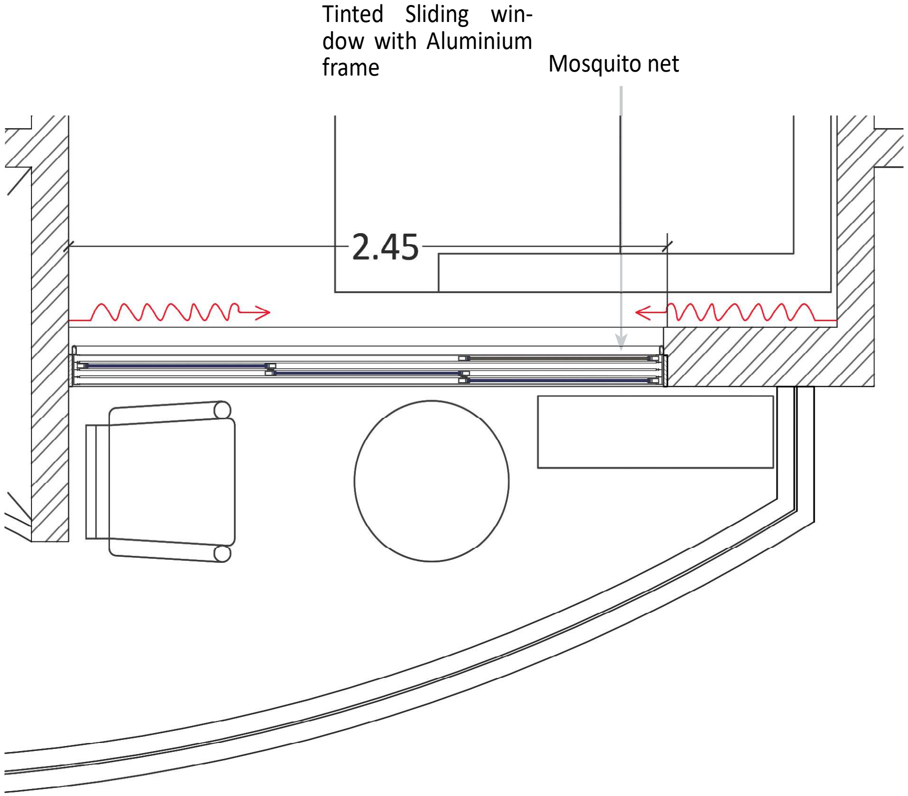


Fig.7.5. Existing Window – Plan

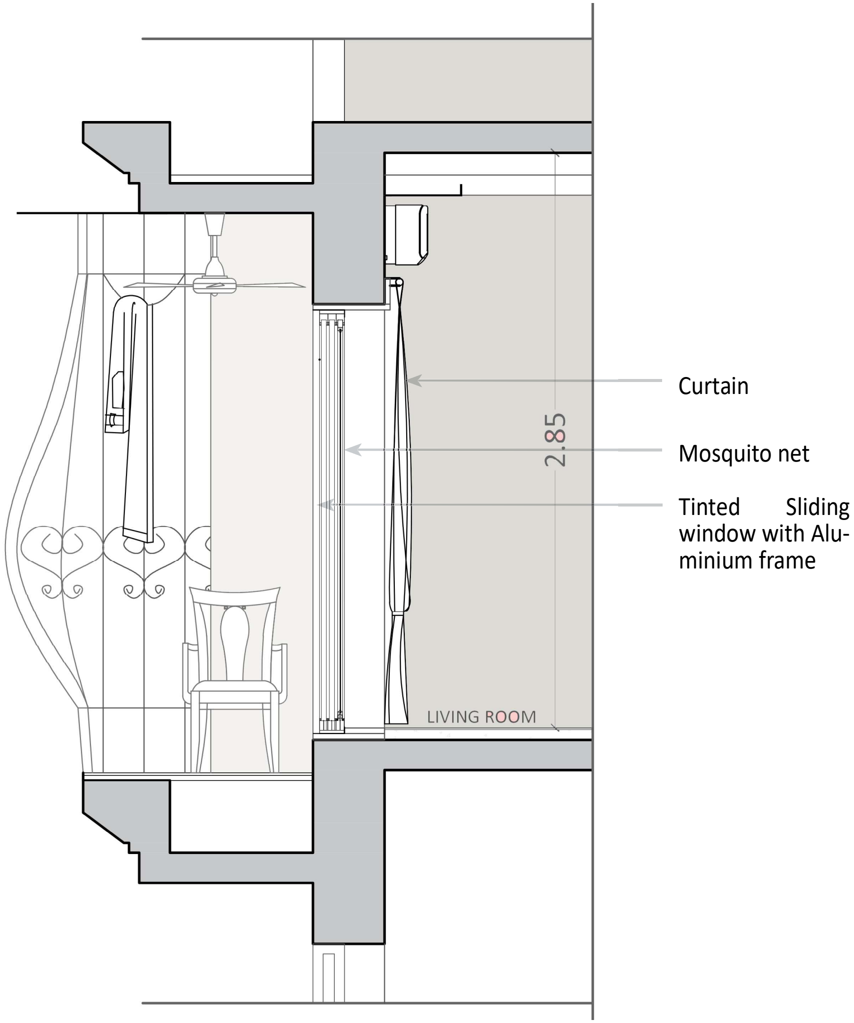


Fig.7.6. Existing Window – Plan

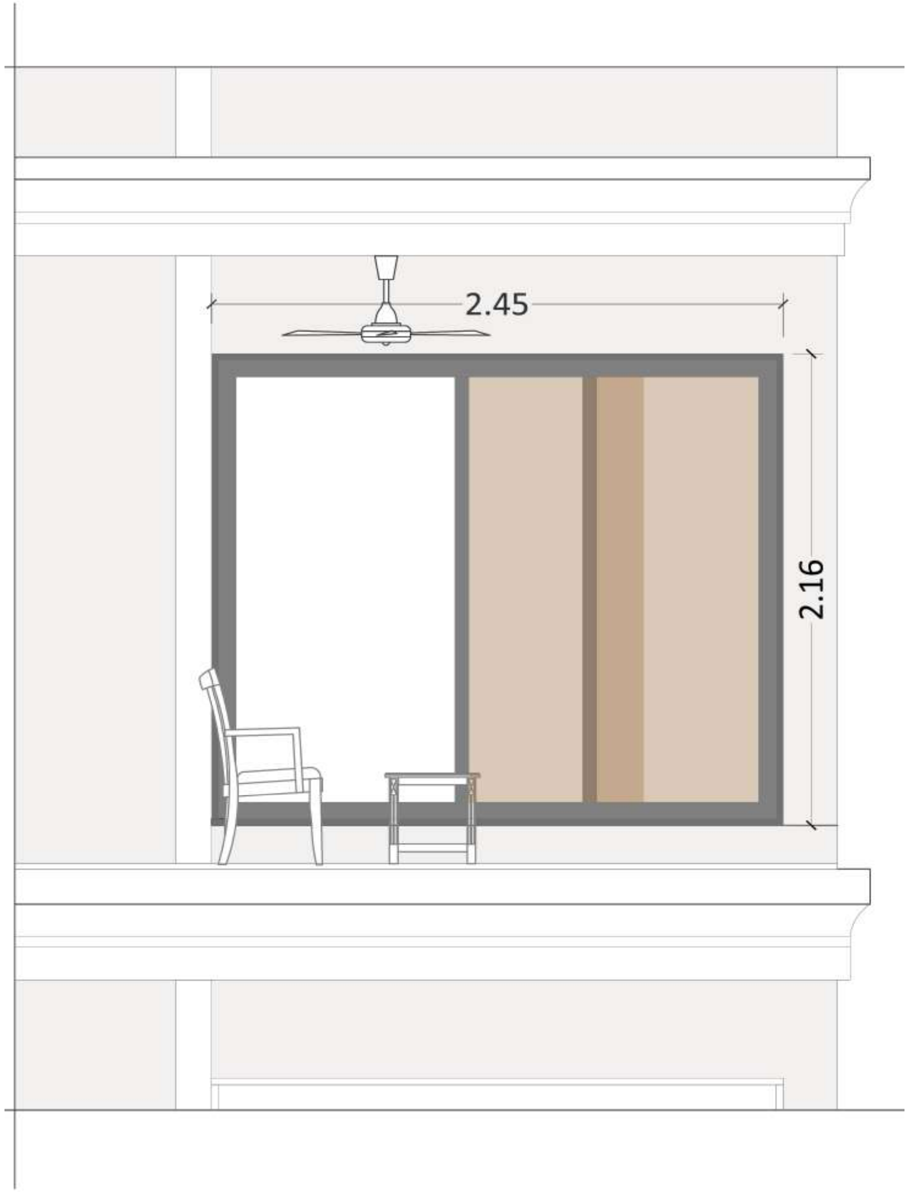


Fig.7.7. Existing Window - External Elevation

CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m².ºC)
Window	IN / OUT	18mm thick aluminium frame +	4.8
		Fabric Open Weave Curtain + 12mm Air cavity + 4mm tinted single glass	Glazing U-value 5.7
External Wall	IN / OUT	15mm thick Plaster + 230 mm thick Brick Masonry + 15 mm thick Plaster	1.8
Flooring	OUT / IN	12mm thick Tiles + 50mm thick Screed + 150 mm thick R.C.C slab + 12mm thick plaster	1.7
Ceiling	OUT / IN	12mm Tile + 50 mm Screed + 150 mm R.C.C slab + 12 mm Plaster + 200 mm Air + 12mm thick Fibreboard	1.0

Table.7.6. Table of Construction considered for Case 01

Graph 01: *For summer – 10th (day 130) to 15th May (day 135)*

The drawings and the table (Table.7.6) provides detailed specification, such as measurements of the building elements like window, wall, floor and ceiling plus material specification for the given building elements along with their internal and external U-values. Window schedule (Table.7.7) was set as per the observed pattern of use and from occupant interview, while the aperture value was set to maximum opening (0.75) that could be achieved with a sliding window. The west facing living-cum-dining space was considered for the purpose of simulation.

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table.7.7. Window Schedule - Case 01 *0 = Close 1 = Open*

Solar radiation, external temperature, plus an upper and lower limit of the comfort band were plotted (Fig.7.8).

Apart from the above parameters, the following three temperatures are also plotted:

1. Monitored Dry Bulb Temperature (DBT): This is the reading obtained from the data loggers placed in Mr.Oza's apartment during the summer months.

2. Simulated resultant temperature (RT): This graph line portrays the existing conditions of the apartment. Wherein, the materials, their thickness and construction techniques are inserted as per the recorded condition during the fieldwork. The internal conditions such as lighting gains, equipment gains and occupancy gains are entered based on the data recorded during fieldwork through observations and user feed back. The simulations are performed for free-running living space.

3. Calibrated resultant temperature (RT): According to ASHRAE 14-2014 guidelines, a process of comparison of the actual measured data under set conditions to the predicted output of the model under the same set of conditions is defined as calibration. Hence, a calibrated model is the one that can recreate the measured data under the same set of parameters (Ruiz and Bandera, 2017).

In this case, calibration is performed to match the monitored temperature. Apart from building specifications and internal conditions, mechanical cooling is added to the input data in TAS. The period of the use of air conditioning is determined through fieldwork observations and user feedback.

Resultant temperatures are plotted because unlike the dry bulb temperature that does not take in to consideration the radiation and moisture present in the air, the resultant temperature considers the exchange of heat through conduction as well as through radiation. Since, thermal comfort is assessed in this case as well as in the following cases, resultant temperature *(RT)* is plotted for all the graphs.

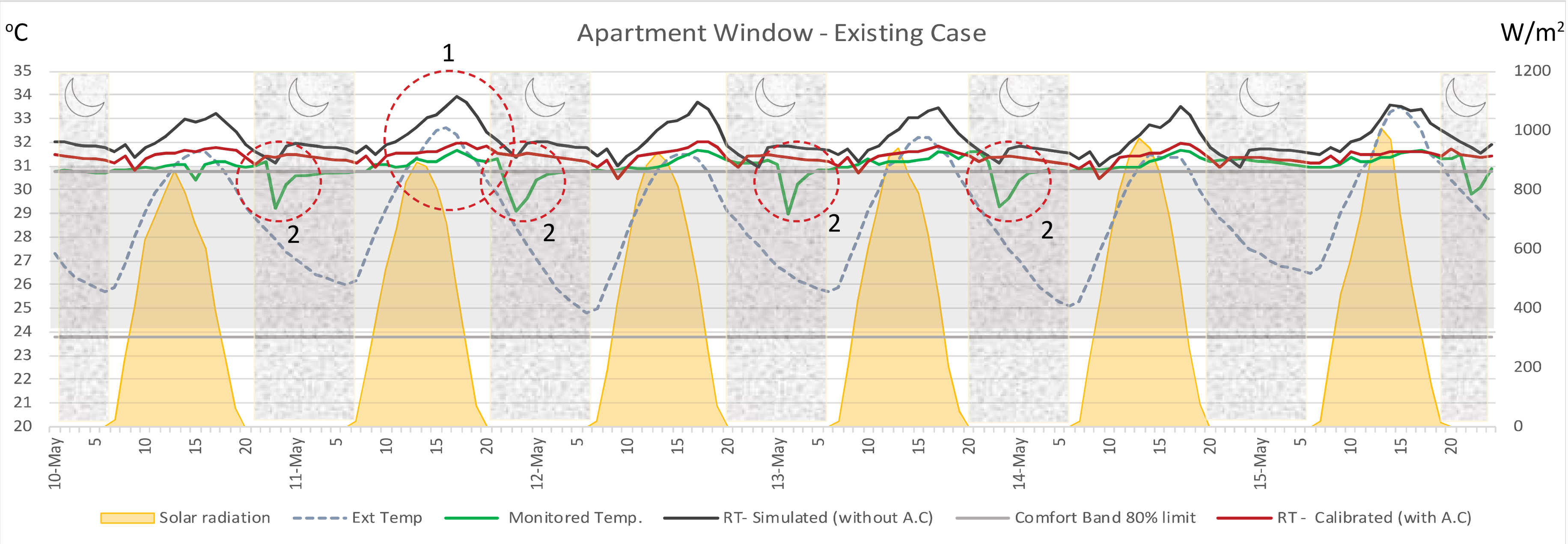


Fig.7.8. Case 01 - Existing Case

Results:

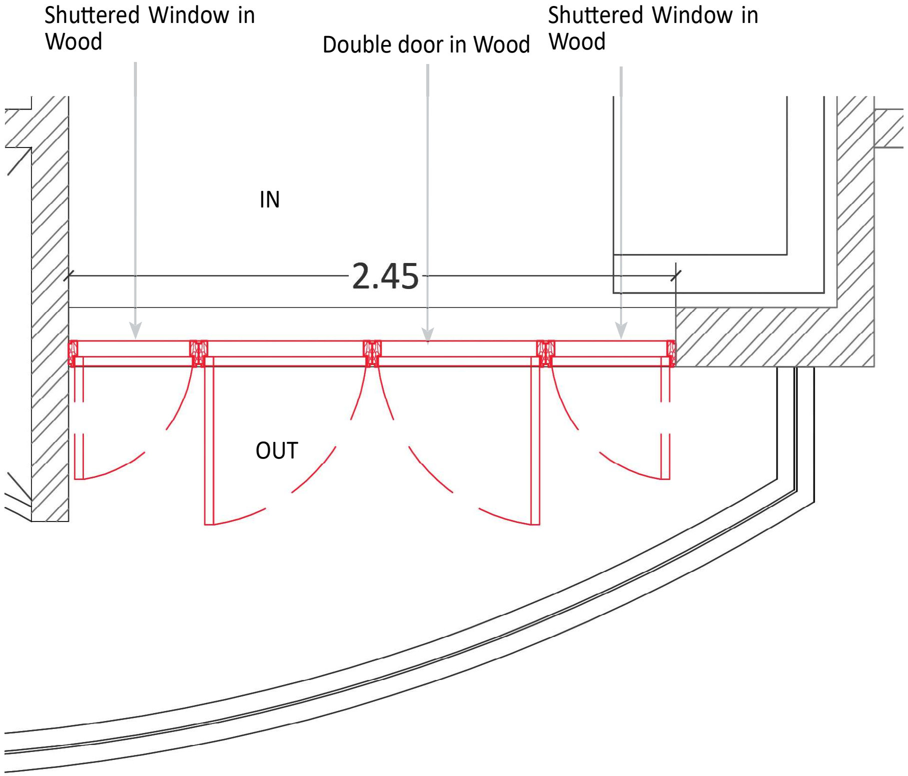
The calibrated and the simulated RT do not fall in the comfort band. It is observed that the simulated RT, rises with the rise in solar radiation and co-ordinates with the outdoor temperature. Whereas, the monitored DBT, as well as the calibrated RT, is 3-3.5°C lower during the same period (1). Thus, it is very clear that from peak solar radiation period till evening, the occupants are most uncomfortable and hence, use mechanical cooling within this time frame to improve their indoor thermal environment.

Further, a 2°C drop in monitored DBT, from 31° to 29°C is observed between 22:00 and 24:00 at four consecutive nights (2). This phenomenon is not seen on the 5th night (14th May). It is assumed that since the drop in external temperature is gradual, the internal temperature does not seem to be influenced by external climatic conditions. There is a possibility that air conditioning is used during this period with minimal internal heat gains during this time.

The monitored DBT, the simulated RT and calibrated RT are more or less in sync with each other, however, the differences can be associated with the difference in the assumed internal conditions (as per the interview with the occupant and observations made during the fieldwork) and actual internal conditions. Having said that, it can be established that, since calibrated RT coordinates with the monitored temperature and simulated RT coordinates with the outdoor temperature, the assumptions that are undertaken for calibration are acceptable and on the basis of this premise further simulations can be performed.

Case 02:

In this case, the existing window of the apartment is replaced by the *chawl* window which is designed to fit to the dimensions of the existing apartment window (Fig.7.9 – 7.11). (Typology 2). Thus, the tinted sliding window with aluminium frame and with mosquito net plus light curtains is replaced with a window + door + ventilator combination. This window is designed in wood with wooden frames.



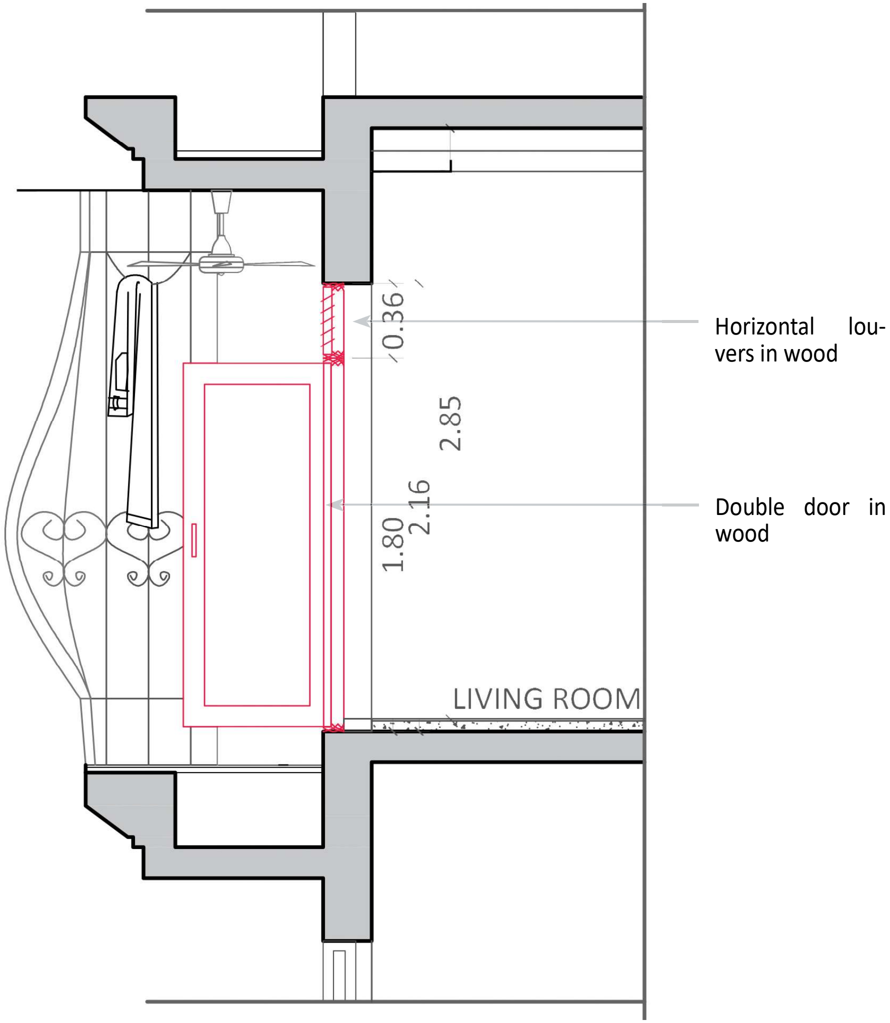


Fig.7.9. Case 02 – Plan

Fig.7.10. Case 02 - Section

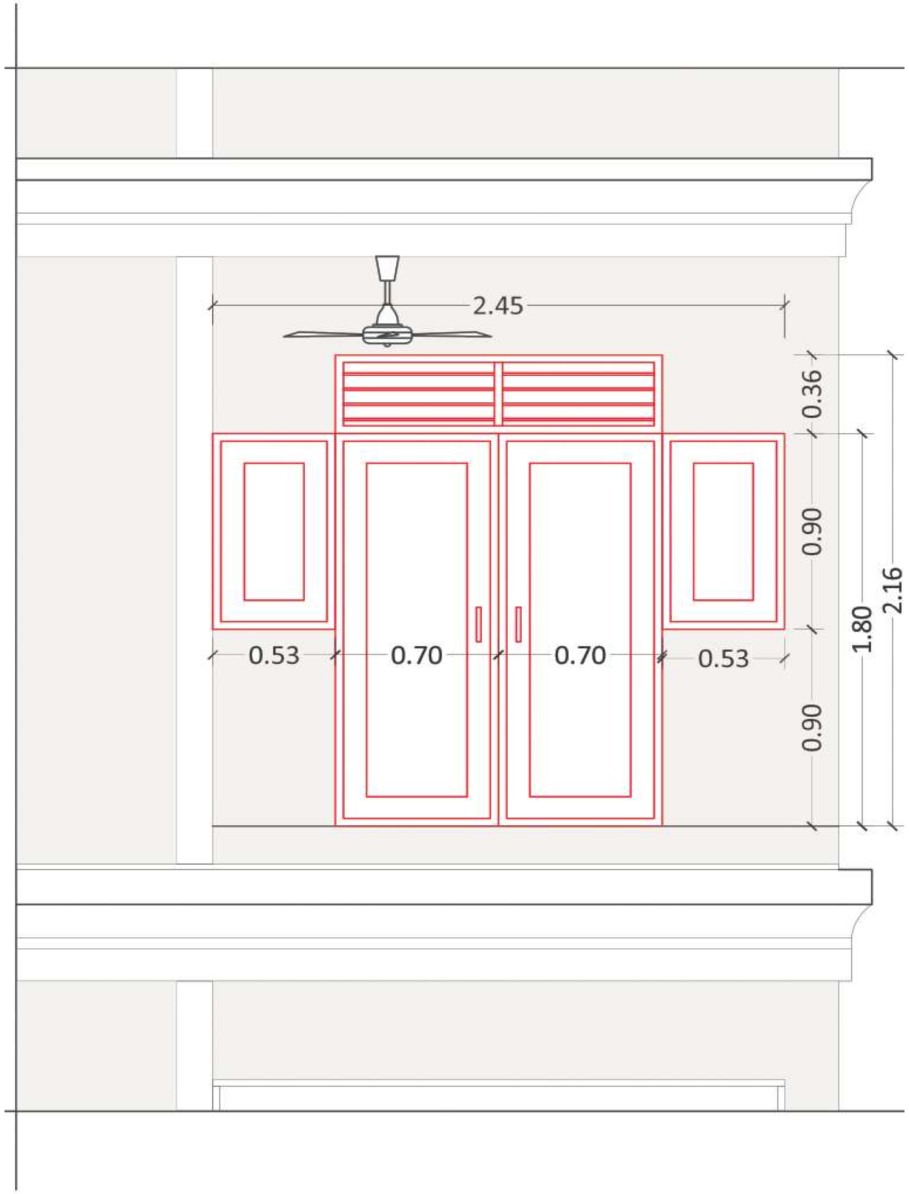


Fig.7.11. Case 02 - Elevation

CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m².ºC)
Window	IN / 2.45 / OUT	35mm thick Teak wood frame +	2.2
		10mm thick wooden ventilator +	3.5
		25mm teak wood door and window shutter	2.5
External Wall	IN / OUT	15mm thick Plaster + 230 mm thick Brick Masonry + 15 mm thick Plaster	1.8
Flooring	OUT / IN	12mm thick Tiles + 50mm thick Screed + 150 mm thick R.C.C slab + 12mm thick plaster	1.7
Ceiling	OUT / IN	12mm Tile + 50 mm Screed + 150 mm R.C.C slab + 12 mm Plaster + 200 mm Air + 12mm thick Fibreboard	1.0

Table.7.8. Table of Construction considered for Case 02

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) – 100% open*

The drawings and the table (Table.7.8) provides detailed specification such as measurements of the building elements like window, wall, floor and ceiling plus material specification for the given building elements along with their internal and external U-values. Since, the double door and shuttered windows can be opened completely as opposed to the sliding windows, 100% aperture area is considered for the purpose of this simulation. The ventilator above the double door is kept open even during the night time (Table 7.10.), whereas, the double door and the shuttered window are operated as per typology 01 schedule (Table.7.9.).

Solar radiation, external temperature, RT of the existing case (case 01) without mechanical cooling, RT of case 02 – where the double door and shuttered windows are kept completely open during the day, along with fully open ventilator plus upper and lower limit of the comfort band were plotted (Fig.7.12).

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table.7.9. Window Schedule for Double Door and Window Shutter - Case 02 *0 = Close 1 = Open*

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table.7.10. Window Schedule for Ventilator - Case 02 *0 = Close 1 = Open*

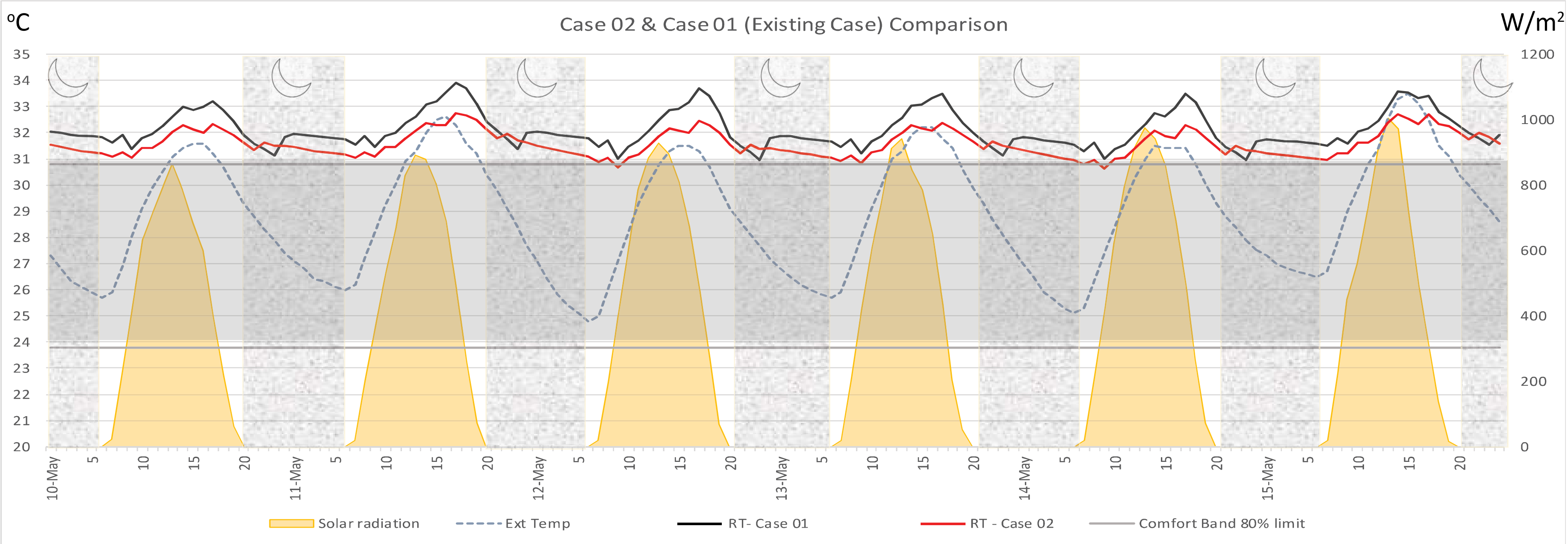


Fig.7.12. Case 02 & Case 01 (Existing) Comparison of Temperatures

Results:

The area of the window in Case 02 is approximately 5.0m^2, same as the area of Case 01 window. The solar radiation received in the living room is higher, since the room is west facing and hence the temperature in this space is also comparatively higher (See Chapter 06, p 178-181). However, the ability to open the windows completely allows maximum ventilation, which probably is the reason why the resultant temperature of the living space drops by a maximum of 1.3°C. This drop is mostly seen after 15:00, at late night and early morning hours. From 23:00 till morning 7:00, the double door and shutters are kept closed and only the ventilator is kept open (Table.7.9). Thus, with no solar radiation at night and with the open ventilator that allows the internal heat to escape, the resultant temperature of the living area seems to drop when compared to case 01. During the day, as the solar radiation gradually decreases, so does the indoor temperature and since Mumbai receives west winds majority of the times during the year, with 100% open window the living area experiences reduced temperature levels.

The observations made from the graph indicates that, having a ventilator allows air exchange at night which in turn helps in dissipating the indoor heat and thus, lowers the temperature of the living area even when the double door and shuttered windows were kept shut. Thus, giving the user various options of operability becomes an essential criterion for regulating their indoor environment.

Case 03:

In addition to replacement of case 01 sliding window by the combination of double door + shuttered window + ventilator type window of the *chawl*, the external wall of case 01 is replaced by the 600 mm thick masonry wall as used in the *chawl.* (Fig.7.13 – 7.14). (Typology 2).

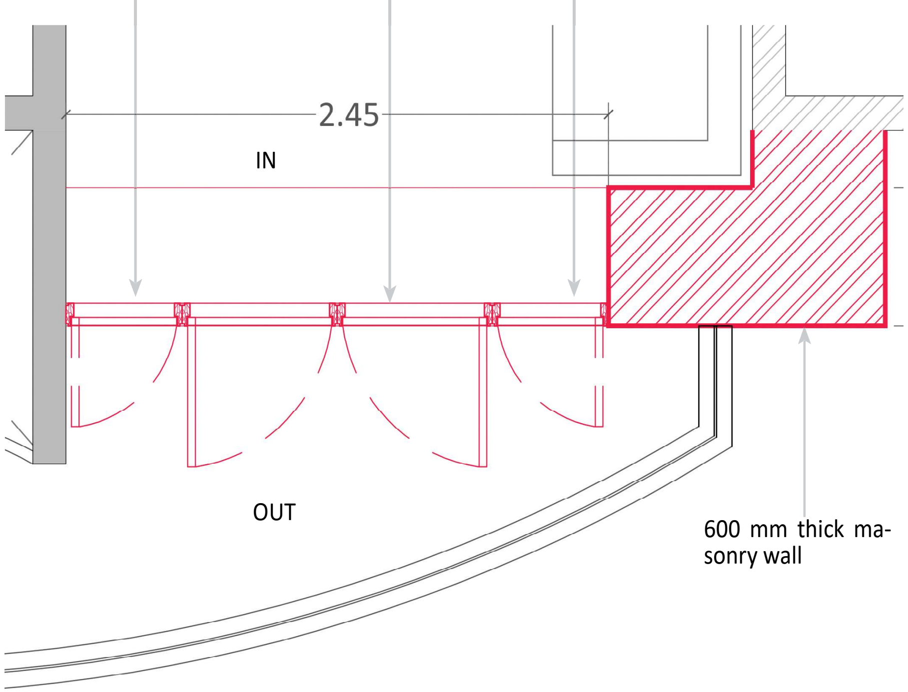


Fig.7.13. Case 03 – Plan

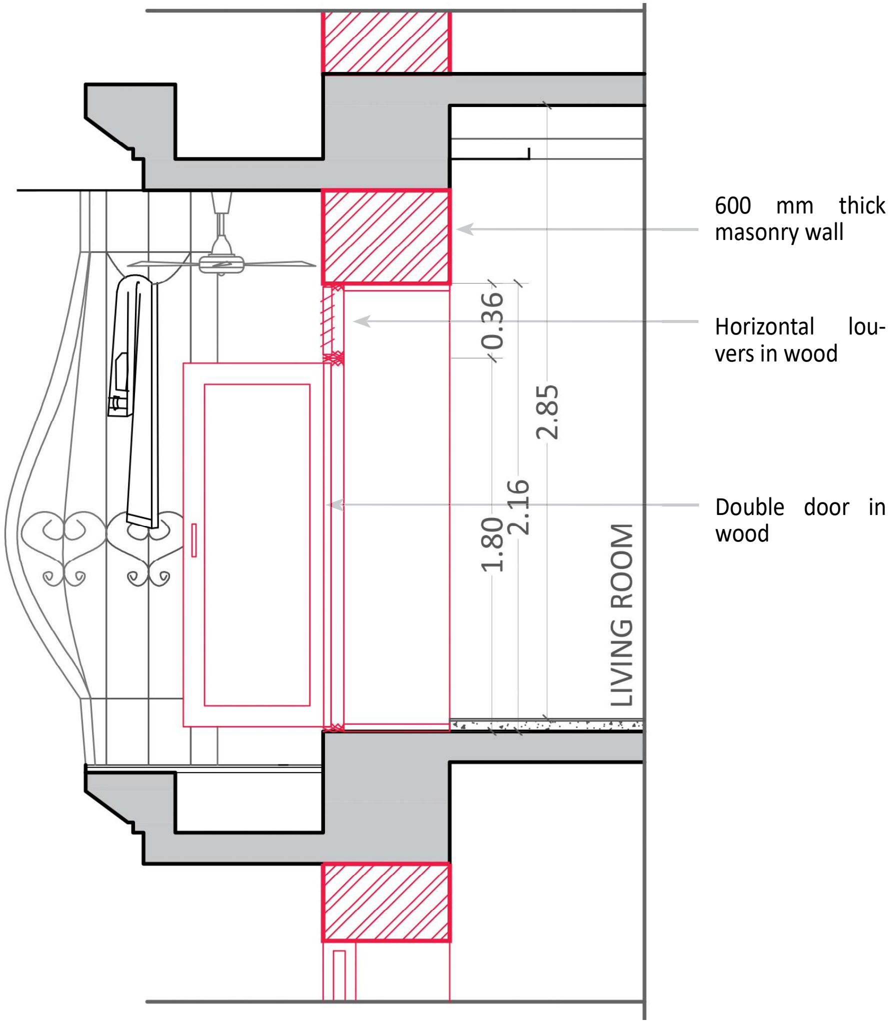
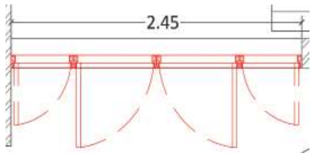


Fig.7.14. Case 03 - Section

<table>
<tr><th colspan="2">CONSTRUCTION TYPE</th><th>MATERIAL</th><th>U-VALUE (W/m².ºC)</th></tr>
<tr><td rowspan="3">Window</td><td rowspan="3">IN

OUT</td><td>35mm thick Teak wood frame
+</td><td>2.2</td></tr>
<tr><td>10mm thick wooden ventilator
+</td><td>3.6</td></tr>
<tr><td>25mm teak wood door and window shutter</td><td>2.6</td></tr>
<tr><td>External Wall</td><td>IN  OUT</td><td>15mm thick Plaster
+
600 mm thick Masonry wall
+
15 mm thick Plaster</td><td>1.0</td></tr>
<tr><td>Flooring</td><td>OUT

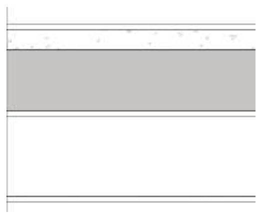
IN</td><td>12mm thick Tiles
+
50mm thick Screed
+
150 mm thick R.C.C slab
+
12mm thick plaster</td><td>1.7</td></tr>
<tr><td>Ceiling</td><td>OUT

IN</td><td>12mm Tile
+
50 mm Screed
+
150 mm R.C.C slab
+
12 mm Plaster
+
200 mm Air
+
12mm thick Fibreboard</td><td>1.0</td></tr>
</table>

Table.7.11. Table of Construction considered for Case 03

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) –Case 01, Case 02 (100% open) and Case 03*

The aperture value considered is 1.0 (100% open) for door + window + ventilator. The window schedules considered, are same as that of Case 02 (Table.7.9 - 7.10).

Solar radiation, external temperature, RT of case 01 with no mechanical cooling, RT of case 02 – where the double door and shutter windows are kept fully open as per schedule (Table.7.9) with fully open ventilator all the time (Table.7.10), RT of case 03 plus upper and lower limit of the comfort band were plotted (Fig.7.15).

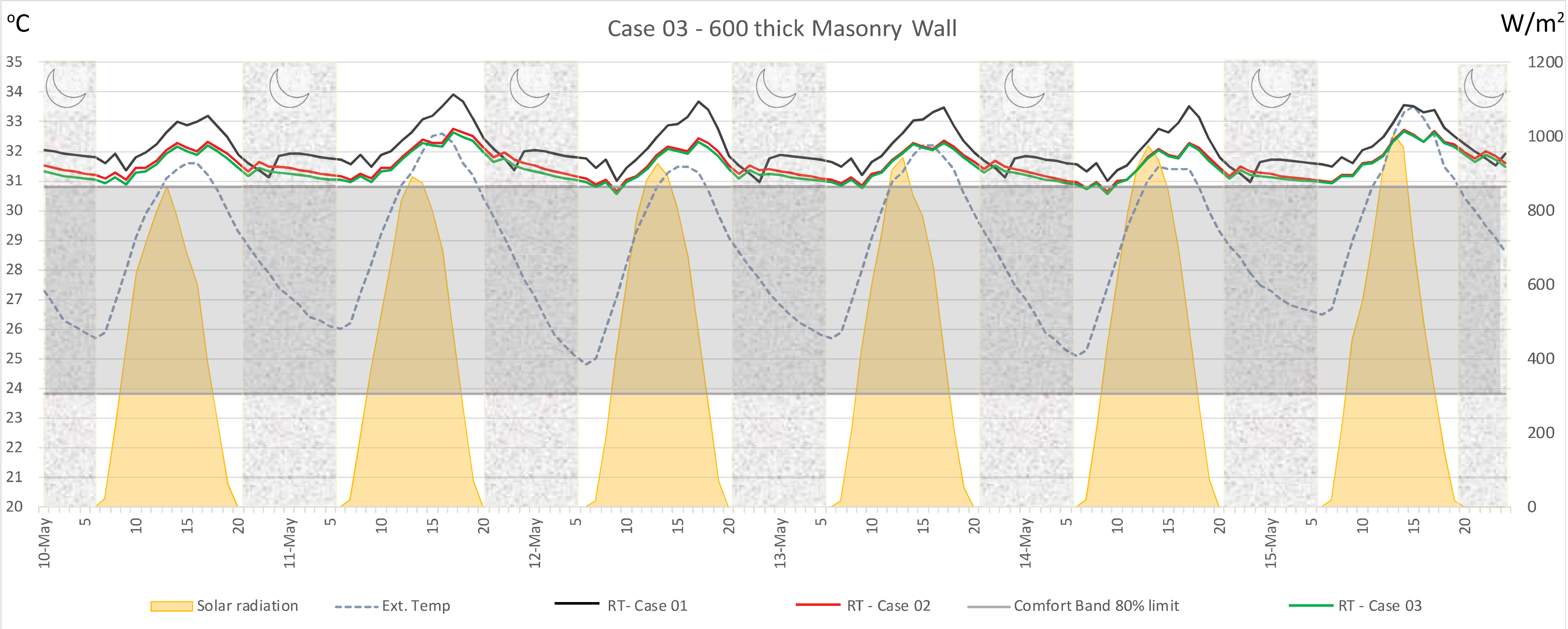


Fig.7.15. Case 03 – With 600 mm thick external masonry wall

Results:

During the fieldwork, it was noted that in the Ahmed Sailor *chawl,* only the external walls were 600 mm thick masonry walls. The same construction was applied in this case, wherein the external 230mm thick masonry wall was replaced by 600mm thick masonry wall, to understand its impact on the internal thermal conditions. Case 03 graph indicates that replacing the construction of the external wall only, that is, increasing the thermal mass of the external wall only, has an insignificant impact on the indoor environment. Also, the increase in thermal mass means increase in the structural specification of the high rise building which in turn raises questions on the durability and affordability of the structure.

Case 04:

In addition to replacement of existing window by the window from the *chawl* and with the replacement of the external wall of the existing case with 600 mm thick masonry wall as used in the *chawl,* the floor and ceiling of the apartment were also replaced by the '*kadapa* stone tiles laid on teakwood sections' as present in the *chawl.* (Fig.7.16). (Typology 2).

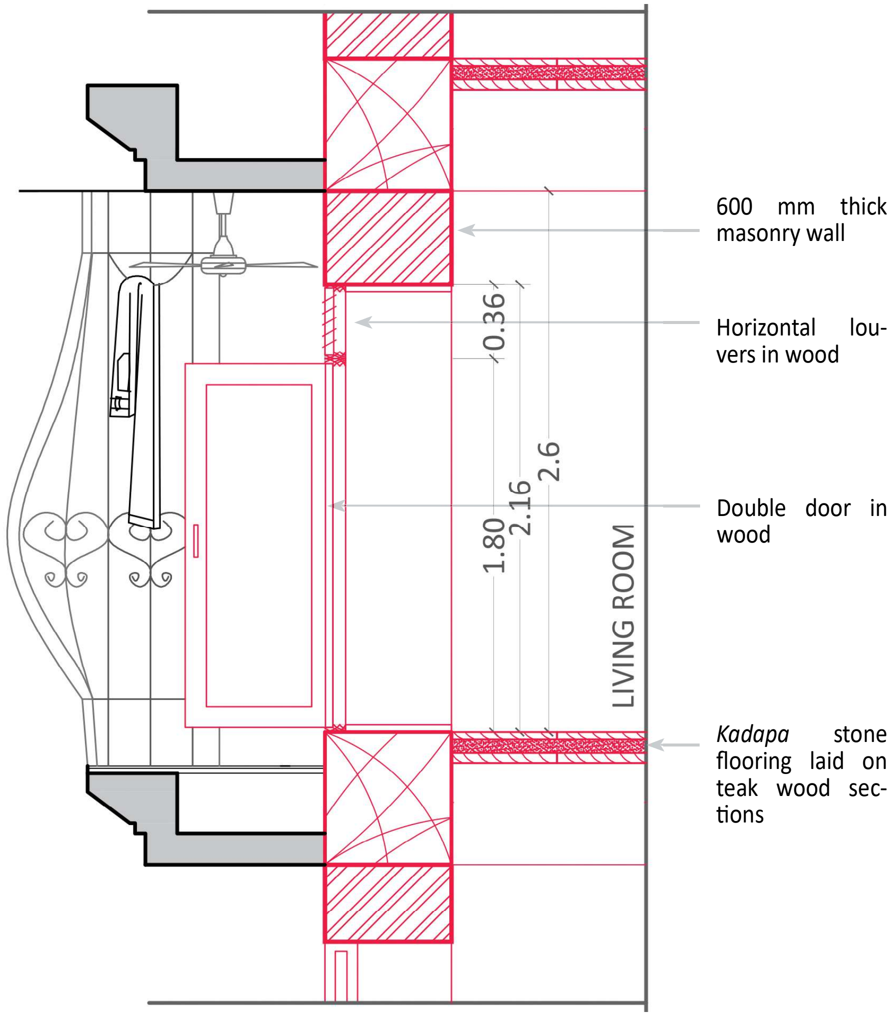


Fig.7.16. Case 04 - Section

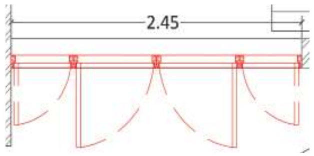
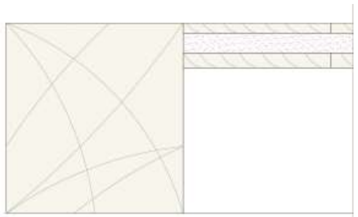
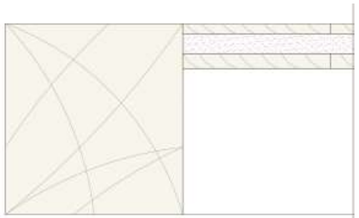
CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m².ºC)
Window	IN  OUT	35mm thick Teak wood frame +	2.1
		10mm thick wooden ventilator +	3.5
		25mm teak wood door and window shutter	2.5
External Wall	IN  OUT	15mm thick Plaster + 600 mm thick Brick Masonry + 15 mm thick Plaster	1.0
Flooring	OUT  IN	25mm *Kadapa* stone tiles + 50mm thick Screed + 25mm *Kadapa* stone tiles + 400mm Teakwood section	0.3
Ceiling	OUT  IN	400mm Teakwood section + 25mm *Kadapa* stone tiles + 50mm thick Screed + 25mm *Kadapa* stone tiles	0.3

Table.7.12. Table of Construction considered for Case 04

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) –Case 01, Case 02 (100% open) Case 03 and Case 04*

The aperture value considered is 1.0 (100% open) for door + window + ventilator. The window schedules considered, were same as that of Case 02 (Table.7.9 - 7.10).

Solar radiation, external temperature, RT of case 01 with no mechanical cooling, RT of case 02 – where the double door and shutter windows are kept fully open as per schedule (Table.7.9) with fully open ventilator all the time (Table.7.10), RT of case 03 and case 04 plus the upper and lower limit of the comfort band were plotted (Fig.7.17).

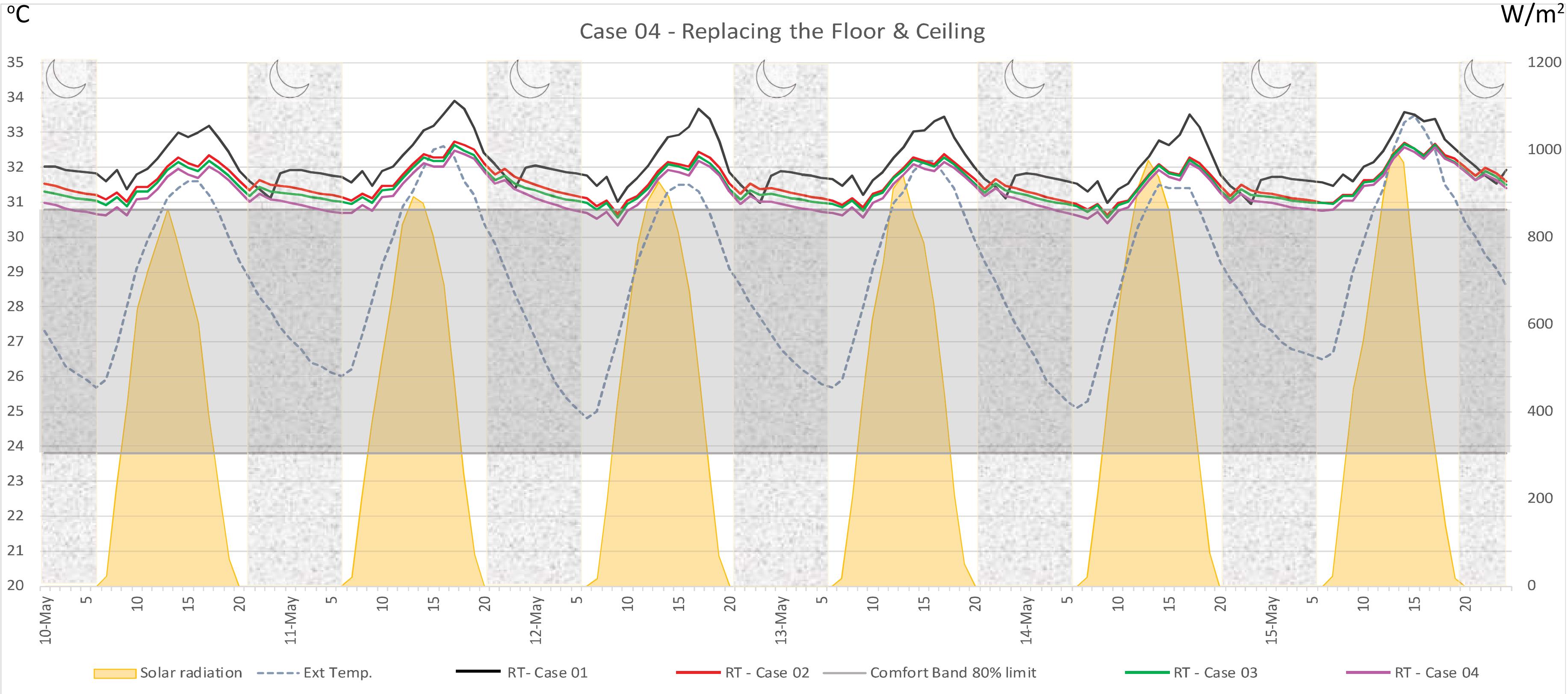


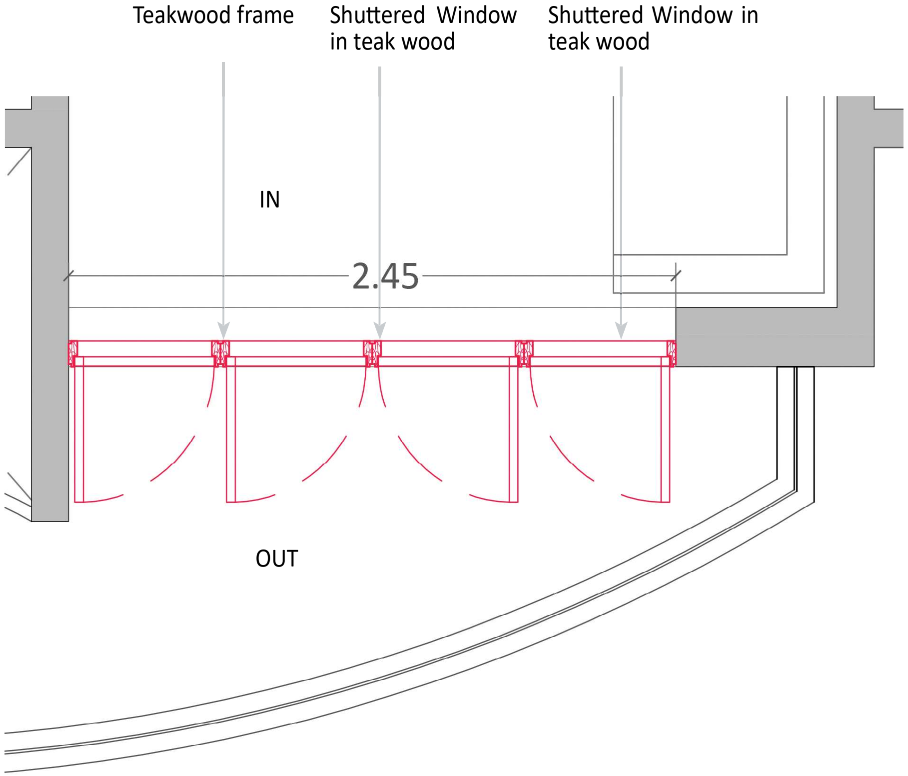
Fig.7.17. With ceiling and floor replaced by stone tiles and teak wood sections.

Results:

As seen in Table.7.12., reinforced cement concrete with tiling structure of the floor and ceiling were replaced by teakwood frame structure with *kadapa* stone tiles. Taking into consideration, the mentioned specifications, the graph (Fig.7.17) indicates that, replacing the window, the construction of the external wall only, that is, increasing the thermal mass of the external wall only, plus replacing the floor and ceiling construction method and materials, has an impact on the indoor environment. The plotted RTs are not within the comfort band, but as compared to case 01, case 04 manages to achieve comparatively lower indoor temperature, especially after sunset and before sunrise. Although it cannot be denied that the temperature difference between case 01 and case 04 is of about 1.5^{o}C, it is quite evident that the most significant impact is achieved by replacing the window (Case02).

Case 05:

In this case, the existing window of the apartment is replaced by the *wada* window which is altered to fit into the dimensions of the existing window (Fig.7.18 – 7.20). (Typology 3). Thus, the tinted sliding window with aluminum frame and with mosquito net plus light curtains is replaced with a series of opaque shuttered windows in teak wood panels and teak wood frame.



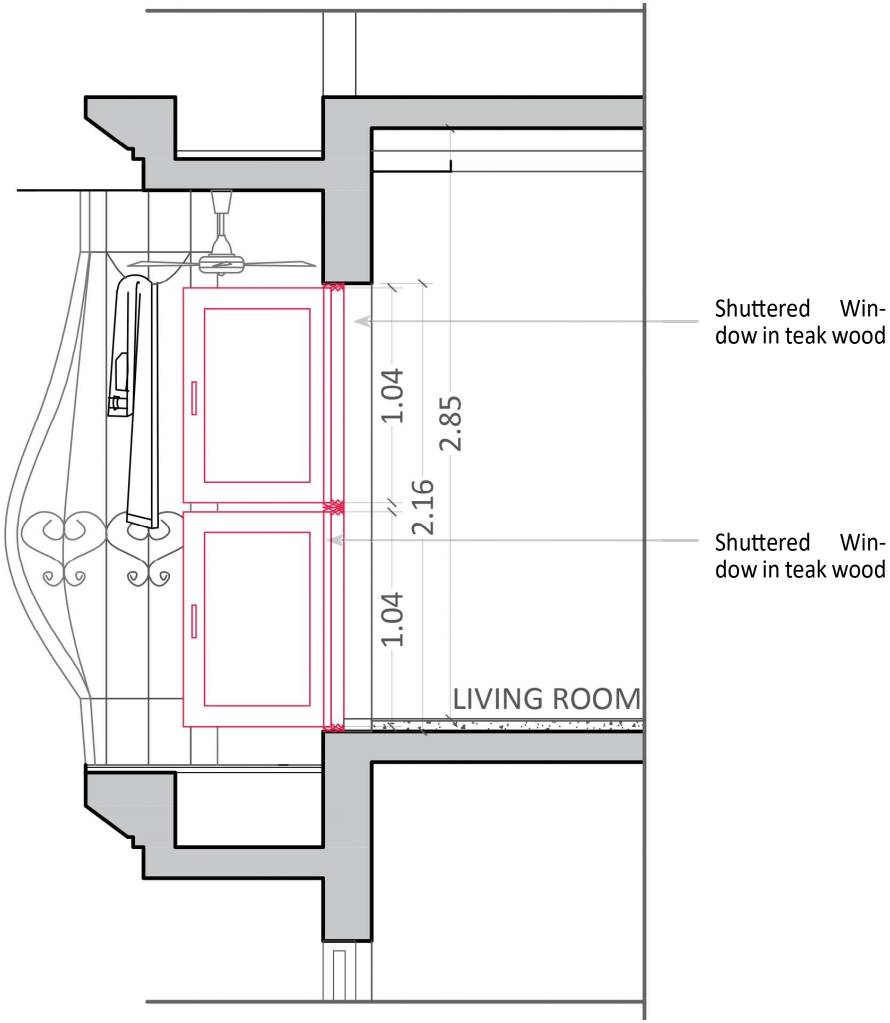


Fig.7.18. Case 05 – Plan

Fig.7.19. Case 05 - Section

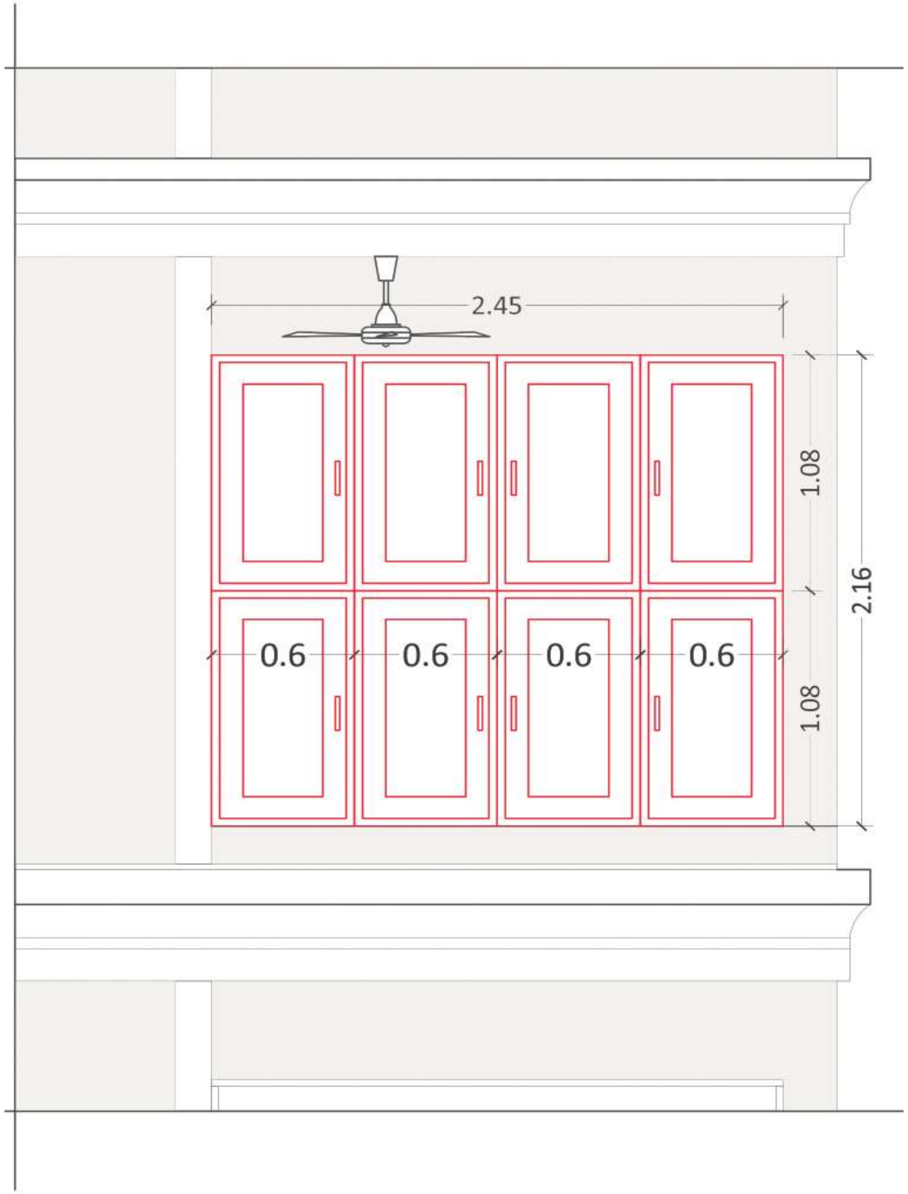


Fig.7.20. Case 05 - Elevation

CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m^2.°C)
Window	IN / OUT	35mm thick Teak wood frame +	2.1
		25mm teak wood window shutter	2.5
External Wall	IN / OUT	15mm thick Plaster + 230 mm thick Brick Masonry + 15 mm thick Plaster	1.8
Flooring	OUT / IN	12mm thick Tiles + 50mm thick Screed + 150 mm thick R.C.C slab + 12mm thick plaster	1.7
Ceiling	OUT / IN	12mm Tile + 50 mm Screed + 150 mm R.C.C slab + 12 mm Plaster + 200 mm Air + 12mm thick Fibreboard	1.0

Table.7.13. Table of Construction considered for Case 05

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) – 100% open*

The drawings and the table (Table.7.13) provides detailed specification such as measurements of the building elements like window, wall, floor and ceiling plus material specifications for the given building elements along with their internal and external U-values.

Since the shuttered windows can be opened completely as opposed to the sliding windows, a 100% aperture area is considered for this simulation. Window schedule (Table.7.14) was set as per the observed pattern of use and from the occupant interview and was same as the existing case.

Solar radiation, external temperature, RT of case 01 without mechanical cooling, RT of case 05 – where the shuttered windows are kept fully open as per schedule (Table.7.14), plus upper and lower limit of the comfort band was plotted (Fig.7.21).

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

Table.7.14. Window Schedule for Window Shutter - Case 05 *0 = close 1 = open*

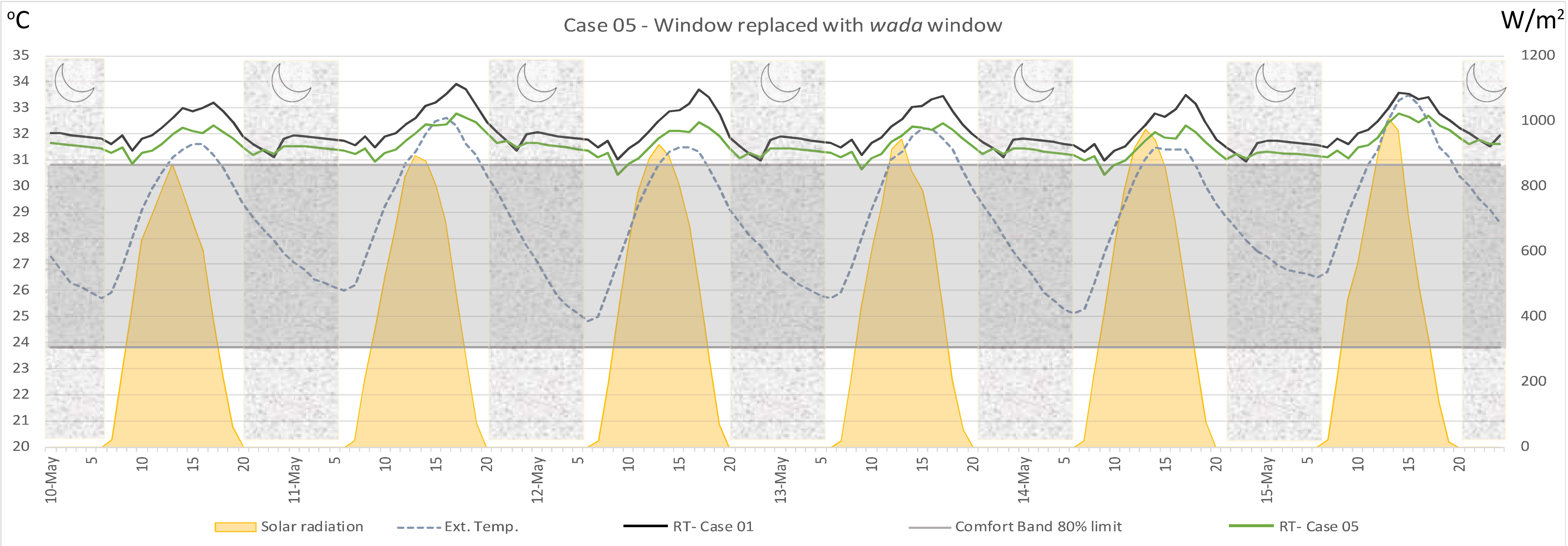


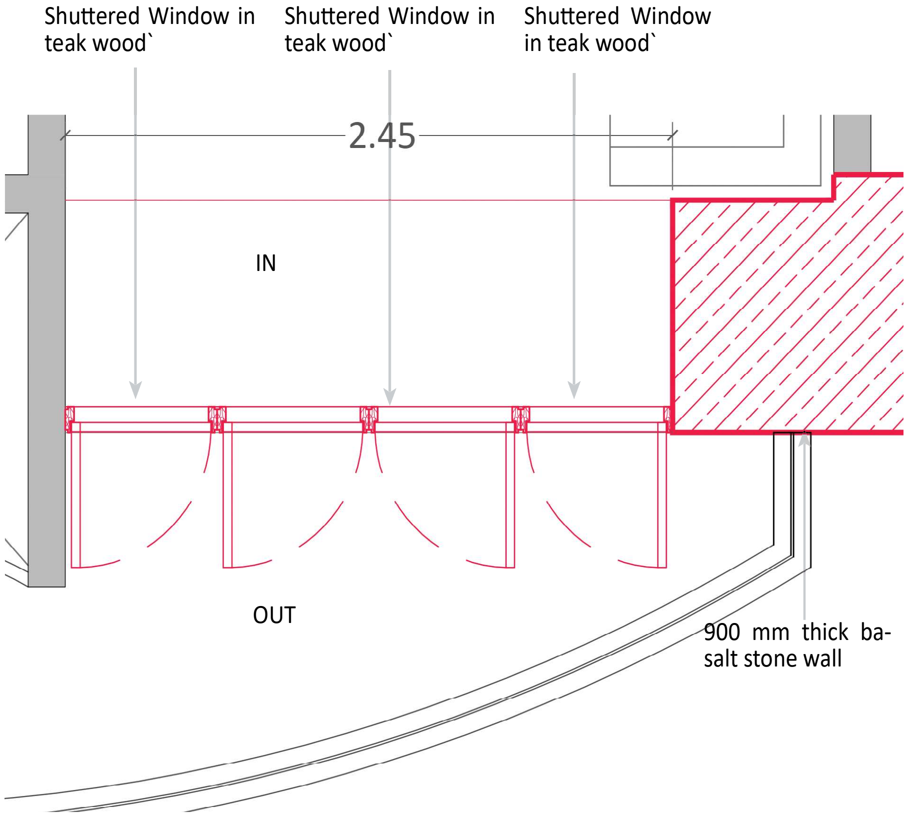
Fig.7.21. Case 05 & Case 01 (Existing) Comparison of Temperatures

Results:

The area of the window in Case 05 is approximately 5.0m^2, same as the area of Case 01 window. The window of case 05 is a set of 8 wooden shutters that open 100%, allowing maximum natural light and ventilation indoors. Thus, according to the case 05 graph (Fig.7.24), although not in the comfort band, a maximum of 1.2^{o}C drop in the indoor resultant temperature is observed in the living space during day time, especially when the solar radiation is declining, between 15:00 and 20:00, respectively. Additionally, slightly lower temperatures, about 0.5^{o}C lower, are also observed in the early morning hours. During the day, as the solar radiation gradually decreases, so does the indoor temperature, plus, Mumbai receives west winds the majority of the time during the year. Thus, declining solar radiation, west winds and a window with 100% aperture, all together aids in attaining lower indoor resultant temperature post noon.

Case 06:

In addition to the replacement of an existing window by the *wada* window, the external wall of the existing case is replaced by a 900 mm thick wall in basalt stone as used in the *wada*. (Fig.7.22 – 7.23). (Typology 3).



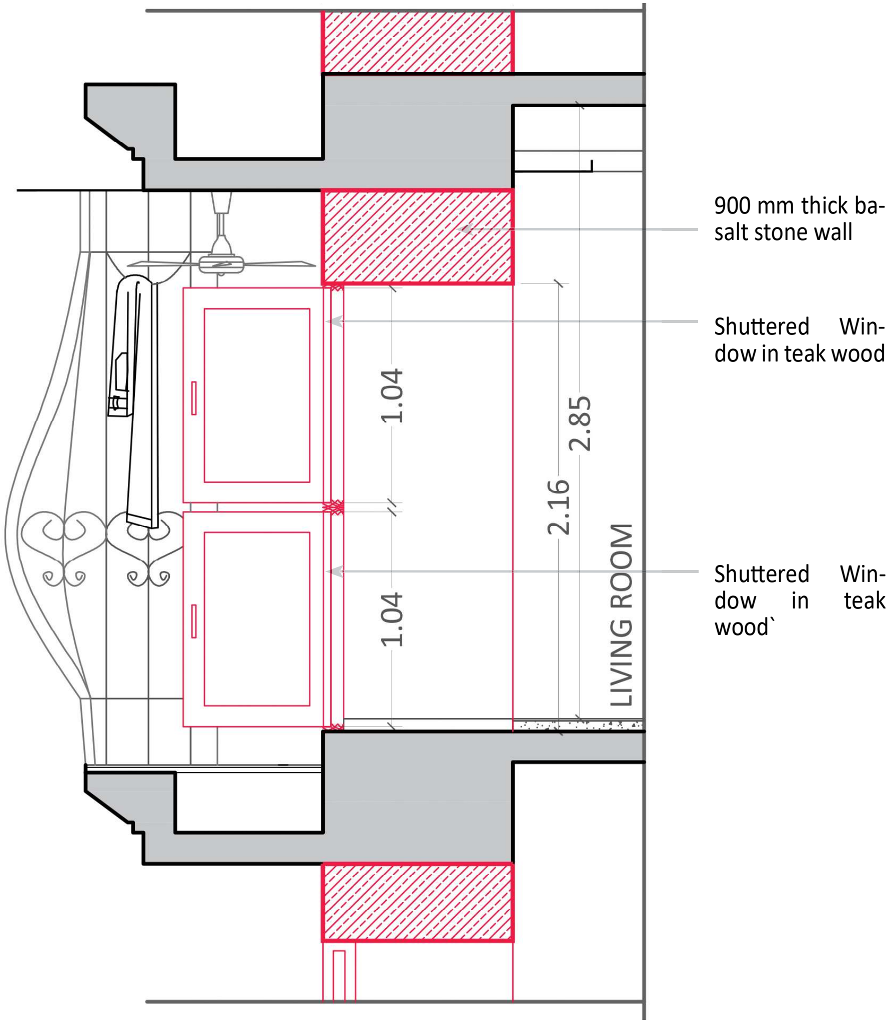


Fig.7.22. Case 06 – Plan

Fig.7.23. Case 06 - Section

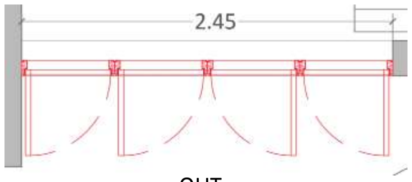
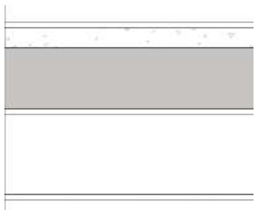
CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m^2.^{o}C)
Window	IN  OUT	35mm thick Teak wood frame +	2.1
		25mm teak wood window shutter	2.5
External Wall	IN  OUT	15mm thick Plaster + 230 mm thick Brick Masonry + 15 mm thick Plaster	1.8
Flooring	OUT  IN	12mm thick Tiles + 50mm thick Screed + 150 mm thick R.C.C slab + 12mm thick plaster	1.7
Ceiling	OUT  IN	12mm Tile + 50 mm Screed + 150 mm R.C.C slab + 12 mm Plaster + 200 mm Air + 12mm thick Fibreboard	1.0

Table.7.15. Table of Construction considered for Case 06

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) –Case 01, Case 05 (100% open) and Case 06*

The drawings and the table (Table.7.15) provides a detailed specification such as measurements of the building elements like window, wall, floor and ceiling plus material specification for the given building elements along with their internal and external U-values.

The aperture value considered is 1.0 (100% open) for all the shutters.

Whereas, the window schedules considered, are the same as that of Case 05 (Table.7.14).

Solar radiation, external temperature, RT of case 01 without mechanical cooling, RT of case 05 – where all the shutters of the window are kept 100% open (Table7.14), RT of case 06 plus the upper and lower limit of the comfort band was plotted (Fig.7.24).

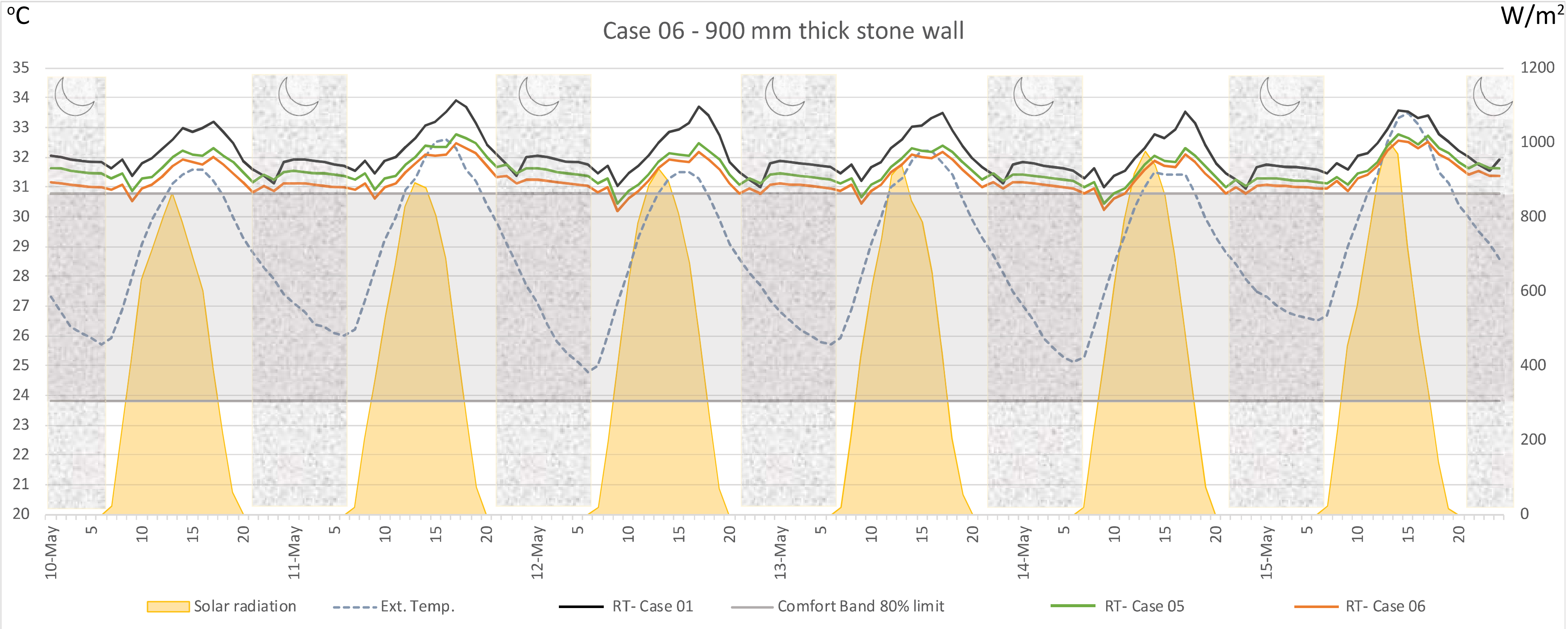


Fig.7.24. Case 06 – With 900 mm thick external stone wall

Results:

During the fieldwork, it was observed that in Pangu *wada*, only the external walls were 900 mm thick stone walls. The same construction was applied in this case, wherein the external 230mm thick masonry walls were replaced by 900mm thick stone wall, to understand its impact on the internal thermal conditions. The graph indicates that replacing the construction of the external wall only, that is, increasing the thermal mass of the external wall only, has an impact on the indoor environment, especially during evenings and night time. However, since, the 900mm thick wall, along with the other walls, is plastered and also since the windows are kept shut during night time (to keep the mosquitoes from entering the house) as per the existing window schedule, the scope for nighttime ventilation is minimized to a great extent. Therefore, when compared with the resultant temperature of case 01, a maximum drop of only 1.5°C in the internal RT can be observed. Also, the increase in thermal mass means an increase in the structural specification of the high rise building which in turn raises questions on the durability as well as affordability of the structure.

Case 07:

In addition to the replacement of the existing window by the *wada* window and the external wall of the existing case by 900 mm thick wall in basalt stone, the floor and the ceiling of the apartment are also replaced by the one used in the *wada* (Fig.7.25). (Typology 3).

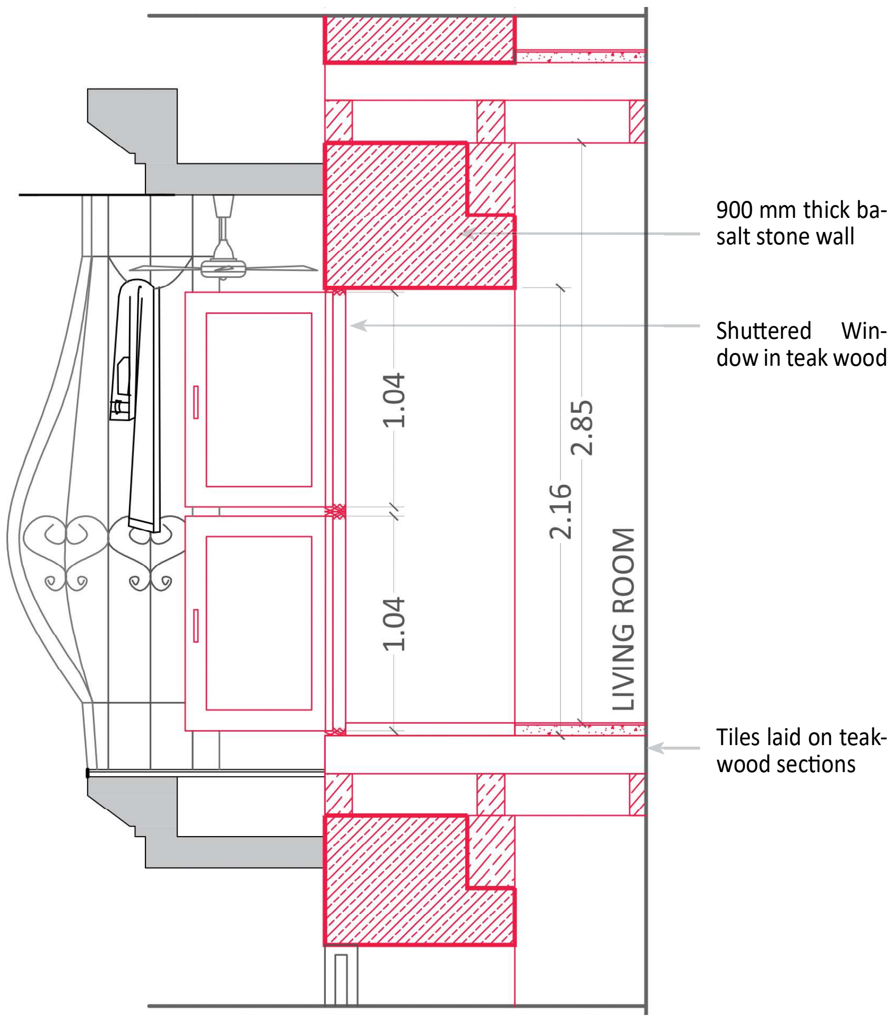


Fig.7.25. Case 07 - Section

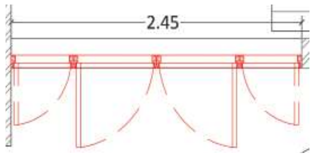
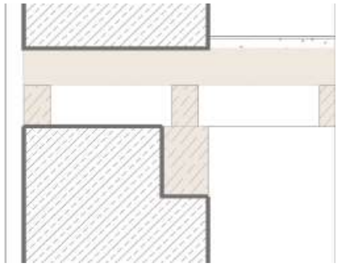
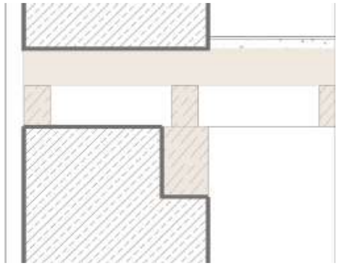
CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m².°C)
Window	IN  OUT	35mm thick Teak wood frame +	2.1
		25mm teak wood window shutter	2.5
External Wall	IN  OUT	25mm thick Plaster + 900 mm thick Basalt stone Masonry + 25 mm thick Plaster	1.5
Floor	IN  OUT	12mm thick Tiles + 50mm thick Screed + 180 mm thick teakwood section + 200 mm teakwood section	0.3
Ceiling	OUT  IN	200 mm teakwood section + 180 mm thick teakwood section + 50mm thick Screed + 12mm thick Tiles	0.3

Table.7.16. Table of Construction considered for Case 07

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) –Case 01, Case 05 (100% open) Case 06 and Case 07*

The drawings and the table (Table.7.16) provides detailed specifications such as measurements of the building elements like window, wall, floor and ceiling plus material specification for the given building elements along with their internal and external U-values.

The aperture value considered is 1.0 (100% open) for all the shutters.

The window schedules considered were same as that of Case 05 (Table.7.14).

Solar radiation, external temperature, RT of case 01 without mechanical cooling, RT of case 05 – where the shutter windows are kept fully open as per window schedule, RT of case 06 and case 07 plus upper and lower limit of the comfort band were plotted (Fig.7.26).

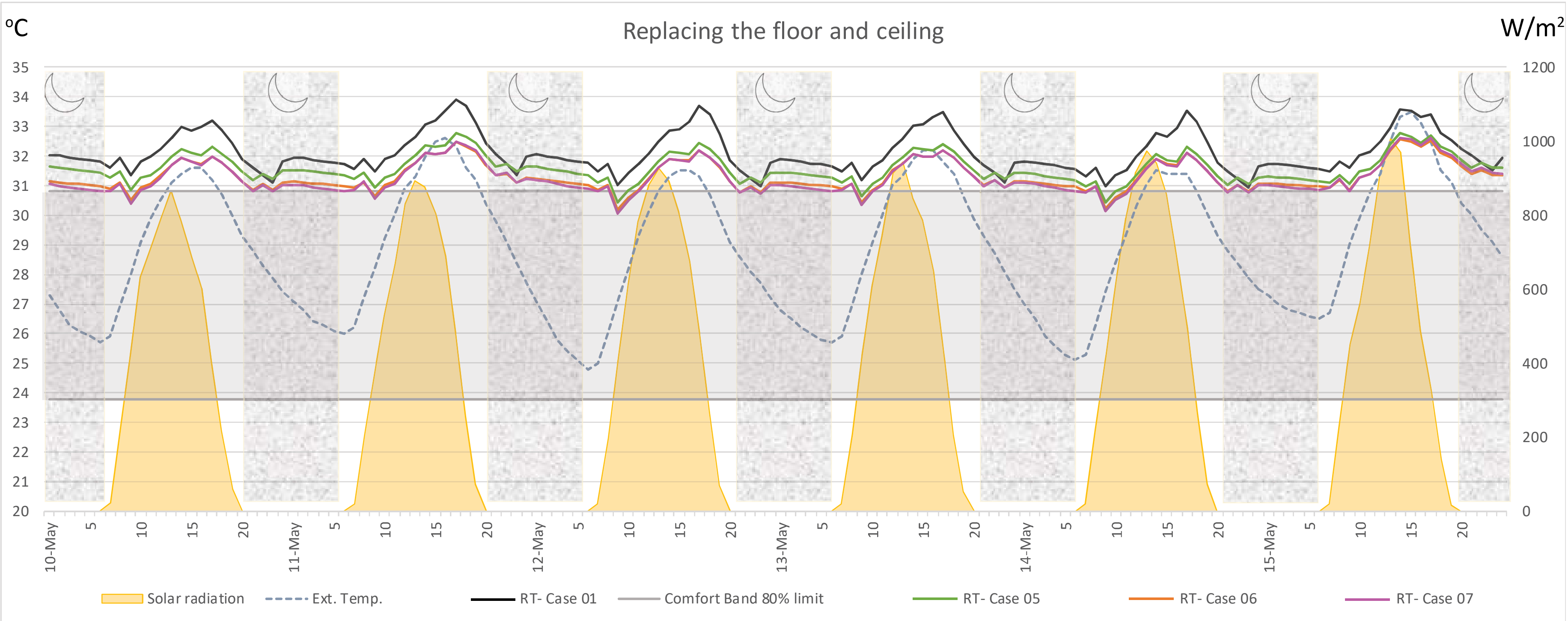


Fig.7.26. Case 07 - Replacing floor & ceiling with teak wood sections

Results:

The graph indicates that replacing the window, the construction of the external wall only, that is, increasing the thermal mass of the external wall only, plus replacing the floor and ceiling construction method along with the materials, has an impact on the indoor environment. Although none of the simulated temperatures are within the comfort band, as compared to case 01, case 07 manages to achieve lower indoor resultant temperature, especially after sunset and before sunrise. It can be observed that during night time, the drop in the resultant temperature from case 05 is about 0.2°C to 0.3°C. Whereas, the temperature difference between case 01 and case 06 and 07 is of about 1.5°C to 1.6°C. Also, the difference in the temperature when the solar radiation is the maximum, between case 01 and the rest of the cases (05,06,07) is also about 1.6°C. This shows that although windows play a significant role in providing thermal comfort, other architectural elements such as walls, floors, ceiling when desinged effectively, also help in further reducing the higher indoor temperature levels. Hence, it is necessary to explore the significance of effective design interventions in creating comfortable indoor environments.

Discussion:

The main purpose of performing computational analysis was to investigate the role of windows in particular, as well as, of the other architectural elements such as floors, ceiling, and walls, on the indoor environment. To asses these two parameters, seven cases were formulated.

The monitored RT, as well as case 01 readings, showed higher indoor temperature even when the occupancy gains, equipment and lighting gains were minimum. This was due to the west orientation of the room, which received high solar radiation in the living area. Case 02 and 05 saw the replacement of the single glazed sliding window with *the chawl* window and the *wada* window. In both cases, a drop in the RT of at least 1°C was observed. Further alterations like changing only the external wall construction from 230mm brick to 600mm masonry wall (case 03) and 900mm (case 06) thick stone wall saw a minute drop in temperature. Lastly, when the flooring and ceiling were replaced with teakwood sections (case 07) and *kadapa* stone flooring (case 04), there was an insignificant change in the resultant temperatures as compared to their respective previous cases. The maximum difference in the resultant temperature noted between case 01 (without mechanical cooling) and case 04 was of 1.3°C

The main observations made from the seven cases are:

1. Case 02 indicated that only by replacing the window in the same area as the existing window, showed a prominent drop in temperature. The combination of different types of windows, double door + shuttered window + ventilator, offered the occupants various permutations and combinations that they had the freedom to apply to regulate their indoor comfort conditions. For example, the ventilator allowed continuous ventilation and restricted solar radiation, the shuttered windows and doors could be opened completely, partially or could be kept completely shut as per the user requirement. Being opaque, the shutters and the doors restricted direct solar radiation from entering the room, but at the same time also restricted natural ventilation and light into the living space. Therefore, these advantages and limitations give a further scope of improvement in the design of the window, where it becomes essential that the window has a provision to address all the environmental factors necessary to achieve overall comfort.

2. The most important point is that the window is the only architectural element that allows the user to regulate the indoor environment anytime, irrespective of the changing seasons, changing occupancy throughout the year as per the user requirement. Other elements such as floor, ceiling or walls do not give a choice to the user. Once the floor or the wall is constructed, the user does not have an option to change the thermal properties of the same anytime during the day, month or year. The materials can only be changed through refurbishment which becomes a tedious and expensive process.

3. Although the above point is reasonable, it also cannot be denied that to achieve maximum comfort, it is important to have a design intervention that is logical and affordable, which uses the properties of each element effectively to attain maximum comfort. For instance, in cases 03, 04, 06 and 07, wall sizes were increased, the material of the wall was replaced with stone (case 06) and the floor and ceiling were replaced by thick wooden sections. These substitutions helped in reducing the temperature but in high-density cities like Mumbai, it is not possible to lose space by providing thick walls nor is it possible to provide wooden sections that would cost a fortune and would also

be high on maintenance. Thus, a more feasible option would be to have an adaptive window that allows night-time ventilation along with exposed high thermal capacity surfaces that tend to release absorbed heat at night time, thus, making the space comparatively cooler. So, if windows are designed keeping in mind all the attributes such as size, orientation and so on, along with a sensible strategy for other elements, they can help to a great extent in minimizing the use of mechanical cooling systems and contribute to reducing the total energy consumption.

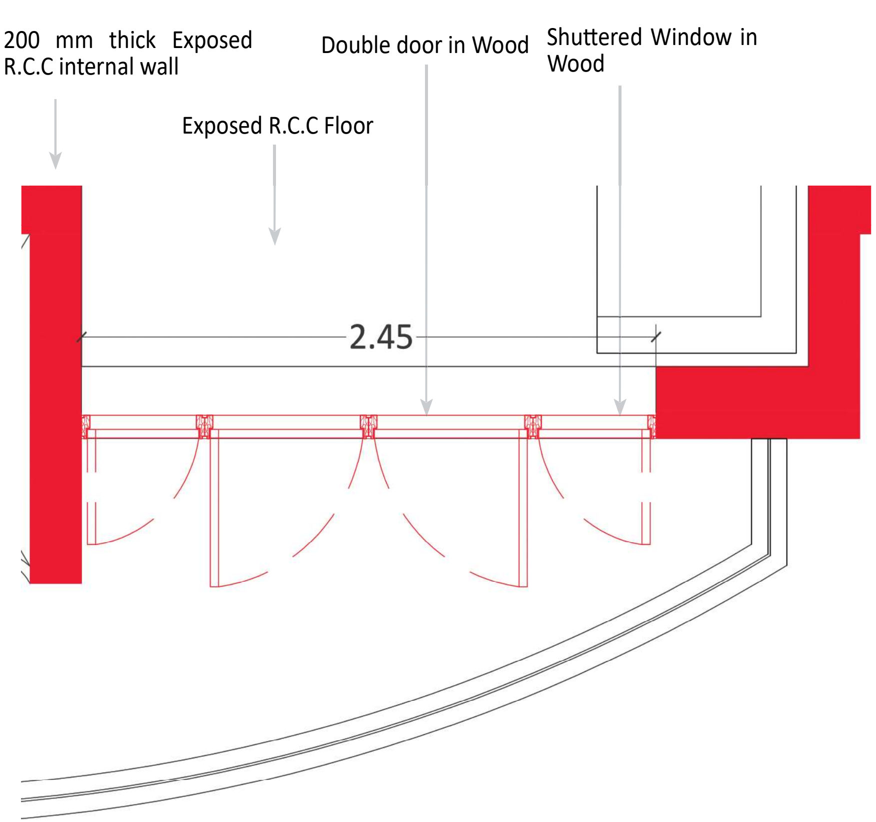


Fig.7.27. Case 08 - Plan

Concerning the previous point, a simulation is performed in TAS to understand the impact of night-time ventilation through effective openings and thermal mass together. From the seven cases that demonstrated the influence of windows on the indoor environment, it was observed that the door + window + ventilator combination worked the best and provides maximum adaptive opportunities to the user.

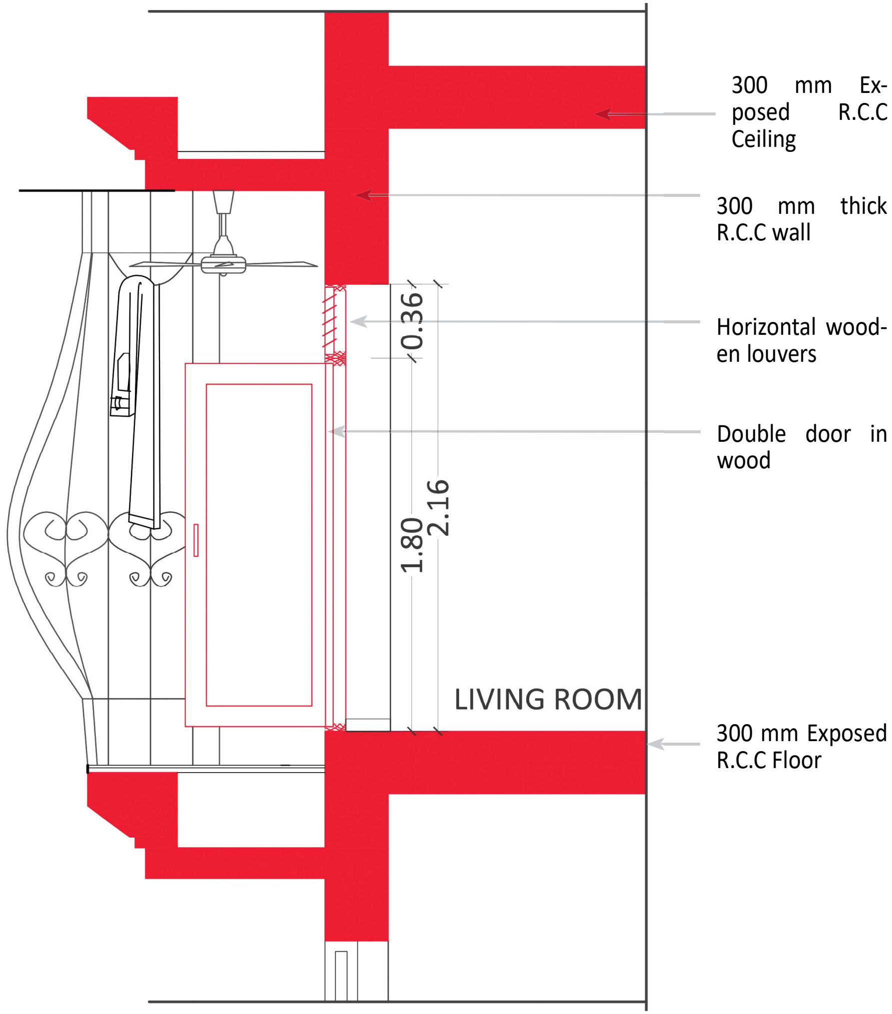


Fig.7.28. Case 08 - Section

Hence, the combination window was chosen for this simulation along with high density exposed concrete for walls, floor and ceiling (Fig.7.27 - 7.29).

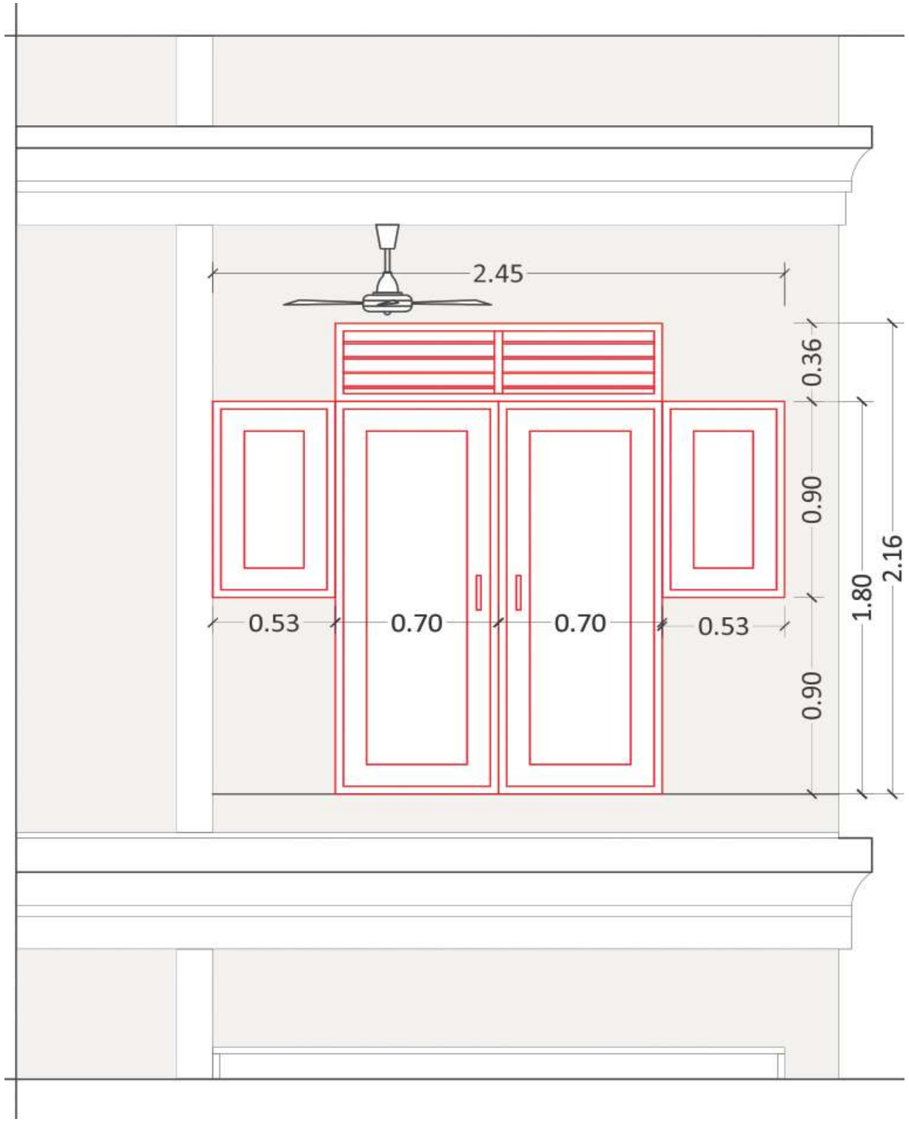


Fig.7.29. Case 08 - Elevation

CONSTRUCTION TYPE		MATERIAL	U-VALUE (W/m².ºC)
Window	IN 2.45 OUT	35mm thick Teak wood frame +	2.1
		10mm thick wooden ventilator +	3.5
		25mm teak wood door and window shutter	2.5
External Wall	IN OUT	300 mm thick exposed R.C.C wall	2.1
Floor / Ceiling	OUT IN	300 mm thick exposed high density R.C.C slab	2.1

Table.7.17. Case 08 - Table of Construction - Case 08

Graph 01: *For summer – 10th (day 130) to 15th May (day 135) – 100% open*

The drawings and the table (Table.7.17) provides detailed specification such as measurements of the building elements like window, wall, floor and ceiling plus material specification for the given building elements along with their internal and external U-values.

The double door and shuttered windows can be opened completely. Hence, an aperture area of 100% is considered for the double door, shuttered window as well as the ventilator.

The ventilator above the double door (Table.7.19) is kept open throughout the night. However, the double door and the shuttered windows (Table.7.18) are kept completely shut from 11:00 till 16:00, the time when the living space receives maximum direct solar radiation. Solar radiation, external temperature, RT of the existing case (case 01) without mechanical cooling, the RT obtained from this simulation plus upper and lower limit of the comfort band were plotted (Fig.7.30).

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Table.7.18. Window Schedule for Double Door and Shuttered Window *0 = close 1 = open*

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table.7.19. Window Schedule for Ventilator *0 = close 1 = open*

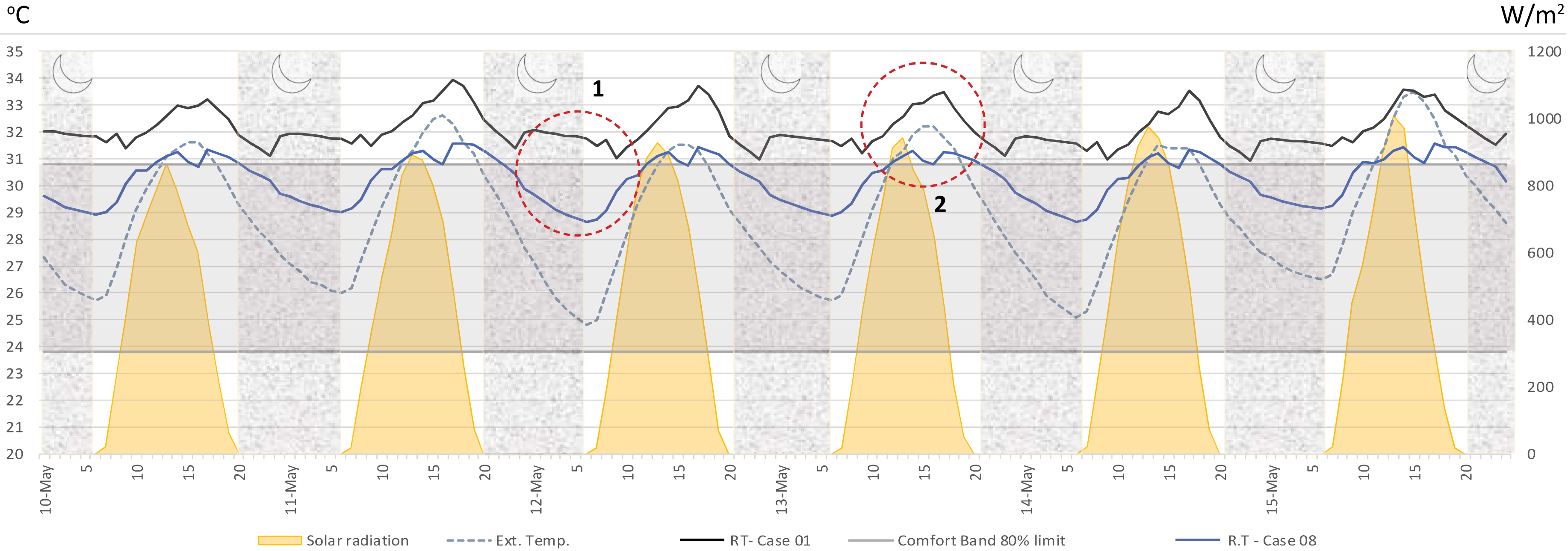


Fig.7.30. Comparison of Case 01 simulated RT & Case 08 RT

Results:

The combination window of double door + shuttered window + ventilator was chosen for this simulation, since it provided several operative options to the inhabitants and also, according to the prior cases, was the best performing window. A high density exposed R.C.C framework was chosen for walls, floor as well as the ceiling, since this material is durable, maintenance-free, absorbs heat and also releases heat at night time, plus it was only 300 mm thick as compared to 600 or 900 mm thick framework, to be thermally efficient.

The aperture values assumed for case 08 are opposite to the aperture values considered for all the seven cases before this. Where the double door and shuttered windows were kept open during the day and completely shut during the night in previous cases, the same were kept open throughout the night and were kept shut when the living space received maximum direct solar radiation, from 11:00 till 16:00.

It is evident from the graph, that leaving the shuttered windows, double door and the ventilator completely open at night time allows the extraction of the released absorbed heat from the walls into the external environment, thus, significantly reducing the indoor resultant temperature. An effective night time ventilation strategy recorded a maximum 3.1^{o}C drop in temperature (1). During the daytime as well, when the solar radiation is at the peak, the simulated temperature is about 2.4^{o}C to 2.7^{o}C lower than case 01 (2).

The window design, the aperture values and their schedules, plus the materials chosen for floor, ceiling and walls, together contribute in getting the internal temperature in the acceptable limits of comfort. The resultant temperature of the living space enters the comfort band from 20:00 till 11:00. Whereas, during the rest of the day, although not totally in the comfort band, the temperatures are quite low as compared to case 01 (FIg.7.30).

The significant drop in the day-time temperature, when the maximum solar radiation is received, was mainly because the opaque shuttered windows and doors were completely shut with only the top ventilator available for air exchange. However, completely shutting the windows and doors would mean blocking the natural light and also the ventilation of the living space. Further, an important issue that was highlighted by the occupants during the survey, was of mosquitoes especially after sunset (See chapter 06, p 221). One of the main reasons the windows were closed after sunset was to keep the mosquitoes from entering the house. Hence, keeping the doors and windows open during night-time, does not seem practical.

Thus, there are advantages as well as limitations in the design interventions considered for this case. Nonetheless, this analysis aimed in determining the potential of windows along with the other architectural elements in achieving a comfortable indoor environment, which the graph justifies. It is believed that there is a further possibility of improvement and overcome the limitations cited above, for example through the installation of solar shades to minimize solar gains and at the same time allow required air exchange and daylight to enter the living space.

Case 08 with External Shading

Along with various advantages, a window has many disadvantages as well (See Chapter 06, p 218) such as, it permits noise, dust, solar radiation, glare into the occupied space. However, these concerns are resolvable through the application of various design features along with smart technology on the inside or the outer side of an opening. One such design feature is solar shading, which has the potential to not only restrict the heat gains but also to provide privacy, glare reduction, partially obstructing noise and dust plus minimising excess daylight if designed effectively. Hence, the role and potential of a well-designed solar shading cannot be neglected.

The results from Case 08 strongly support the methodology of the application of efficient intervention in the form of window design and choice of material along with effective night-time ventilation (See p: 259-561). This combined strategy could achieve the lowest resultant temperature in the living room out of all the eight cases. However, during the peak solar radiation hours, from 11:00 to 16:00, the temperature in the living area was still higher. Hence, in addition to the above strategies, it becomes necessary to understand the importance and effect of solar shading which has been a traditional means to obstruct higher solar radiation entering a habitable space.

Solar shading or brise-soleil, which means sun-breaker in French, are provided on the external face of the building to block the sun. Similar to *jaali* or the lattice screens used in *jharokhas* and *mashrabiyas'* (See chapter 03), solar shading acts as an outer covering that conceals the actual functions of the building and blends with the urban streetscape.

Hence, the application of external solar shading was considered and applied to case 08, since it had the potential to reduce the solar gains and shade the glazing area (DeKay and Brown, 2014). Keeping the materials and window configuration same as case 08 vertical fins were added on the external face of the apartment where the balcony ends (Fig 7.31 - 7.33.). The rationale behind the use of vertical fins is as follows:

1. The existing apartment already had a horizontal projection of 1.2 m. Since the regulations do not allow further projection, horizontal shading could not be applied.

2. Instead of placing the fins immediately on the door + window + ventilator combo, they were placed on the outer face of the balcony, that led to the formation of transition space, similar to jharokhas (See Chapter 03, p 57). Internal shading such as blinds or curtains manage to block the glare but at the same time also block natural ventilation and do not contribute to reducing the cooling loads (Prowler, 2016). Hence, external shade is a better option since it allows natural ventilation, reduces glare, allows sufficient daylight to enter the living area and also keeps the solar radiation from entering the habitable space.

3. Moveable vertical fins were chosen over horizontal fins since vertical fins work best on the east and west façade (Wroblaski, 2011). The Society of Building Science and Educator (SBSE) and Comfortable Low Energy Architecture (CLEAR), also suggests the application of vertical fins in the west and east façade since the sun angle is comparatively low and the sun hits the façade directly. As the sun's altitude keeps changing throughout the day, making the fins rotate ensures optimal shading.

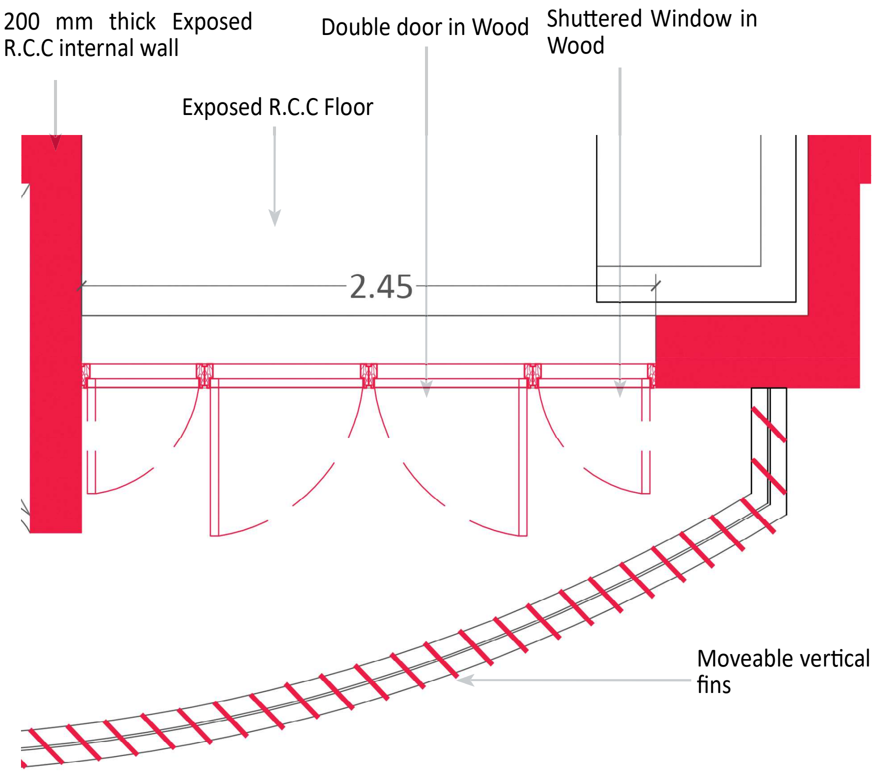
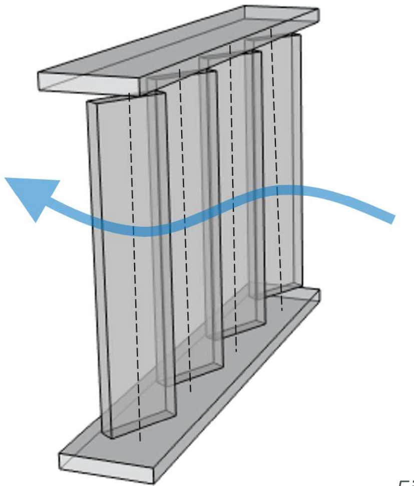


Fig.7.31. Case 08 with external shading - Plan



- Helps in Solar gain reduction
- Reduces glare
- Allows natural ventilation
- Provides privacy
- Allows daylight into occupied spaces

Fig.7.32. Moveable vertical fins

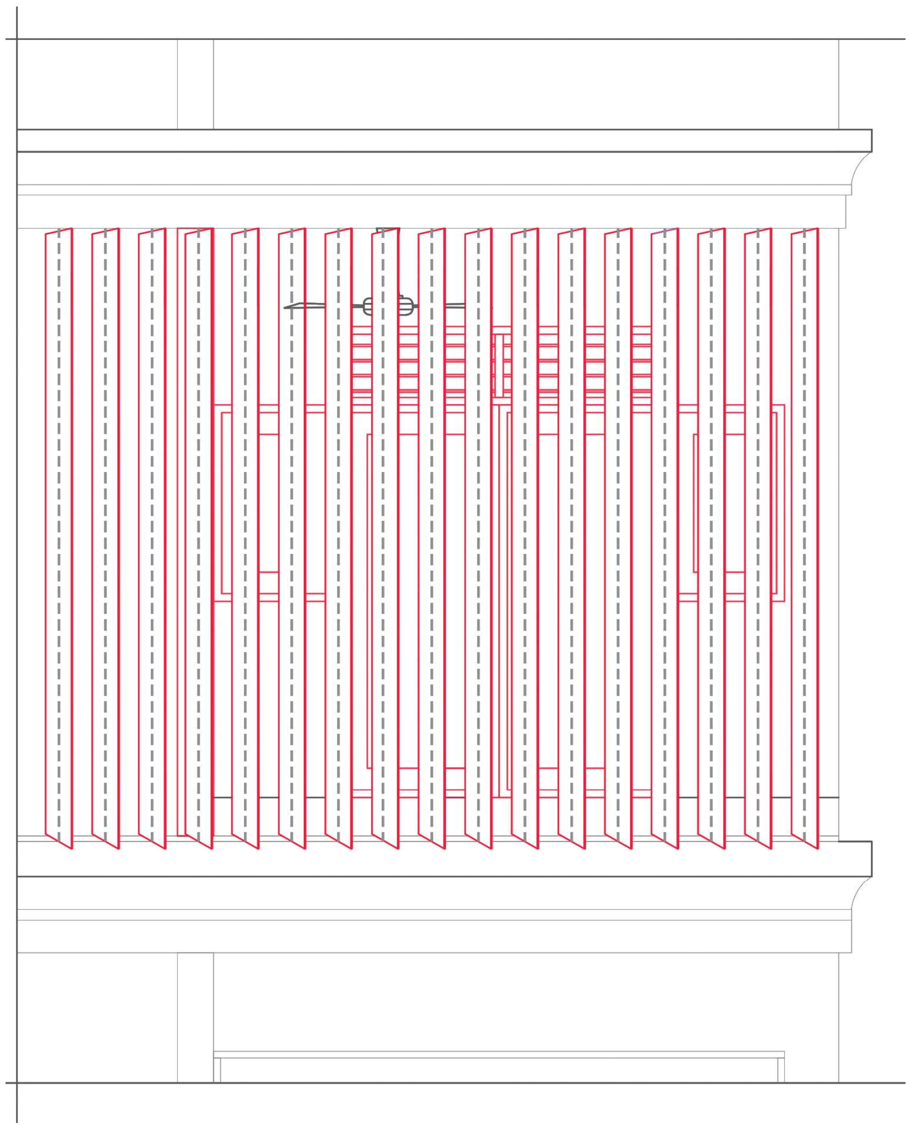


Fig.7.33. Case 08 with external shading - Elevation

Graph 01: *For summer – 10th (day 130) to 15th May (day 135)*

The measurements of the building elements, their material specification plus their internal and external U-values are the same as assumed in case 08 (Table 7.17).

The ventilator above the double door, the shuttered windows and the double door are kept open (Table.7.20, 7.21) throughout the night. For this simulation, the vertical fins are placed at an angle of 60 degrees throughout day and night (Table 7.21).

However, the double door is kept completely shut from 11:00 till 16:00, the time when the living space receives maximum direct solar radiation. During this time the shuttered windows are kept half open.

Solar radiation, external temperature, RT of the existing case (case 01) without mechanical cooling, the RT obtained from case 08, RT after the addition of external shading to case 08 plus an upper and lower limit of the comfort band were plotted (Fig.7.34).

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Table.7.20. Window Schedule for Double Door *0 = close 1 = open*

Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Window Status	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table.7.21. Window Schedule for Ventilator, Shuttered windows and Vertical Fins *0 = close 1 = open*

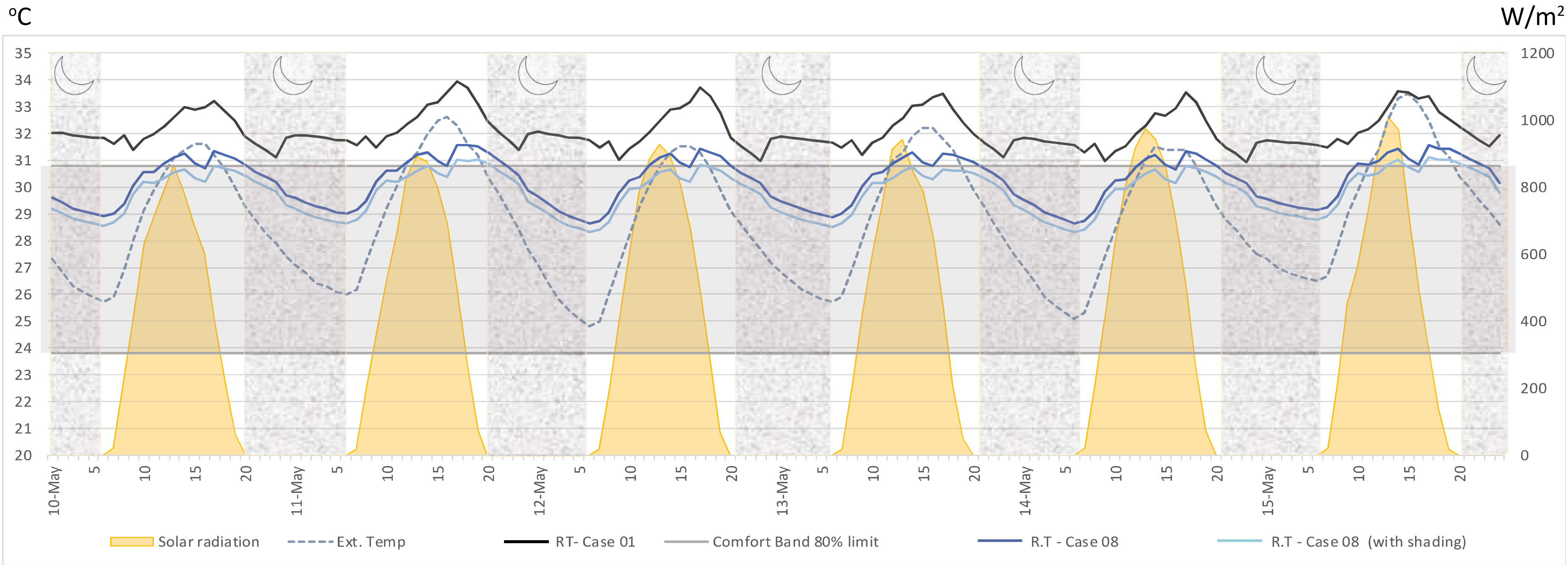


Fig.7.34. Comparison of Case 01 RT & RT of case 08 with external shading

Results:

The outcome from this case suggests the significance of the application of environmental controls such as solar shading since they are capable of reducing the need for mechanical cooling and maintain the indoor thermal comfort. The graph (Fig 7.34) shows a drop of up to 0.8ºC in the resultant temperature as compared to the resultant temperature obtained in case 08 without the application of external shading. The difference between the resultant temperature of case 01 (without mechanical cooling) and the resultant temperature of case 08 with external shading is 3.5ºC. The resultant temperature is almost within the comfort band when the living room receives maximum solar radiation during a peak summer day. Therefore, efficient window design along with suitable material and effective shading technique should be applied together to limit the heat gain from radiation, achieve maximum thermal and visual comfort and achieve maximum energy efficiency.

As a result, it can be concluded that providing an operative window that allows the occupant to adapt to their changing indoor environment due to factors such as lighting, occupancy, equipment gains or solar gains is extremely important along with an efficient application of other architectural elements such as walls, floor and ceiling, to achieve maximum comfort. Furthermore, operable shading systems that allow the occupant to adjust them according to their needs, that reduces solar heat gain, glare, noise and dust plus provides privacy, the view outside and natural ventilation must also be considered.

The simulations performed in this section strongly suggest that the windows do play the most significant role in achieving thermal comfort and creates a social and cultural context. However, they are more efficient and effective when they are a part of a logical design intervention that also takes into consideration window design, building materials, building form and orientation, building techniques, climatic conditions, surrounding context and application of appropriate environmental controls.

There is always a scope for improvement in the internal conditions through logical design interventions to achieve the desired comfort.

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CHAPTER 8

CONCLUSION

The comprehensive purpose to engage in this research was the urgency of addressing the problem of rising energy demand, the extensive use of mechanical cooling, especially in the Indian households, loss of adaptive character of windows in modern Indian architecture and the projection of the future climatic trends. Furthermore, according to the estimations made concerning population growth (See Chapter 01, p 3) would result in sharp growth of reliance on the mechanical systems for heating, cooling, and lighting. Hence, this research aimed at readdresssing alternative solutions, to reduce the dependence on artificial systems. Therefore, this research emphasized on the importance of occupant use of adaptive tools such as 'windows' to achieve comfort in Indian households. Also, the reason this study focused on 'windows' as an appropriate alternative solution is because apart from providing thermal comfort windows are also responsible for social and visual linkage. They are capable of creating a social bond between people as well as the environment. They form an important relationship between the outside community and the life inside the buildings. Hence, there was a need to explore the environment through which this association takes place.

As a result, the research questions set at the beginning of this study were as follows:

1. To decide through this research, how windows are capable of creating thermal comfort in present times.

2. With the growing use of mechanical systems as the most conve-

nient means to attain comfort, are windows still needed? And do they work effectively enough?

3. What is the importance of having 'adaptive windows'?

4. Is it essential for windows to provide the user with various permutations and combinations to create an environment as per their comfort?

5. Through this research is there a scope to create an awareness of the importance of window design while designing spaces?

The above objectives were met through literature review, fieldwork, and calibrations which were segregated under different headings. The reflections from each chapter and how it contributed to answering the above questions are discussed below.

The meaning of window

The literature in this section defined windows, architecturally as well as technically. The history of the window pointed out the importance of 'openings' in architecture. Although they have evolved and are still evolving, the basic need for having a window, which is to provide ventilation, light and a view, has not quite changed. The most interesting part of this chapter is how windows have transformed over the period of time and factors such as materials (glass, paper), location (different parts of the world), the functions that windows must fulfil (privacy, diffused light), were all responsible for a range of diverse window design all over the world.

Apart from history, the second half of the chapter discussed the environmental functions of windows such as thermal comfort, solar shading, heat gains and losses, ventilation and view. Furthermore, elaboration of these factors also pointed out that, although windows are essential, they are also capable of creating issues for the occupants, such as glare, too much noise, dust, lack of privacy and so on. However, through appropriate design interventions that require adding layers to the existing window design such as the addition of internal or external shades, adding tinted glass, the addition of metal or wooden lattices and so on, the said issues could be resolved.

The discussion on each of the factors allowed to conclude that windows played an extremely important role in adjusting the indoor environment to meet the comfort levels of the occupants. Additionally, it also plays a significant role in the social, cultural, physiological and psychological well-being of humans.

Although the history of windows signifies the prominence of windows from the beginning of their existence in the built form until today. The climatic condition worldwide has been changing constantly.

But windows have not necessarily advanced due to the changing climatic conditions, however efforts were always made, primarily, to modify windows to regulate indoor climatic conditions as per the occupant requirement. Thus, the continuous evolution in the form of materials, building techniques and style of window shows how humans have modified openings in a bid to achieve a better performing window (for example the constant upgradation in the type of glass – single, double, triple glazed, tinted, low-E, argon-filled and so on) over the period of time.

Examples of Windows

Four different types of windows, two vernacular and two modern, were illustrated in this section. Each window belonging to different regions had a significant relationship with the place and the period they belonged to. Although the windows differed in terms of design, materials and construction techniques, one could draw similarities too. For example, the use of lattice screens in Moulmein rise building in Singapore could be correlated with the use of *jaali* screens in India.

Looking at the purpose these windows served, they provided control to the users to meet their requirements of environmental, social and cultural comforts. Hence, it becomes clear that windows cannot be of the same size, design, material everywhere. They must be versatile. They must modify according to the location and orientation of the building, weather conditions, affordability, user requirement, the social and cultural importance of the place and people. Therefore, the reflection from this chapter strongly confirms the need to understand the potential of a good window design that allows the users to take full advantage of the window and its elements to attain comfort.

Indoor Environmental Comfort

This part of the study reminds us of the potential of a thermal environment for cultural roles, symbolism, and sensuality that is being neglected and replaced by a thermally neutral world. It expresses our fascination with the ability to control our indoor environment irrespective of the outdoor climatic conditions and thus, it presses on the need to reconsider and redefine the concept of 'comfort'.

So, in present times rephrasing comfort means emphasizing on the practice of an adaptive approach that is an amalgamation of the thermal and visual relationship between the building and the occupants and at the same time determines the affordability and quality of comfort provided by them while being energy efficient.

Hence, *'comfort' does not mean achieving temperatures in the comfort band anymore, but it should be about offering the inhabitants the means to achieve the desired comfort that they seek, which makes it a dynamic process.*

Therefore, one of the important parts of this section is the research studies on the use of controls performed by experts such as Fergus Nicole, Richard de Dear and others. These studies were based on the role of adaptive controls available to the occupants and led to the conclusion that suggested comfort, and the process of achieving comfort is a result of influence of various factors such as window opening behaviour, the pattern of use of mechanical systems, solar shading and also factors such as air and noise quality, level of illuminance, solar radiation, floor area, age, gender and so on. Hence, achieving comfort cannot be monotonous and that is why the comfort regulating architectural element – the window has to be adaptive and it must provide the user with several permutations and combinations to attain comfort.

Introduction of Case Studies

The aim of taking up three completely diverse housing typologies belonging to different eras, was mainly to identify their window systems and how the windows have evolved over a period of time. To explore how they performed in the current climatic conditions and the present urban settings and how affordable they were. With the three housing typologies, three window types were identified.

1. The contemporary window: An observation made during the fieldwork indicated monotony in the current window design trend. The use of glass and aluminium frame sliding windows were widely used in modern building design, irrespective of the orientation of the building, without considering the weather conditions or the needs of the occupants. The ongoing trend was also to give provisions to the occupants for installing air conditioning units, on which the occupants relied heavily. One of the main observations made was the alterations made to the existing window by the occupants on different floors of the studied tower to cater to their requirements. This pointed out the dissatisfaction amongst the users with respect to the typical windows provided by the developer and at the same time their will to have a better fenestration design. Thus, it becomes important to design and consider adaptive window strategies that provide the user with options to regulate their indoor atmosphere that also caters to their socio-cultural routines.

2. The hot and humid window: The *chawl* window had its own identity, were three simple window designs were combined to create a fantastic window system that not only provided comfort to users but also contributed largely to their daily social and cultural activities. The courtyard and the introvert plan of the *chawl* further added to the user satisfaction of a comfortable indoor environment as well as in providing a strong connection with the inhabitants of the *chawl* along with a sense of safety. Although common issues of privacy and rodents also prevailed here, the use of mechanical systems was very little.

This case study portrayed windows as a strong architectural element and also projected the importance of other factors such as the form of the building, use of materials, construction methodology, space design and so on.

3. The hot and dry window: Unlike the *chawl* window, the windows from the *wada* were simple shuttered windows. However, it was observed that the type of the window and their sizes changed with the orientation of the building. For instance, all the windows on the external side were floor-length windows. Whereas, the windows looking into the courtyard were much smaller. There were also fixed circular windows that allowed only natural light to penetrate the living spaces. This typology emphasized on the importance of the placement of windows. It showed that windows should modify as per the orientation and cannot be the same on all sides of the building. Hence, factors such as sun path, the form of the building, the immediate context, the function of the indoor spaces are some of the factors that should be taken into consideration while designing a window.

Fieldwork

In continuation to ‘the introduction of case studies’, this section on ‘fieldwork’ specifically focused on the monitored environmental performance of the three typologies.

1. The Apartment – The contemporary window (Fig.8.1): The readings from the monitored data showed high reliance on mechanical systems in spite of the modifications made to the existing window. The added layers to the new full-height window had very less impact on the indoor environment, moreover, it allowed more solar radiation

to enter the living spaces which further made the indoor condition more uncomfortable with higher indoor temperature as well as too much natural light. Thus, it is important to understand that various factors must be taken into consideration while designing a window, to create an efficient window system that can adapt to the changing needs of the user, changing the outdoor climate and changing internal gains.

2. The *Chawl* - The hot-humid window (Fig.8.2): The data collected for this typology pointed out the importance of cross ventilation. It also emphasized on the significance of the surrounding context, the form of the built structure and more importantly the significance of a window system that allows the occupants to not only control their indoor environment but also control their privacy and social interaction with the neighbours. Therefore, the central courtyard and a fantastic

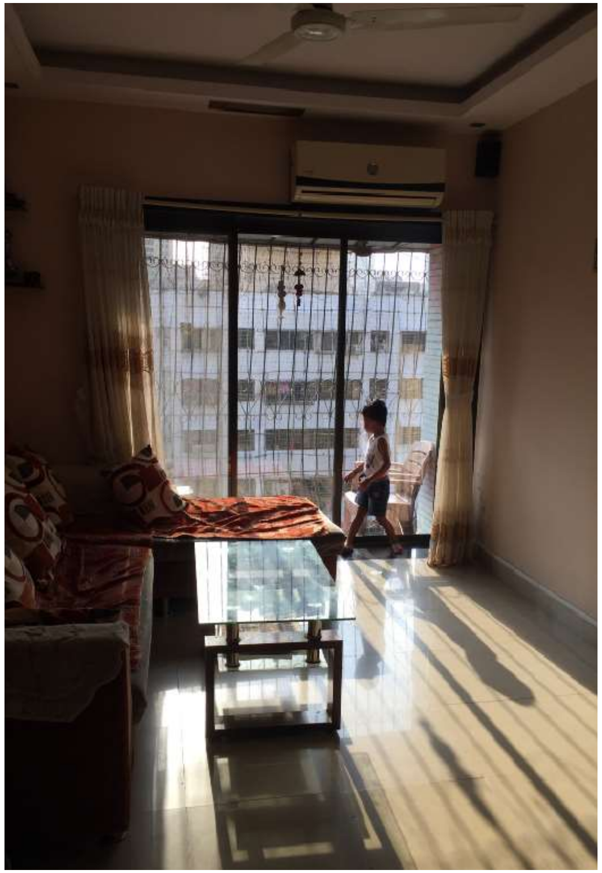

Fig.8.1. Apartment - Contemporary Window

Fig.8.2. Chawl - Hot - humid Window

Fig.8.3. Wada - Hot - dry Window

window + door + ventilator combination that ensured cross-ventilation created a comparatively comfortable livable space for the occupants without any need for any mechanical cooling systems.

3. The *Wada* – The hot-dry window (Fig.8.3): Even though *wada* had similar attributes to that of the *chawl,* especially in terms of the form of the building which comprised of a central courtyard, the monitored data showed that the typology did not perform as expected. In spite of having a central courtyard and numerous windows, the congested surrounding environment and not using the available windows to its full potential led to the unsatisfactory indoor conditions. The spaces lacked cross-ventilation because in spite of having windows they were always kept shut. Thus, this only shows that, although other architectural elements are important, the effective use of the windows plays a significant role in providing thermal and visual comfort.

The second half of this section addressed the findings from the BUS survey and questionnaire designed specifically to understand the role of windows in Indian households. The surveys not only highlighted the advantages of the windows but also pointed out the problems that the inhabitants usually face due to them. Although most of the problems are resolved by adding layers to the existing window, such as curtains, mosquito nets, metal grills, bird nets and so on, the most widely applied solution was the use of air conditioning. Therefore, the conclusions from this section draws attention to the least applied method of solution, which is through design.

Implementation of careful design strategies on an urban scale such as noise barriers and thoughtful tree plantation can help in reducing the noise and dust. Similarly, design interventions on building level such as creating the form and placement of the building by taking into consideration the sun-path could reduce the solar gains. Furthermore, implementation of careful design details of different architectural elements such as their size and specification. And most importantly, logical design of the openings along with all the other architectural features, since they can be adaptive modules which can resolve majority of the issues faced by the occupants such as attainment of thermal and visual comfort, privacy, noise, dust, insects and so on.

Performance Analysis

The last section of this research consisted of computational simulations that were carried out based on the data collected during the fieldwork. A total of eight cases were formulated which were simulated in TAS software. The main observations made from the cases are:

1. Having an adaptive window improved the quality of the indoor environment and offered the occupants various permutations and combinations which they had the freedom to apply to regulate their indoor comfort conditions.

2. While designing an adaptive window it is very important to keep in mind – the immediate context, the form and orientation of the building, location of the window, size of the room and most importantly, the environmental, social and cultural requirements expected from the adaptive window module plus its affordability and durability.

3. The simulations allowed to conclude that windows are the only architectural element that allows the occupants to control their indoor environment at any time. It was observed that the resultant temperature dropped by about 1.2°C to 1.5°C just by replacing the window (See Chapter 07). Although other architectural elements such as walls, floors and ceiling also provided thermal comfort, they cannot be adaptive, unlike windows, and adapt according to the change in seasons, change in internal gains or change as per the user requirements.

4. However, it also cannot be denied that adaptive windows are most efficient when they are part of a holistic design intervention that uses the properties of each architectural element effectively in attaining maximum comfort. The design approach considered for case 08 in chapter 07 consisted of a combination of windows, effective choice of materials, consideration of logical window opening schedules and efficient external shading design. The application of these parameters could achieve 3.5°C lower resultant temperature in the living room as compared to the existing case. The simulations exhibited that if an all-rounded approach is practised it can help in minimising the use of mechanical systems for cooling which in turn would contribute in reducing the annual energy consumption for every household.

Further Work:

The findings from the extensive fieldwork of the three different typologies and the computational simulations opened a wide window of investigation of different window systems in India. The research strongly highlighted that the information regarding different types and properties of windows, especially vernacular windows is extremely limited. Due to the huge gap in the data available to the users, designers, students and developers, least efforts are being made in the area of window design and further less in the area of adaptive window design. Therefore, the next step is to bridge this gap. The aim now is to create a database of openings such as windows, doors and roof lights both vernacular and contemporary, irrespective of the style of architecture and the period they were built in. The objective is to study these windows, understand the construction techniques, materials and the role of the design of the window in regulating the indoor environment and the adaptive opportunities they provide. This database would then be published digitally, through a blog or in the form of a book or both. The ambition of compiling openings is predominantly to provide the inhabitants, students, designers, developers, and the research community, an insight into what a well-designed window is capable of achieving, in terms of indoor quality of light, ventilation and thermal comfort, in terms of internal as well as external aesthetics. Furthermore, it will also try to highlight the concept, history and theory behind the making/designing of windows. The purpose of this compilation would be to provide the users with various options that can be adapted according to their environmental, social and cultural needs.

On the other hand, the application of such extensive fieldwork could be used in designing an advanced prototype of an affordable adaptive window which could be tested computationally as well as by building a 1:1 model that can be tested in an artificial environment created in an environmental laboratory or an actual environment. To achieve these objectives, the involvement of window manufacturing companies such as Fenesta, or collaboration with designers and manufacturers such as Monodraught, who are specialist in natural cooling, ventilation and lighting, can also be considered. This part of the application of the fieldwork study certainly has the potential to form the second phase of this research or a new research subject.

Furthermore, to bring the concept of adaptive windows into practice, a combined effort from the users, designers, developers, and manufacturers would play a vital role that could be achieved through the propagation of the concept of adaptive strategies. Organising workshops, the formation of technical guidelines for designers and CPD workshops and training sessions, conferences that provide the essential information on adapting adaptive passive strategies, websites that provide information on design, execution and affordability of these window systems are some of the ways in which steps can be taken towards creating habitable spaces in natural settings and minimize the use of mechanical systems.

Thus, overall, this research would provide the scientific community, design students, designers and consumers with options which they could combine to create openings and break free from the current stereotypes, with an ultimate goal to help in reducing the use of mechanical systems and promote sustainable living.