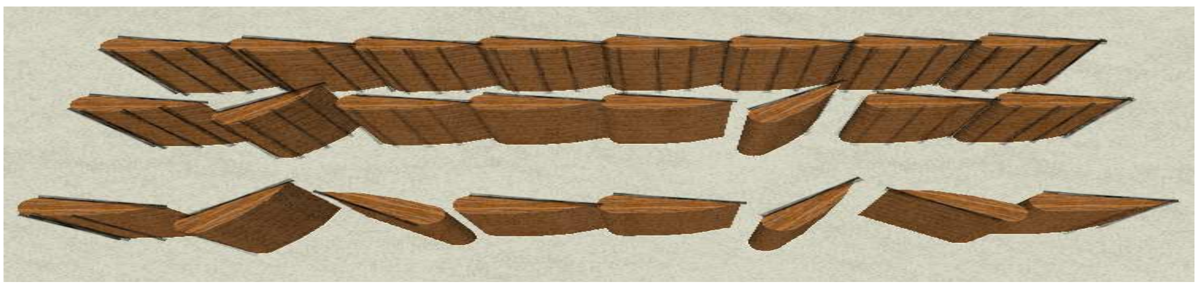
Graduation Report

Design of a Climate Adaptive Façade System using Bamboo for Urban India



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Preface

I always wanted to apply whatever I have learnt here at TU Delft in the context of the country that I come from, India. I also wanted to address a problem from different viewpoints in order to have a holistic understanding. Graduation Project provided me the perfect platform to explore this as I received adequate guidance from my mentors who are all experts from different fields. I would like to take this as an opportunity to thank my mentors, Prof. Dr. Ir. Jan Willem van de Kuilen, Drs. Wolfgang F. Gard, Ir. Roel Schipper and Ir. Bob Geldermans for their constant support, academically as well as morally, without which successful completion of this project would not have been possible. Special thanks to Dr. Ir. Wim van der Spoel for his time and guidance during several occasions through the course of this project. Lastly, huge amount of gratitude to my family and friends for all their support and good will which helped in lifting my spirits during difficult times.

Sindhu Murali
September 2013

Summary

Indoor climate and human comfort is attaining increasing interest in large urbanized areas. While for the user this is mainly as a result of increasing operational costs associated with the devices for heating and cooling, the bigger concern for environmentally conscious engineers and designers lies in reducing the emission of green house gases. Further, use of locally available eco-friendly materials are also gaining popularity as they have the potential to reduce the embodied energy to a great extent.

In this master thesis project, a design concept for a dynamic façade system for urban India (mainly for the hot-humid climate zone) using bamboo has been developed. The design is based on promoting cooling by natural ventilation in combination with positioning the façade elements in such a way that reduces the impact of heat released due to thermal mass on the indoor climate. Thermal comfort has been assessed based on Adaptive Thermal Comfort models for the hot-humid climate zone. CFD tool of the software, DesignBuilder in combination with excel calculations were carried out to perform the necessary building physics calculations.

Further, the environmental impact of the design has been evaluated by the Cradle2Cradle framework.

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Chapter 1: Introduction

1.1 The Problem

31% of the total population of India lives in cities (World Bank Data, 2012) with the four main metropolitan cities of the country making it to the list of the top twenty most populous cities of the world.

With urbanization there is not only an increasing need for space in the cities, but also a complete change of lifestyle. As cities grow, there is a growing demand for basic needs such as food, energy and material resources. Owing to the lack of space and resources to cater to the various demands of the huge population, city dwellers import almost everything that they need from several miles away. In the words of Rees and Wackernagel, "cities and urbanized regions are intensive nodes of consumption sustained almost entirely by biophysical production and life-support process occurring outside their political and geographic boundaries" (Rees and Wackernagel, 1996).

The 'ecological footprint' that these urban spaces create is several times larger than the actual physical space occupied by them. Today humanity uses the equivalent of 1.5 planet earths to provide the resources we use. This means it now takes the Earth one year and six months to regenerate what we use in a year. Quoting Global Footprint Network, "if the current consumption and population trend continues, by 2030, we will need the equivalent of two earths to support our needs and we of course have just one" (Global Footprint Network, 2013). Reducing the ecological footprint is therefore the need of the hour. Any new development strategies we come up with should try to meet our energy, food and material demands in a sustainable way.

The construction industry is one of the main contributors to the carbon footprint and at a larger scale, to the ecological footprint. Nearly 40% of greenhouse gas emissions are attributed to the design, construction, and operation of buildings (Whole Building Design Guide, 2011). Globally, 24% of the raw materials that are removed account to meet our construction demands. The associated processes- extraction, processing, transport and installation of materials also consume large quantities of energy and water (Science for Environment Policy, 2011). These concerns related to energy consumption, carbon dioxide emissions and water demand, are all not new anymore. Switching to renewable sources of energy and promoting eco-friendly alternative materials have long been identified as the sustainable solution to answer this crisis situation.

Such materials were widely used prior to the advent of steel and concrete and continue to be used in many parts of the developing world. Most buildings, even in urban spaces, can probably do with alternative local materials- the ones which are cost effective, bioclimatic and probably as strong and durable as the 'modern' materials. Using materials that are readily available rather than transporting them from across the world, can be a good start to dealing with the wish to reduce our dependence on fossil fuel. For developing countries like India which cannot afford to invest in extravagance and lavishness, it is not only the environmental benefits but also the cost benefits that these materials offer.

1.2 Changing Trends – Building and Energy in Indian Perspective

Until a few decades ago, use of electrically powered 'machines' to aid in thermal comfort was very rare because they were either not discovered or could be afforded only by a select few. Passive building techniques were then widely used to meet comfort requirements of the occupants. However, in the recent times, these kind of techniques are either not applicable or are neglected. With the growing population in cities, high rise buildings have gained popularity. Improper city planning has lead to congestion of buildings. In such situations passive design principles no longer seem entirely effective. For those who can afford the luxury, easy solutions for comfort are provided in the form of fuel-powered devices. Even in situations where neither the climate nor the landscape poses serious design challenges, it is being overlooked. This has lead to a situation where all buildings, irrespective of their region, are beginning to look no different from one another.

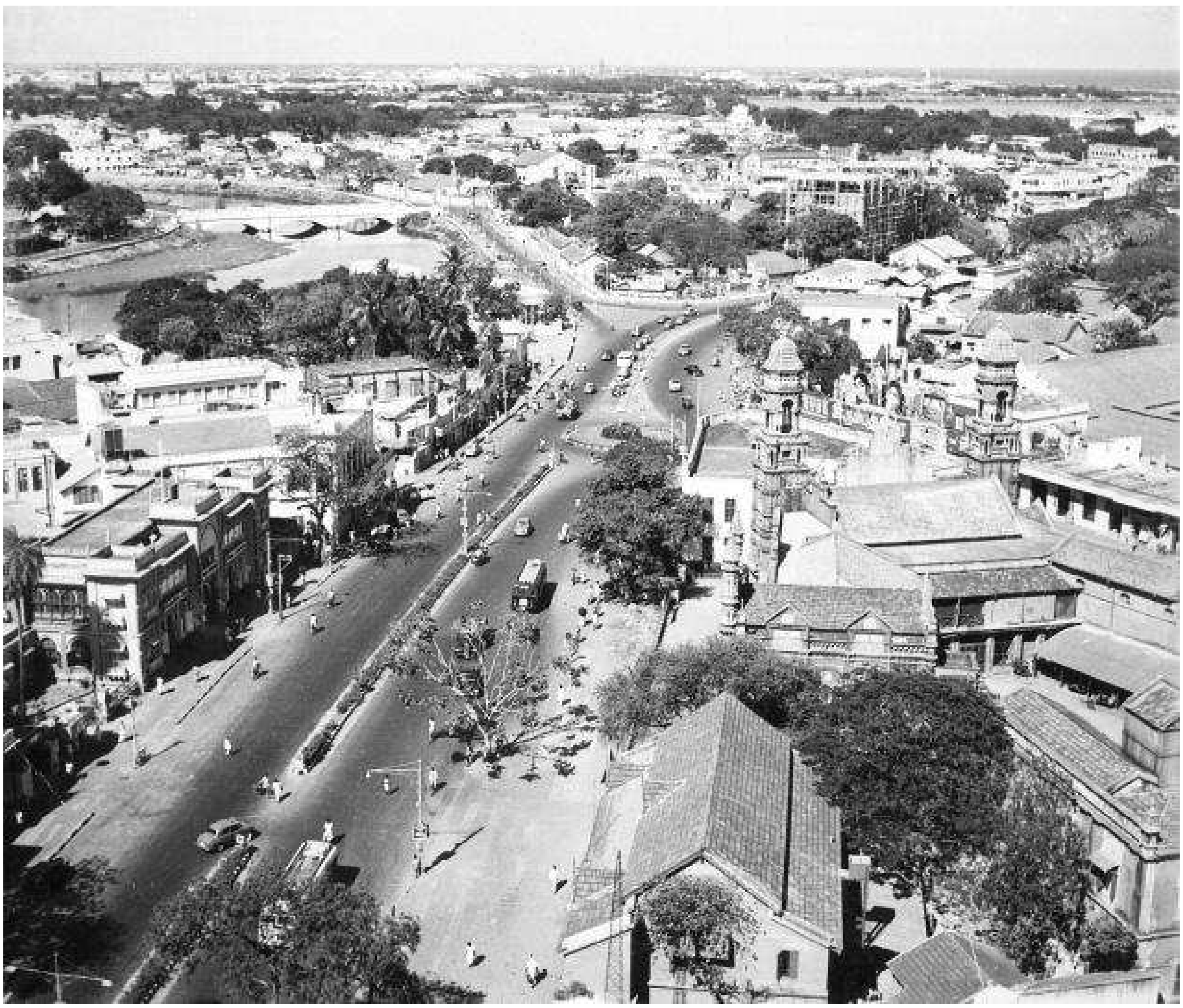

Figure 1 Mount Road, Chennai, 1950 [Source: http://housing.co.in/blog/2013/08/15/from-madras-to-chennai-in-pictures/]

Figure 2 Buildings around Mount Road, Chennai, 2013 [Source: Unknown]

Figure 3 Large concrete buildings replacing the modest traditional buildings, Mumbai [Source: Unknown]

1.3 Embodied Energy and Operational Energy

Energy in the building sector can be classified into two major types:

1. Embodied Energy
2. Operational Energy

Embodied Energy refers to the energy that is sequestered in the material during all the processes that it goes through: from extraction to production, transportation to the site, on-site construction, and final demolition and disposal at the end of its life. Operational energy on the other hand refers to the energy required to maintain a comfortable indoor environment through processes such as heating and cooling, lighting and operating appliances.

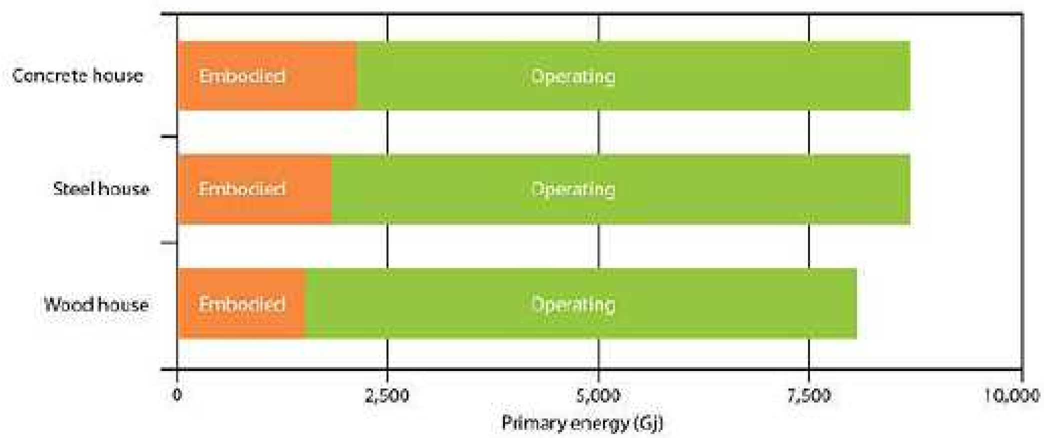

Figure 4 Operational and embodied energy for different building materials [Simone Hegner, ETHZ – 2007]

Figure 4 compares the embodied and operational energy for 3 different types of constructions: concrete, steel and wood. From the image we can gather that the embodied energy is less than one third of the total energy consumption for the various different constructions.

1.4 The Façade

Since the façade serves as an interface between the interior and exterior space, it plays a critical role in determining the indoor environment. Exchange of air, heat and coolth through the façade directly influences the energy demands of the building. That is, the operational energy costs are inversely proportional to the degree to which the façade is able to respond to its environment and meet the desired performance requirements (thermal, visual, acoustic and hygienic requirements) of the occupants. In this study, the façade therefore will be the central point of attention.

1.5 Bamboo as a construction material in India

The need for the shift towards renewable materials in order to provide a solution to our energy issues has already been discussed. In the context of India, bamboo is a promising alternative material. India is home to over 45% of the world's bamboo forests. Some species of bamboo possess properties comparable to modern construction materials, making it a suitable building material (Lobovikov et al., 2007).With its fast growth rate and limited time to replenish, it can be a good substitute for wood. Extensive Life Cycle Analysis(LCA) for bamboo based products have been carried out by van der Lugt in the past and he has concluded that "bamboo, if based on best-practice technology, even when used in Europe can actually be CO_2 neutral or better. When used in the country of production the results will be even more positive" (van der Lugt et al., 2003, 2005, 2006, 2009).

Going by these numerous benefits this study was focused on using bamboo as a material in the mainstream construction industry. The role of the façade in determining the operational costs to a great extent was recognized and hence the topic was further narrowed down to the applicability of bamboo as a façade element.

1.6 Scope of the Study

Based on the literature, the following two key points can be derived:

- Bamboo, if used as a building material in countries where it grows, can greatly reduce the carbon footprint associated with the building industry.
- If the requirements of a façade are given due consideration and reflected in the form of an appropriate design, the operational costs associated with the usage of the building can be minimized.

Combining these two, the following hypothesis was derived:

> A façade element made of bamboo designed in a manner appropriate for the local climate will reduce the carbon footprint as well as the operational costs associated with a building.

1.6.1 Objective

To design a climate responsive façade system using bamboo that aids in achieving thermal comfort in a free running building.

1.6.2 Boundary Conditions

- Design: Available passive solutions to maximize thermal comfort (and consequently minimize operational energy) were the starting points of the design. Simultaneously the material possibilities of bamboo were also studied. The end design is a combination of the two.

- Reference period of the facade: The life time of the façade element is not considered as it largely depends on the nature of bamboo based products which are already available in the market. Manufacturers of bamboo based panels for exterior climate usually estimate a life time of 25 – 30 years.
- Climate: The climate zone for the design was chosen based on the type of climate where it is already a popular building material after verifying its relevance for the same. At the end however, the design was tested for other climate zones as well to determine its usability in other zones.
- Type of Building: A single room building of area 100 m^2 with an open floor plan was considered. Different functions and their demands as far as the façade is considered are discussed and suggestions for possible functions which can best benefit from the design are made.
- Location: The focus is on urban areas in India.

1.6.3 Research Questions

The work aims at answering the following questions:

- Does the designed façade element contribute to the performance of the indoor climate positively? (The focus here is on the thermal comfort).

- Will the end product meet the standards to be qualified as a Cradle2Cradle product?

1.7 Summary of Chapters

The following section explains the layout of the following chapters of the report.

Chapter 2 introduces bamboo as an engineered product. Main topics include the material possibilities of bamboo, the various uses of bamboo including its place in the construction industry and a brief explanation of the various commercially available engineered bamboo based construction elements. The chapter ends with an account on the distribution of bamboo in India and the trade policies involved.

Chapter 3 focuses on choosing a climate that is ideal for bamboo to be used as a construction material. After the choice for the climate is made, the climate characteristics of three Indian cities belonging to the particular climate belt are discussed. Finally one of the three cities is chosen as the location for the rest of the study.

Chapter 4 discusses briefly the passive design measures for the chosen climate. The measures which can be adapted with respect to a façade element in an urban scenario are identified.

Chapter 5 elaborates on the different requirements that have to be met by a façade. This is followed by a comparison of the requirements for various functions and the criticality involved for the various functions. Further figurative standard requirements as set by the National Building Code of India (2005) are provided whenever available. Based on this background information an appropriate choice for the function is made. This was necessary as the various heat loads depend on the chosen function.

Chapter 6 compares different types of constructions (light weight/ heavy weight- with and without insulation) and their performance in the chosen climate. The nature of construction that best suits the climate is then chosen. The chapter ends with an analysis of the current scenario.

Chapter 7 recognizes the need for an alternative method to assess thermal comfort. This is followed by a discussion of proven methods to improve thermal comfort in the said zone. Effective ventilation is identified as an important factor for achieving thermal comfort. Finally the problems associated with implementing the same in an urban context is addressed briefly.

Chapter 8 looks into the theory behind natural ventilation and ways of achieving the same. Based on the theory, several cases are recognized and their performance is studied using a CFD program. The outputs are compared to arrive at a possible solution. The need for a dynamic control is identified as an optimum strategy for effective natural ventilation.

Chapter 9 is an extension of Chapter 6. It looks into the theory behind thermal mass and evaluates the thermal properties of bamboo. An optimum thickness of the construction is then chosen based on transient heat transfer calculations. Again, the need for a dynamic control of the façade elements is identified as a possible strategy to achieve thermal comfort. Calculations to support the same are presented and possible errors in the calculation are discussed.

Chapter 10 extends the proposed design principle to the other two cities belonging to the same climate zone as well as two completely different climate zones.

Chapter 11 aims at combining the two main principles derived in the earlier chapters and present briefly the design of the façade system as a whole. A suitable bamboo based engineered material is chosen based on the inventory provided in Chapter 2. Further, a possible mechanism for control is suggested and the drawbacks of the same are critically analyzed.

Chapter 12 looks into the bigger picture of assessing briefly the proposed design in terms of its impact on the environment. The concept of Cradle2Cradle is chosen as the criteria for evaluation. Various aspects which need to be fulfilled for a product to be certified as 'Cradle2Cradle' are described briefly and the steps where the product fails to meet the requirements including correcting measures are briefly outlined.

Chapter 13 brings the end of this report with conclusive remarks and suggestions for improvement.

Chapter 2: Bamboo as a Modern Engineered material

2.1 Merits and Demerits

Over the years, several advantages of bamboo as a plant as well as a material with potential to create engineered products have been identified. On the other hand, several associated drawbacks have also been recognized. Knowledge of what is possible and what is not can help in making wise design choices. Some of the main advantages and disadvantages according to the pioneers in the field are as follows (Mathur, 1981; Janssen, 1987; Mishra, 1990).

2.1.1 Advantages

- It is a renewable material that grows very rapidly (much faster than hardwoods), which can be cultivated for quick and continuous return on capital.
- Bamboo forests are said to sequester 30 % more carbon than similar sized hardwood forests.
- The deep root system of the plant protects the soil against erosion.
- The capital costs involved in the planting and harvesting of bamboo is very low and it can be grown in homesteads.
- It possesses good mechanical properties and a high strength-to-weight ratio. It can thus be made into structural components that are lighter but stronger than those made of conventional materials. Its lightness and high elasticity is especially suited for housing in regions prone to earthquakes.
- Culms can easily be split into strips with simple tools even by workers with a low level of skill.

2.1.2 Disadvantages

- The single most important drawback of bamboo is that it is prone to fungal attack. Preservative treatment is therefore required to obtain a reasonable life-span.
- Addition of chemical preservatives thwarts safe decomposition.

2.2 Treatment and Preservation

Treatment of bamboo can broadly be classified as traditional or chemical.

Traditional methods often involve methods and materials which are readily available. Smoking, soaking, seasoning and lime washing are popular treatment methods. It is also about knowing the ideal time to cultivate in order to minimize the starch content as much as possible. "The amount of starch present in the culm determines its susceptibility to borer and insect attack. When new shoots begin to grow, the plant would have given all its starch to the bamboo, resulting in a lower starch content in the older culms, which in turn makes them more resistant to insect attack. This is therefore the ideal time to cut the older culms for construction" (Ranjan et al., 1986).

In regions where plenty of water is available, whole culms are often immersed in flowing water to leach out the starch from them. The bamboo which is treated this way is often transported by the same flowing water (Reubens, 2010). Smoking involves treatment of the culms over fire and this is found to be effective against fungi and insects. Various sources also suggest washing the culms with lime water to be an effective treatment procedure against fungal attack. The effectiveness of these methods is not known yet, however they are quite popular among traditional communities as they do not need much capital investment or highly skilled labourers (Janssen, 1987).

Chemical Treatment Methods which use preservatives prove to be more effective than traditional methods, but the disposal of these chemicals in the environment is often a problem. Therefore from the sustainability point of view, use of chemical treatment methods does not fare very well. Jansen, in his book ‘Building with Bamboo’ discusses about a Boron based fertilizer used in Costa Rica - Disodium Octoborate Tetrahydrate consisting of 66% active boron. Although the preservative here is a chemical, the bamboo, at its later stages can be used as a fertilizer. Therefore there is zero waste at the end of its life.

In the ‘Bamboo House project’ (2009) carried out by the Auroville Earth Institute in India, culms were soaked in alum (Aluminium Sulphate) solution for 30 minutes. This technique is believed to preserve them for 30 years however there is no proof yet.

Chemicals based on the element boron are considered to be safe. Examples include copper-chrome-boron (CCB), boric acid and borax (Janssen, 1987).

Chemicals can be introduced into bamboo by 2 most commonly used methods: modified Boucherie process for whole green culms and dip-diffusion for split culms. This is not discussed in this report as it is not in the scope of the work. More details about these methods can be obtained by referring Jansen’s book- ‘Building with Bamboo’.

2.3 Gaps in knowledge

So far, a large number of species of bamboo have been identified all over the world. The type of soil, water content, climatic conditions, wind and rain patterns, etc., all determine the physical characteristics of each of the species. Mechanical and physical properties of a number of bamboo species still need to be studied in order to attain better understanding. The different nature of each of the species also makes standardization of testing procedures difficult. Although a few codes of practice have been designed and are followed in different countries, there is no one standard manual that can be universally used. Absence of a code of practice for bamboo limits engineers to design structures with the same confidence as they would with recognized engineering materials such as steel, concrete or timber. Another problem is the vast gaps in knowledge between the traditional communities and scientific groups. Exchange of knowledge- especially those related to joining techniques and preservation treatments can prove to be beneficial for both groups.

2.4 Uses

Bamboo is used at different stages of its maturity and in its various forms- as whole culms, as half culms, as strips, or as fibers depending on the end product. The possibilities with respect to workability of the material are endless. It can be molded, made into veneers and boards, used as reinforcements in concrete or other similar media, etc (Ganapathy, 1999).

Around the world bamboo has found a wide range of interesting applications. Traditional communities in several regions of the world, including India, depend solely on bamboo for most of their daily needs including food and shelter. Apart from usage as a building material, other common traditional uses of bamboo include making of furniture, utensils, cages for animals and birds, baskets for storing grains and other agricultural products, certain indigenous musical instruments, etc., to name a few (Janssen, 1987; Ranjan, 1986; Reubens, 2010).

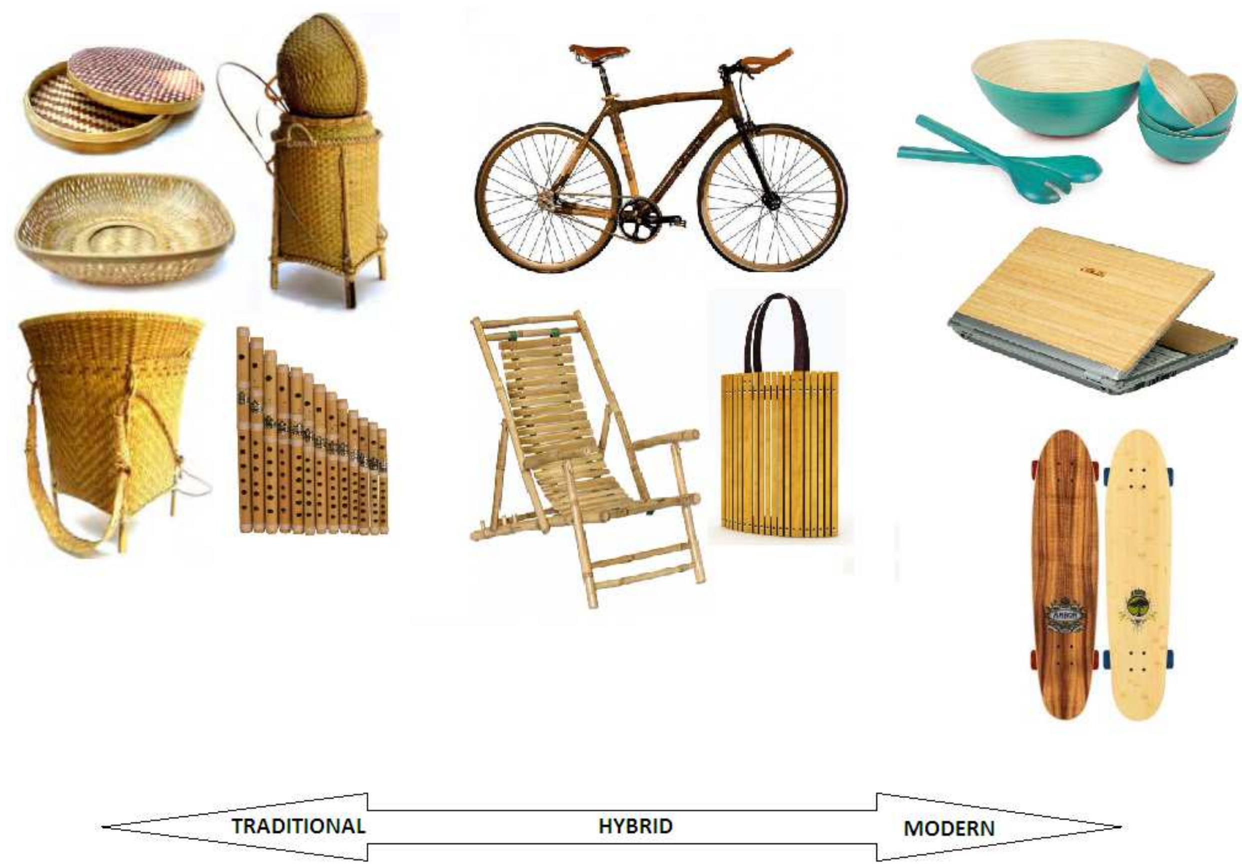

Figure 5 Wide Range of uses of bamboo [Sources: Reubens, 2010; http://www.gizmag.com; http://www.corebamboo.com; http://www.ariokano.com; http://www.greendiary.com; http://notebookitalia.it; http://www.surfinggreen.com]

2.5 Bamboo no longer 'Poor Man's Timber'

Owing to more advanced knowledge about the material and the 'green' benefits it has to offer, in the recent times it has also gained popularity as an engineered product. Designers are continuously exploring the possibilities of the material, and working on ways to make it suitable for a larger and more sophisticated market. Modern applications include casings for laptops, as parts for cycles and boats, skateboards, designer furniture, as clothing, etc (van der Lugt, 2008; Reubens, 2010).

Figure 6a Bamboo Chair by Tejo Remy and and Rene Veenhuizen.

Figure 6b Rising stool designed by Robert van Embricqs.

Figure 6c Dell Bamboo Computer Sleeve.

[Source: Website of MOSO Bamboo]

2.5.1 Material Possibilities

Designers all over the world have been experimenting with the different material possibilities of bamboo. The Department of Industrial Design of Rhode School of Design documented the results of a design studio which was committed to exploring innovative uses and applications of bamboo. A variety of design possibilities are identified and the fabricated end results documented in the form of a manual. The series of processes that were carried out to achieve each of the results are recorded in the manual. Images from the manual show that bamboo can be sliced, carved, laminated, bent to form complex but perfect patterns , sawn into thin sheets, moulded into intricate shapes, blended with other materials , or woven into fabrics- the possibilities are endless (Martinez and Steinberg, 2000).

2.5.2 Dutch Design Week

Pablo van der Lugt, during the course of his PhD thesis which aimed at stimulating bamboo commercialization through design interventions, brought together several Dutch designers who were relatively new to working with bamboo. The designers were introduced to the material and were asked to come up with several bamboo based products. The results of this exercise again depict the several possibilities of bamboo. The various design solutions eliminates the “poor man’s timber” image that bamboo has and instead portrays it as a modern-industrial product that is well suited for a Western commercial market (van der Lugt, 2008).

In the building industry bamboo has found its place in almost every field where timber is used. It is a popular flooring option and indoor cladding material. But it is also used in more demanding situations such as for outdoor decking.

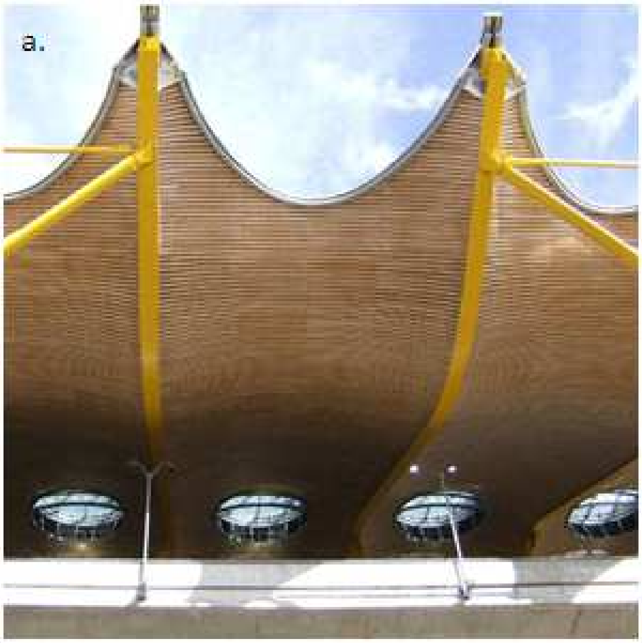

Figure 7a Madrid Barajas Airport designed by Richard Rogers [Source: Website of MOSO Bamboo]

Figure 7b Outdoor Decking, MOSO X-treme [Source: Website of MOSO Bamboo]

2.6 Engineered Composites

Raw bamboo, in the form of strips, fibres or ground particles is commonly used with adhesives or binders in order to improve its performance. The resulting composite performs better in terms of resistance to rotting, fungus and insect attack, temperature and humidity related splitting etc. Several types of composites have been developed over the years. Some of them are discussed briefly under this section. More information is provided in Appendix A.

2.6.1 Bamboo Mat Boards

Bamboo mat boards (BMB) are versatile panel materials that are produced from woven mats of bamboo soaked in an adhesive resin which are later pressed firmly together in a hot press. The thickness of the boards can go up to 6mm and the number of individual mats varies between 2 and 7. BMB has physical and mechanical properties similar to plywood due to its high internal bond strengths and plane rigidity (Ganapathy et al., 1999):

- Durability and resistance to boiling water, weather and biological agents similar to phenolic-bonded plywood.
- Better scratch and stain resistance properties than plywood.
- Fire resistance similar to fire-retardant treated plywood.
- "It is much more flexible than wood-based-plywood and can be used in structural applications such as stressed skin panels, wall bracings and web beams for which plywood is not suitable" (Ganapathy et al., 1999).

Figure 8a Close up of the Bamboo woven mat [Source: Website TECA]

Figure 8b Finished BMB used as wall infill [Source: Unknown]

BMB has been in use in India for a long time now and the development method has undergone a lot of changes over the years. Improvements to the resin was made by reducing the quantity of phenol formaldehyde (PF) (from 1.3 kg/m^2 to about 0.3 kg/m^2) and replacing it with lignin obtained from pulp mill effluent. According to Ganapathy et al. (1999) these changes not only reduced the amount of PF, but also ensured uniform bonding and surface appearance. Further by incorporating a preservative in the glue (lignin), the durability was found to increase (Ganapathy et al., 1999).

During the course of the IDRC (International Development Research Centre) -sponsored BMB research project at IPIRTI (Indian Plywood Industries Research and Training Institute), several bamboo species were studied for BMB manufacture: D. strictus, D. hamiltonii, D. brandisii, M. baccifera, O. travencorica, B. nutans, B. bambose, B. balcooa, B. tulda. All were found to be suitable (IPIRTI).

The manufacturing procedure of BMB can be found in Appendix A.

2.6.2 Bamboo Mat Corrugated Board

Figure 9 Bamboo Mat Corrugated Board [Source: http://www.guaduabamboo.com]

BMCS is made similar to BMB, except the boards are pressed in a specially designed sinusoidal platen dies. BMCS is water proof and resistant to decay, termites/ insects and fire and has a load bearing capacity that is comparable to other roofing materials. Properties of BMCB are provided in Appendix A.

2.6.3 Bamboo Mat - Veneer Composites

Resin coated bamboo mats, woven in herringbone pattern using slivers of about 0.6 mm thickness, and rotary cut veneers from plantation wood are used for the manufacture Bamboo Mat Veneer Composites. Specific construction of bamboo mat and veneer layers is used and thickness of manufactured board can be in the range of 4 mm to 25 mm.

Bamboo mat Veneer composite boards can be made in existing plywood or Bamboo mat board manufacturing factories without major additional capital investment. BMVC has superior physical mechanical properties compared to Bamboo Mat Board (BMB) and general purpose plywood and on par with structural plywood, particularly for thickness greater than 6mm (Website IPIRTI).

2.6.4 Bamboo laminates

Bamboo laminates are made from slivers milled out from the bamboo culm. After primary processing which comprises of cross cutting, splitting and 2-side planing, the slivers are treated for starch removal and prevention of termite/borer attack. The slivers are then subjected to hot air drying followed by 4-side planing for attaining uniform thickness. These are then coated with adhesive on the surface and are arranged systematically. This is followed by curing in a hot press at a temperature of about 70˚C using steam & pressure at around 1.7 N/mm^2. The pressed laminate is then put through trimming, sanding and grooving machines to give a pre-finish shape.

Culm diameter and wall thickness are two very important parameters that limit the conversion of bamboo into strips of suitable sizes for making laminates. Of the several Indian bamboo species, B.balcooa, B. nutans, B. bambos and B. tulda appear to be suitable (Bansal and Prasad, 2004).

An innovative resin to reduce the processing energy requirement was developed by The Advanced Composite Mission of TIFAC in India. The low-temperature curing water based resin (melamine fortified urea formaldehyde) meets the formaldehyde emission as per the international laws. Further, a water based acrylic pre-coat was developed to prevent moisture related deterioration of bamboo composites.

2.6.5 Strand woven bamboo (Plybamboo)

Strand Woven Bamboo (SWB) is similar to bamboo laminate and can be used indoors as well as outdoors. In order to make it suitable for outdoor applications, large quantities of PF resin is used. Typically compressed strips of bamboo, in combination with the resin is compressed at high pressure. The resulting product is much denser (1080 kg/m^3). An important advantage of SWB is that it has less strict restrictions to the quality requirements of the strips serving as input as compared to other industrial bamboo products. This not only maximizes the raw material content, but also poses lesser demands on the production facility (van der Lugt, 2008).

A disadvantage of SWB is the high resin content which makes it score less in the sustainability point of view (van der Lugt, 2008). However, companies such as MOSO Bamboo, in the Netherlands have succeeded in developing highly durable SWB for outdoor application (by the name MOSO X-treme) using a patented heat treatment process.

2.6.6 Bamboo Particle Board

This is similar to wood particle board, except plywood is replaced by wood. Variations have been made by replacing the formaldehyde resin by (waste) plastic. The resulting bamboo plastic composite has been found to be better for water-resistance, durability and dimensional stability properties, at the same time also overcoming the free formaldehyde emission problem. Other variations include cement-bonded particleboard, gypsum-bonded particleboard and bamboo particle plaster board (van der Lugt, 2008).

A comparative list of other bamboo based engineered products along with the ones already mentioned here is given in Appendix A.

2.7 Distribution of different species of bamboo in India

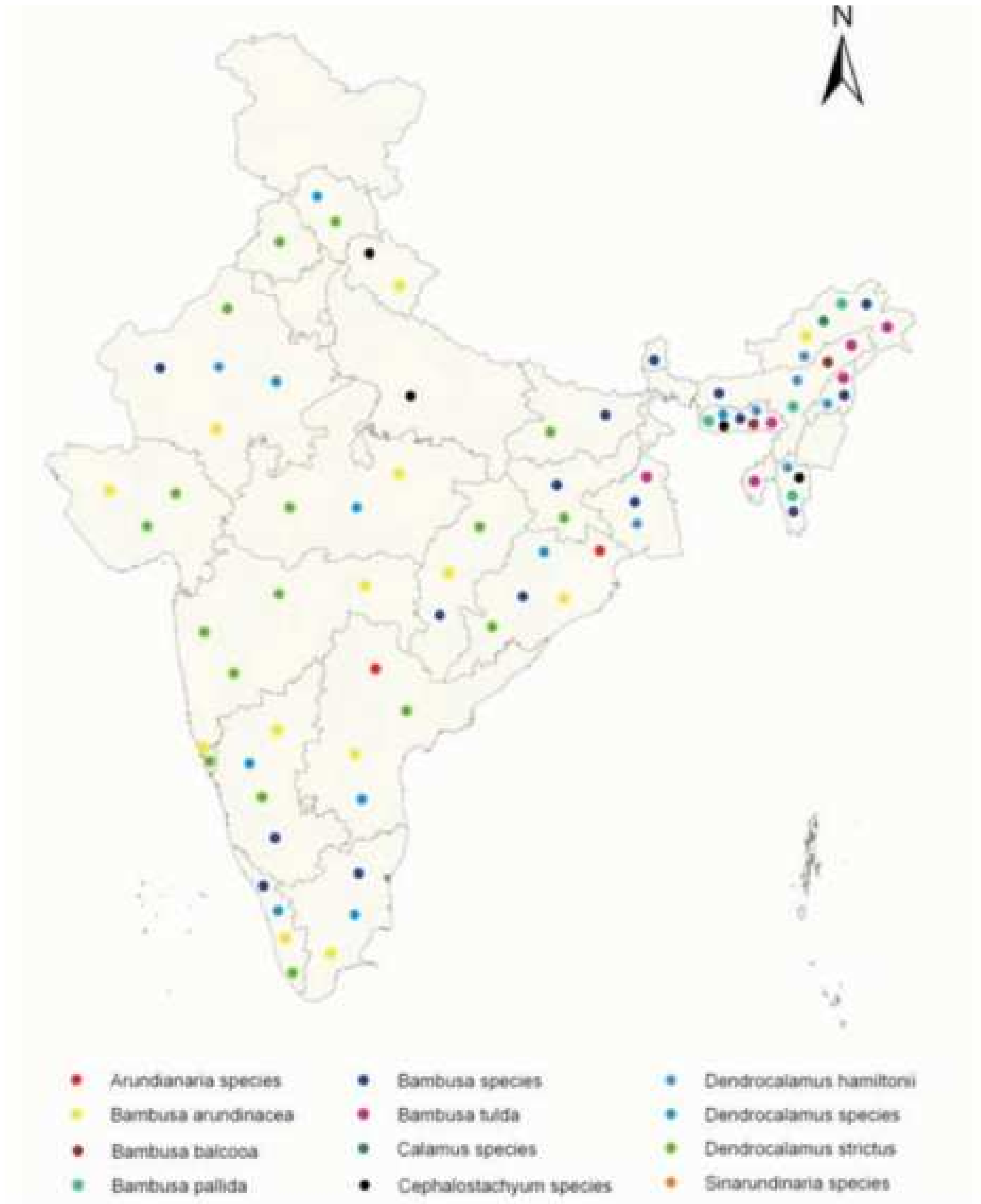

Figure 10 Distribution of different species of bamboo in India

Bamboo covers about 13% out of the total 67.5 MHa of forest area in India. Although most states have sizeable quantities, it is the North-Eastern states which account for a large share of the richest species. In India, the commonly used species for construction are Bambusa balcooa, Bambusa tulda, Bambusa bambos, Dendrocalamus giganteous, Dendrocalamus hamiltonii and Dendrocalamus asper.

16% of the total bamboo area is privately owned whereas the remaining 84% is publicly owned. Every year 13% of the total growing stock is commercially harvested (Lobovikov, 2007).

2.8 Bamboo Trade Practices in India

Until recently the Forest Ministry of India had classified bamboo as a tree despite its scientific description as a grass. Non-wood forest products, including bamboo, do not have standard classifications and are usually distinguished based on their structure (roots, leaves, bark) or the end use. Bamboo product classification is even more complicated due to its multi-functionality. Most of the economic activities related to bamboo are not recorded officially (Hazra, 2007). In the national statistics, therefore it is often difficult to separate the contribution and role of wood and bamboo fibres.

The classification ensured that under the Indian Forest Act, 1927, fallen bamboo got classified as timber and remained under the firm control of the forest authority which harvested and sold it to the industry. "The tribals got a pittance on some occasions even as the industry got bamboo at low rates over long lease periods" (Vyawahare, 2009).

As regards the private forests or private plantations, the state laws, if any, governed the harvesting of bamboo. Prior to the harvesting or felling of any tree from private lands, a certificate of origin is required from the state forest department, which is issued after due inspection and according to procedures laid out in the State laws that govern private forests for the respective states. The rules so framed by the State governments can include among others, granting of licenses to persons felling or removing trees or timber or other forest-produce from such forests for the purposes of trade, and the examination of forest-produce passing out of such forests. Therefore, bamboo if included under the definition of a tree, and if treated as a forest produce even if its harvesting is from private lands would require a certificate of origin, which would then form the basis of the issuance of the transit permit (Hazra, 2007).

Most of the states in the country have their respective laws on bamboo, as prior to 1976 forest was a state subject. In the following states mentioned below, bamboo grown in captive plantations is not a forest produce and therefore the requirements of harvesting permission or permit of transporting bamboos thus grown is not required : Assam, Meghalaya, Manipur, Mizoram, Nagaland, Tripura, Arunachal Pradesh, West Bengal, Kerala, Tamil Nadu, Karnataka, Gujarat, Maharashtra, Bihar & Jharkhand, Madhya Pradesh, Chattisgarh, Uttar Pradesh & Uttaranchal (Vyawahare, 2009).

Chapter 3: Building with Bamboo – Boundary Condition for Climate

Bamboo, owing to its availability and by virtue of its nature, is a popular building material in the vernacular architecture of different communities of the world. In India and around the world bamboo is predominantly used for construction in the hot-humid climate zone. This could be attributed to two main reasons: local availability of the raw-material and the ability of the material to perform well in such a climate. The characteristics of a hot-humid climate and the properties of bamboo which makes it ideal for such a climate are discussed briefly.

Figure 11 Traditional bamboo houses in a village in North-East India

3.1Hot-Humid Climate

The diurnal variation in temperature in the hot-humid zones is very small due to the high water vapour content in the air and considerable cloud formations. Thermal mass relates to the ability of a material to store heat and release it at a later point in time is an important criteria in the design of façade elements. When a heavy thermal mass material is used in a region with a hot-humid climate, the heat which is stored in the material during the day makes its way into the indoor space when the temperatures drop during the nights. This increase in temperature further increases the already high night temperatures, making occupancy highly uncomfortable. High thermal mass is therefore undesirable in the hot and humid climates (Fry and Drew, 1982).

Bamboo, when used in small thicknesses has a very low thermal mass, which means it does not have the capacity to store any heat. Traditionally, bamboo was (is) used for the construction of the load bearing structure as well as a filling element for walls, floors and roofs. Therefore the entire structure has a very low thermal mass. Bamboo being an organic material is prone to deterioration due to moisture. Therefore adequate protection against rain is provided in the form of long eaves. These also act as shading devices which is much needed for a hot climate. Eaves made of bamboo offer the flexibility for adjustment based on the orientation of the rain and sun. Thermal comfort in hot-humid climate is mainly achieved by natural ventilation which creates a cooling effect on the skin. Plenty of ventilation prevents the accumulation of heat and moisture in the indoor space as well as within the construction. Constant exchange of air with the exterior coupled with a light weight construction that does not store any heat leads to an indoor situation that resembles the exterior climate.

Its lightness and the possibilities to control the size and type of openings based on wind, orientation of rain, or shade requirements makes bamboo a suitable building material for the hot-humid climate zone.

The local availability of the raw-material for construction (bamboo) and the tradition of building with bamboo in the hot-humid climate zones which is adequately supported by scientific theories lead to the choice for a hot-humid climate zone as a boundary condition for the climate for this design.

3.2 Hot-Humid Climate Belt of India

3.2.1 Classification according to the National Building Code of India

According to the National Building Code of India (2005), a hot-humid climate is defined as one with

- A relative humidity above 55% for a mean monthly maximum temperature of 30˚C.
- A relative humidity above 75% for a mean monthly maximum temperature of 25˚C.

3.2.2 Köppen Classification

Köppen Classification denotes a hot-humid climate zone as 'Tropical wet and dry' climate/ 'Tropical Savanna Climate. Such a zone is characterized by high temperatures throughout the year with an annual average temperature between 25˚C and 27˚C. Distinct wet and dry seasons can be identified. Mean annual precipitation varies between 75 and 150 centimeters, with most of the rainfall occurring during the summer (Schneider, S. H., et al., 2011). 'The share of diffuse radiation in the total radiation is very high due to the high humidity levels and cloud coverage' (Schütze and Willkomm, 2000).

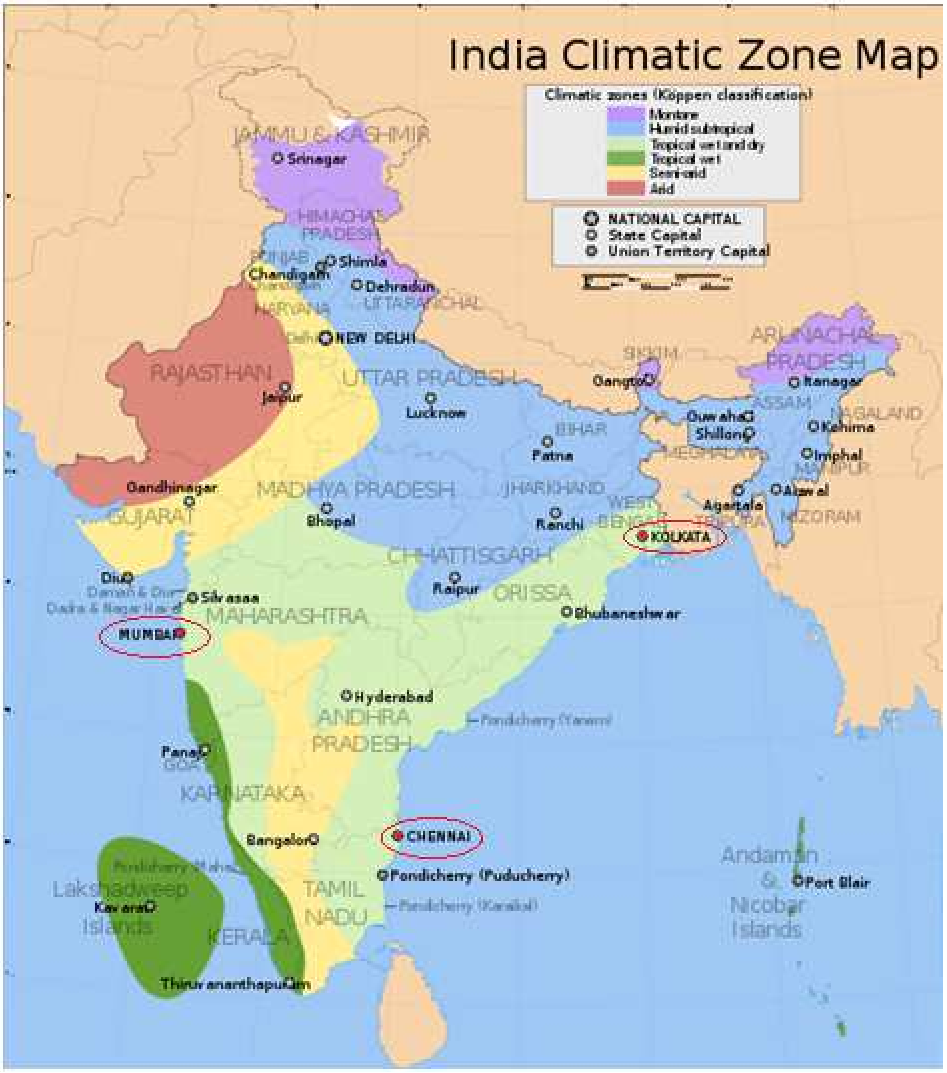

Figure 12 Climate zone map of India according to Köppen Classification [Source: mapsof.net]

Since the research focuses on the design of a suitable façade for an urban region, urban locations in the hot-humid zone of India are considered. Three major metropolitan cities of the country fall under this climate belt: Mumbai, Chennai and Kolkata (Figure 12). The local climate, rainfall patterns and the physical properties of the outdoor space such as the air quality, noise levels were briefly studied.

Although technically all three cities are classified under the hot-humid belt, there are some significant differences in terms of the climate- particularly the range of the dry bulb temperatures, the amount and intensity of rainfall and the wind patterns.
Some observations include:

- The average high temperatures of Mumbai are much lower than Chennai or Kolkata, however it also remains almost constant throughout the year.
- The monsoon season in Mumbai is much more severe (accompanied by high winds).

- Wind directions for Chennai are quite erratic. Kolkata has much lower wind speeds compared to the other two with also a relatively large calm wind period.

3.3 Ambient Air Quality in the three cities

Pollution is a major concern in all the three cities that have been considered. Sulphur dioxide, oxides of Nitrogen and suspended particulate matter are known for causing pollution related respiratory ailments. The concentration of these pollutants in the three cities is compared with respect to the National Ambient Air Quality Standards (NAAQS) in Table 1.

From the figures in the table, it can be concluded that Chennai has a reasonably better air quality when compared to that of Kolkata and Mumbai. The air quality is of importance especially for buildings which are free-running. For the initial calculations, the climate of Chennai is chosen as a boundary condition, solely based on the air quality as deciding criteria. In the later chapters the findings for Chennai will be tested for the other two cities as well.

Sulphur dioxide (SO_2) Concentration (µg/m3)											
City	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2008(P)	NAAQS
Chennai	21.7	8.1	15.9	12.6	11.9	12.5	17	19.9	15	12.2	9.5	60
Kolkata	35.7	21.3	0	34.3	44.5	17.4	18	11.4	17	9.33	7.7	
Mumbai	31.1	18	25.1	11.5	14.9	12.1	16	9.07	8	6.67	8.7	

Oxides of Nitrogen (NO_x) Concentration (µg/m3)												
City	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2008(P)	NAAQS
Chennai	17.5	9	13	16.7	10.7	14.4	18	18.4	26	16.8	15.4	60
Kolkata	29.9	29.3	0	32	30.5	34.8	74	81.7	71	59.7	64.0	
Mumbai	64.2	35.3	34.3	19.5	29.6	25.5	23	17.4	21	18.3	39.3	

Suspended Particulate Matter (SPM) Concentration (µg/m3)												
City	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2008(P)	NAAQS
Chennai	127	115	107	127	88	92	98	132	155	136	142	140
Kolkata	354	498	0	279	308	315	251	256	251	266	225	
Mumbai	210	213	298	187	221	252	231	225	224	247	260	

Respirable Suspended Particulate Matter (RSPM) Concentration (µg/m3)								
City	1999	2000	2001	2002	2003	2004	2008(P)	NAAQS
Chennai	71.7	65	77.6	74.8	86	60	63	60
Kolkata	140	145	117	128	121	134	103	
Mumbai	115	107	67.2	68.7	70	78	127	

(P: Provisional)

Table 1 Ambient Air Quality Standards of Chennai, Mumbai and Kolkata

The weather pattern of Chennai is discussed in detail in this section. Detailed weather description of the other two cities is given in appendix B. The source is based on ISHRAE Weather Data and Climate Consultant was used to generate the graphs for visual understanding.

3.4 Climate Description of Chennai

Chennai (also known as Madras as named during the colonial era), is located on the South-Eastern coast of India and is the capital city of the state of Tamil Nadu. The city is home to 6.5 million people, ranked the 6th most populous city in India. It has a population density of 26,702/km^2 which is roughly 21 times that of the province of South-Holland- 1227/km^2 and 11 times that of the city Amsterdam- 2412/ km^2 (CBS, 2012). The city boasts a long and beautiful coastline with several natural beaches including the Marina beach which is the world's second longest urban beach.

The weather in Chennai is hot and humid for most part of the year. Extreme variation in seasonal temperature is prevented due to its location on the thermal equator and the proximity to the coast. The hottest part of the year is late May to early June, popularly known as 'Agni Nakshatram' (which literally translates to "fire star") in the region. The temperatures during this time of the year is around 35-40 °C during the day and around 20-32°C during the nights. The coolest part of the year is January, with day and night temperatures in the range of 25-28 °C and 16 -20 °C respectively (Figure 13).

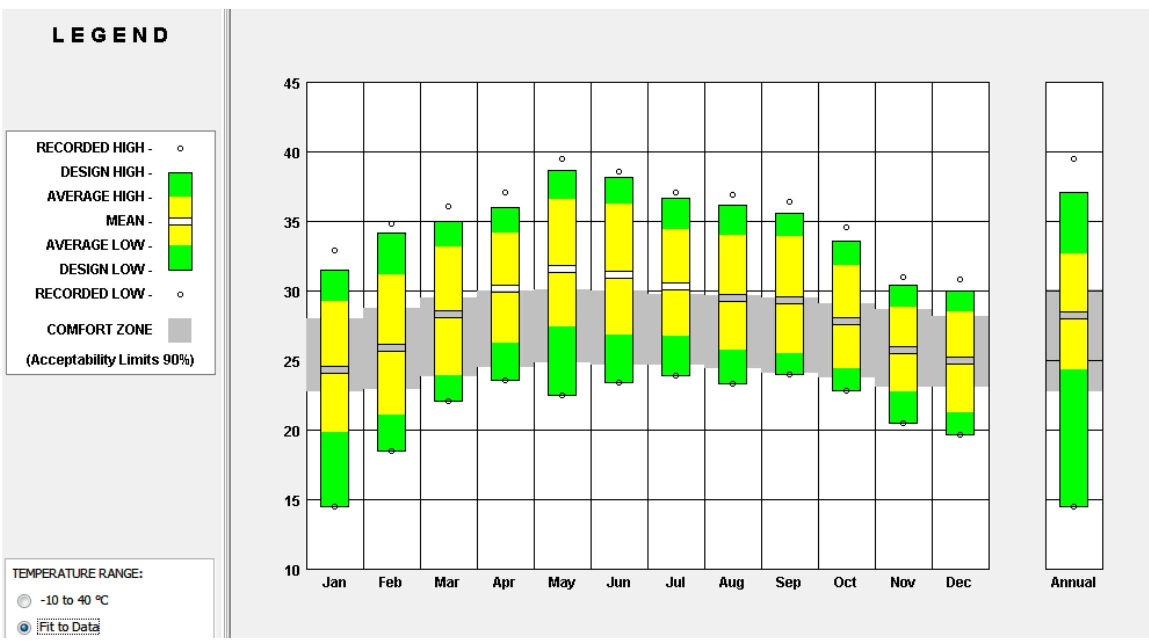

Figure 13 Annual Temperature Distribution of Chennai [Source: Climate Consultant]

The grey region in the diagram, 'Comfort Zone' is calculated according to the Adaptive Thermal Comfort Model in ASHRAE Standard 55-2004. In naturally ventilated spaces where occupants can open and close windows, their thermal response will depend in part on the outdoor climate, and may have a wider comfort range than in buildings with centralized HVAC systems. This model assumes occupants adapt their clothing to thermal conditions, and are sedentary (1.0 to 1.3 met). The model is particularly used when there is no mechanical cooling/ heating system.

The relative humidity is high throughout the year- with values higher than 80% during the nights and early hours of the day. This is also the reason behind the considerably low dip in the night time temperatures. During the day, the relative humidity is around 40-60%. For a few hours in the hottest part of the year, it drops below 40% resulting in air that is not only warm but also relatively dry. For some days in the winter, relative humidity is constantly higher than 60%, even during the day (Figure 14).

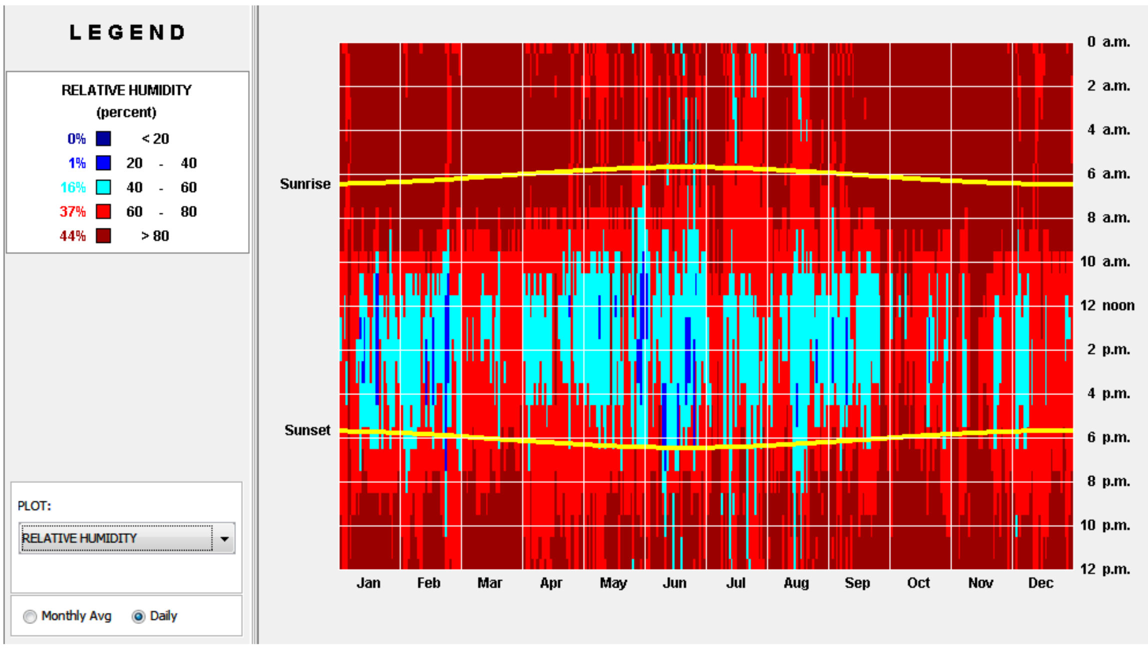

Figure 14 Annual Relative Humidity Distribution of Chennai [Source: Climate Consultant]

The average annual rainfall is about 1400 mm (Indian Meteorological Department, Chennai). The monsoon season in the region is from mid-October to mid-December and is mainly caused by the North-East monsoon winds. The South-West monsoon causes mild to heavy summer showers in the months of June and July. Apart from the regular rains, the effect of cyclones occurring at the Bay of Bengal is often felt in the city (Figure 15).

25 years average (1982-2006)

Months	Av. Annual Rainfall (mm)	Rainy Days
Jan	27.0	1.4
Feb	26.4	0.8
Mar	3.6	0.3
Apr	11.9	0.8
May	51.6	2.0
Jun	85.7	3.7
Jul	106.9	6.8
Aug	120.3	7.7
Sep	151.0	7.3
Oct	268.1	10.5
Nov	512.5	11.3
Dec	184.8	6.0
Total	**1549.9**	**58.6**

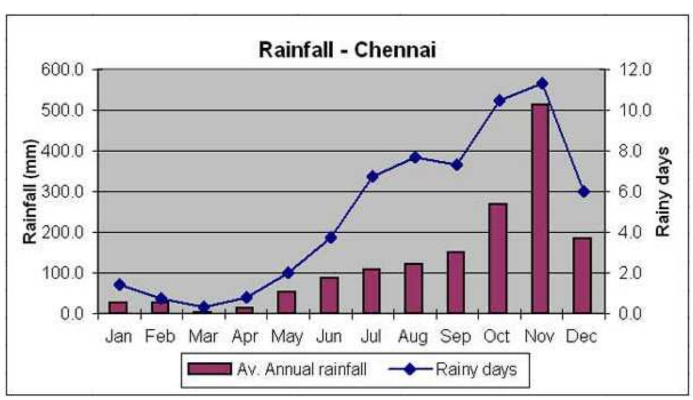

Figure 15 Annual Rainfall Distribution of Chennai

Prevailing winds in Chennai are usually South-Westerly between March and October and North-Easterly during the rest of the year. The predominant wind direction is along a certain direction for less than 50% of the year. Roughly calculating the percentage duration that a wind is oriented along a particular direction indicated that for approximately 42% of the year, the wind is North-Westerly. The direction is South-Easterly, South-Westerly and North-Westerly for 22.8%, 23.5% and 11.6% of the year respectively (Figure 16). Wind rose diagrams for the individual months are given in Appendix B.

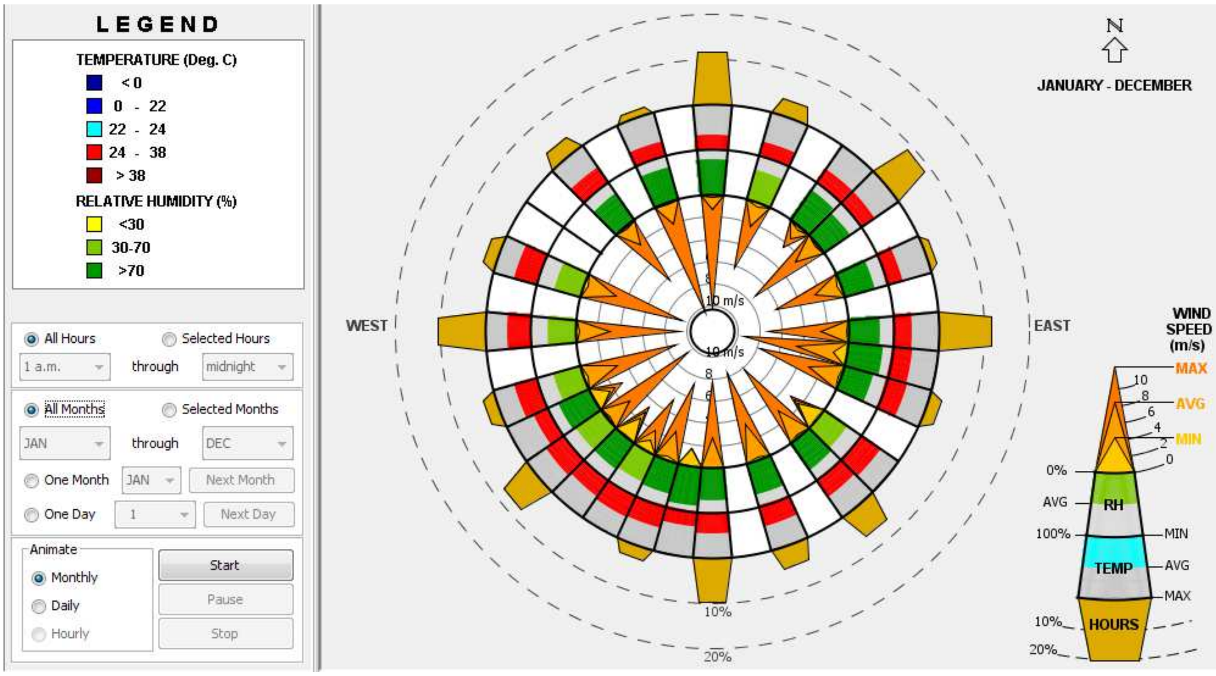

Figure 16 Annual Windrose Diagram of Chennai [Source: Climate Consultant]

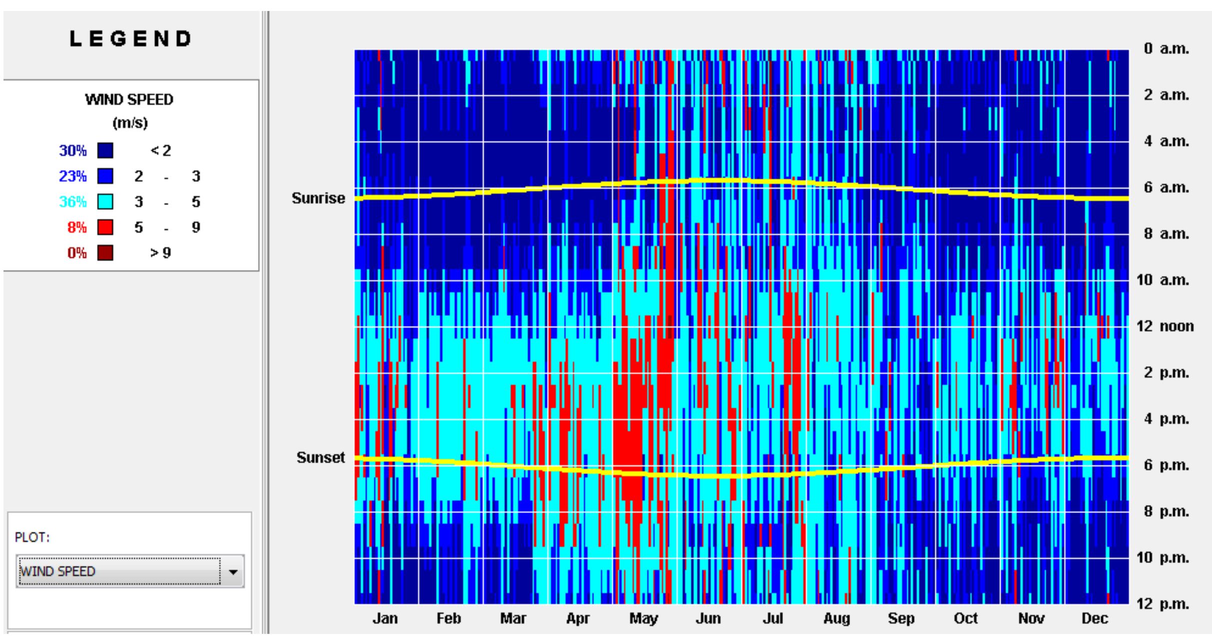

Figure 17 Annual Wind Speed Distribution of Chennai [Source: Climate Consultant]

For about 30% of the year the wind speed is lower than 2m/s. Wind speeds are usually high during the day and subside at the night. However, during the summer, the wind speeds are reasonably high during the night as well. During the afternoon hours in the summer when the outdoor temperatures are very high, there is some relief due to the quite high wind speeds (Figure 17).

The psychometric chart[1] for adaptive comfort indicates that ventilation can be an effective strategy to achieve thermal comfort for 49.2% of the year. The range of dry bulb temperature considered for the calculation here is between 23 - 30˚C. This is often considered to be an underestimation as research has shown that comfort can be achieved at an even wider range of temperatures. More about adaptive thermal comfort will be discussed in the later chapters (Figure 18).

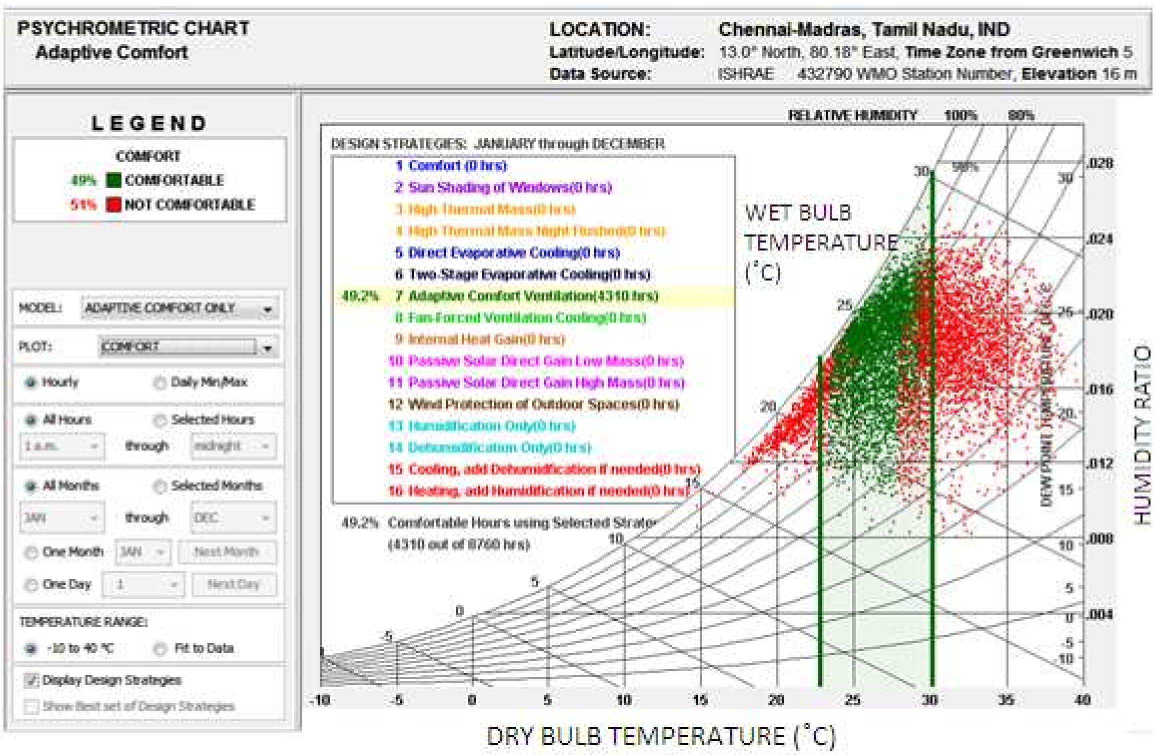

Figure 18 Psychometric Chart for Adaptive Comfort: Chennai

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[1] The Psychrometric Chart is an example of how three different attributes of the climate (Dry Bulb Temperature, Wet Bulb Temperature and Relative Humidity) can be displayed concurrently to show if humans will be comfortable in spaces with these characteristics. More importantly it can also be used to show how to design buildings envelopes that can modify or filter these external climate conditions to create comfortable indoor environments.

Chapter 4 Passive Measures for Building in a Hot-Humid Climate

"As the seasonal climatic variations in warm-wet regions are very slight, the physiological thermal requirements, and hence the building characteristics necessary to fulfill them, are similar for the whole year" (Givoni, 1974). As discussed earlier, high thermal mass can accumulate heat and therefore should be avoided. Continuous ventilation accompanied by high air velocity can avoid discomfort due to the high humid environment and is also instrumental in facilitating sweat evaporation. All design measures in hot-humid climate should therefore revolve around minimizing the heat gains and maximizing ventilation.

4.1 Building Orientation and Shape

The layout of buildings in a hot-humid climate should be in such a way that it maximizes the potential for ventilation within the building. With this as a design basis, a spread out building enables better natural cross ventilation than a compact one.

The orientation of the building, again should ensure ample ventilation possibilities. Oblique wind at angles between 30 and 120 degrees to the wall provides effective cross ventilation if openings are provided in the windward as well as the leeward walls (Givoni, 1974).

4.2 Size of Openings

The size and location of openings is crucial in deciding the effect of ventilation within the building. Large openings in all walls can provide effective ventilation however it has the risk of introducing unnecessary solar loads. For cross-ventilation to be effective the ratio of the areas of the openings is important. If the leeward opening (suction side) is much bigger than or equal to the windward opening, air will be continuously drawn from the building. This in turn brings fresh air from the outside. Continuous air circulation can hence be achieved. The size and the distribution of the openings will be discussed in detail in the later chapters.

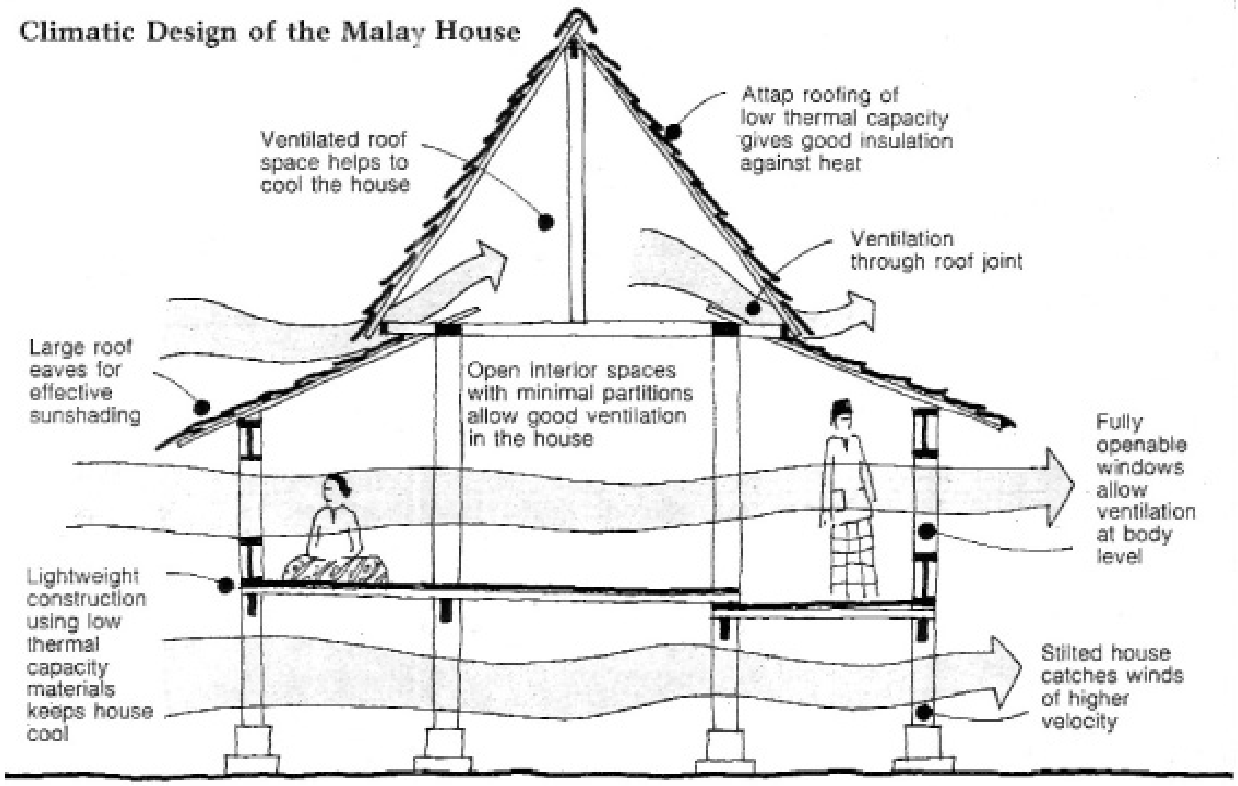


Figure 19 Bioclimatic design of a typical traditional Malay dwelling [Yuan, 1987]

4.3 Choice of Materials and Thermal Mass

The effect of thermal mass and the need for a 'light' construction has already been discussed. However, there are some contradictory theories to this finding. In a study carried out by Givoni (1994), he was able to demonstrate that even when the buildings are continuously ventilated thermal mass can significantly lower the indoor maximum temperatures during the day. In order to lower the night time temperatures he suggests the use of an exhaust fan to promote ventilation. By doing so, indoor temperatures close to the outdoors minimum can be attained even in a high mass building.

This is particularly important in the case of buildings which will be occupied throughout the day. For example, high evening/ night time temperatures in residential buildings is less acceptable than in office or school buildings.

Givoni (1994) also observed that in a high thermal mass building, "the depression of the indoor maximum below the outdoor's increased as the days became hotter." That is a high thermal mass proved to be particularly effective during the hotter periods of the year. Although the type of floors and roofs also contribute to the thermal mass to a large extent, it is not in the scope of the current work. In the context of facades, thermal mass is crucial and therefore it will be discussed in more depth in the following chapters.

4.4 Adiabatic cooling

Adiabatic cooling or evaporative cooling refers to the cooling effect created when heat from the surrounding air is used to evaporate water. The human skin cools itself by the same phenomenon. According to Oliver (1997) evaporation of 0.5g of water can cool a cubic meter of dry air by 1K.

In India, water is often stored in unglazed vessels, often made of hygroscopic materials such as earth or clay. When the moisture from the surface of the vessels evaporate, the water contained in the vessels cool. Such vessels are often placed near openings to cool the incoming air by convection. In Egypt and the middle-East, meshed window coverings made of palm rods are wetted to create a cooling effect. Adiabatic cooling is effective only when the relative humidity of the ambient air is not too high as air that is already quite humid will not have the capacity to hold additional moisture. Further, saturated air when in contact with a colder surface can cause condensation. In hot-humid regions, adiabatic cooling can be effective during the day time hours when the relative humidity is usually not as high as that during the nights or early mornings.

4.5 Solar Heat Radiation

Appropriate shading devices should be provided for openings to protect against direct solar radiation. Shading devices in a horizontal orientation works well for the North and South façade, whereas vertical shading devices are more effective in the case of East and West façades. Presence of overhangs over the opaque surfaces reduces the level of radiation and the eventual heat transmission through the opaque elements. Vegetation can be used to reduce the effect of solar intensity on a building, but it also has the disadvantage of blocking the ventilation or lowering the wind speed.

Among the principles discussed above, thermal mass, and the size and orientation of the openings in the façade are factors which are partly governed by the façade design. Solar heat radiation can be controlled by shading the façade appropriately. These principles will be the starting point of the façade design.

Chapter 5: The Facade

The façade is one of the most important components of a building. Not only does it give an identity to a building but it is also plays the vital role of acting as an interface between the interior space and the exterior. Protection against weather conditions (sun, rain, wind, snow), possibilities for exchange of views towards the exterior, means to ample daylight but preventing glare, acting as a sound barrier against the outdoor hullabaloo, etc. are some of the roles played by the façade. These are all crucial in ensuring the wellbeing of the users of the building. The façade therefore determines how someone feels about a building from the outside as well as a whole living experience within a building.

The complexity of the requirements to be fulfilled by the façade is well conveyed in the form of a sketch by Knaack et.al. (2007) (Figure 20).

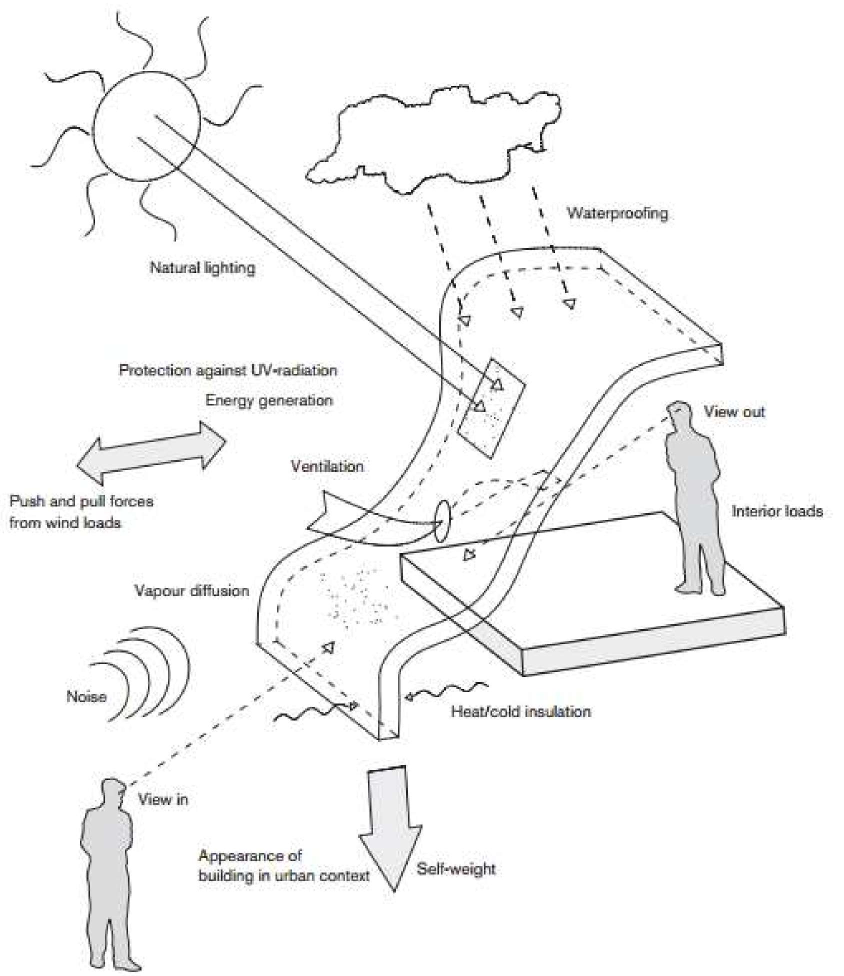


Figure 20 Requirements to be met by the façade [Knaack et al., 2007]

5.1 Shelter

The façade completes a 'shelter', in the sense that, if not for a good façade, appropriate protection against the natural forces such as the sun, rain and wind will not be possible. The inhabitants and their property also need to be protected against dangers such as fire or from burglars. Apart from these, the façade should also act as a barrier against the entry of insects and dust.

5.2 Structural Factors

Structurally, a façade should be able to effectively handle loads that it is subjected to. These mainly include its own self weight and lateral loads such as wind and impact loads. Other structural concerns include the ease of repair and maintenance of the façade. In case of a damage being caused to a façade element, it should be possible to repair or replace the element without much hassle.

5.3 Microclimate and Physical Comfort

Indoor operative temperature, air movement, humidity levels and light intensity are some critical parameters contributing to user comfort. The operative temperature is the temperature that is felt by the user. Apart from the air temperature, it also takes into account the Mean Radiant Temperature (MRT) of the surfaces which radiate heat towards the user (i.e. the surface temperature of the facades, the roof and the floor). The façade plays an important role in regulating the surface temperatures. Opening or closing the façade can regulate the ventilation rate, which, based on the temperature of the incoming air, has the potential to heat or cool the indoor surfaces. Optimum amount of moisture in the air is also crucial for determining comfort. Air that is too dry or too moist can cause health related problems. When moisture saturated air comes in contact with surfaces whose temperature is lower than the dew point temperature, the moisture from the air condenses. If the moisture continues to stay in the surface it may cause the formation of mold which eventually causes damage. Ventilation again can help in drying the surface moisture. Apart from these, constant supply of fresh air is needed to remove the excess carbon-di-oxide within the room.

Research has proven that daylight not only reduces the need for artificial lighting but also improves the efficiency of the occupants. Ample daylight also keeps the user more connected to the outdoor environment. Too much glare, however, can cause visual discomfort. This can be solved to some extent by shading the facades appropriately. Since the façade acts as a barrier between the exterior and the interior, it also controls the noise flow between the two spaces. Overall, the façade acts as the skin of the building, reacting to the constant changes of the external environment.

As it can be seen, some of these parameters are often in conflict with each other. What works during the day, might not work during the night. What is ideal for the summer, will most often not work during the winter. Or what is best in terms of thermal comfort might be disadvantageous for acoustic/ daylight control. Therefore, the façade should function as an adaptive envelope that can constantly change itself according to the changing exterior climate as well as to suit the user's needs.

User comfort is subjective as each user perceives comfort differently. The demand for comfort levels also varies according to the function of the building. The requirements are usually strict for a hospital or a hotel, whereas it is more flexible for residential buildings or schools and colleges. The National Building Code of India provides guidelines for typical range of values for each of the parameters. These are listed below in table 2.

Microclimate and Physical Comfort	Residential		Offices		Schools/ Colleges		Hotel Guest Rooms		Hospitals- Wards	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Internal temperature	*	*	23˚C-26˚C	21˚C-23˚C	23˚C-26˚C	23˚C-24˚C	23˚C-26˚C	23˚C-24˚C	24 - 26˚C	
Relative Humidity	45 - 55%	*	50-60%	not less than 40%	50-60%	not less than 40%	50-60%	not less than 40%	45-55%	
Ventilation (No of air exchanges/ hour) - for non-air conditioned areas	Living Room 3-6; Bedrooms 2-4		6-10		5-7		2-4		6-8	
Rate of ventilation with outside air (l/s/person)- Air Conditioned Building	*		*		8l/s/person (50 persons in 100 m^2)	0.4 m^3/s (for a room volume= 100*3.6 m^3	15 l/s/person (Independent of room size)	*	0.13 m^3/s (for a room volume= 100*3.6 m^3	*
Daylight and visual comfort	*		300-500-750 lux		200-300-500 lux		30-5-100 lux		30-50 (Morning-Evening); 100-150-200 (Reading)	
Acoustics-Air Borne Sound Insulation (dB)	45-50 dB		40 dB/ 20-30 dB		35 dB		*		45 dB	

Table 2 Guidelines for Microclimate and Physical Comfort for different functions [Source: National Building Code of India, 2005]

*No data is available

It must be noted that these values are standardized for all the different types of climate zones of India. Research has shown that people from different climates have different thresholds of comfort levels. For instance, a person (A) living in a hot-humid climate may in all probabilities have a higher tolerance to high temperatures than a person (B) who is exposed to a cold climate. Therefore person A might need lesser air-cooling than person B. By generalizing the values for all climates, additional measures have to be taken to meet the standard requirements even when occupants actually feel comfortable, i.e. energy has to be spent unnecessarily to improve an already comfortable situation, leading to additional operative costs which may otherwise be avoided.

Appropriate ways to standardize and measure comfort for the hot-humid climate will be discussed later in this report. The design solution will be based on this approach and will not restrict to the standard 'figures' as mentioned in the National Building Code.

5.4 Aesthetics, Cultural Aspects/ Tradition

The façade is the face of the building. It is something by which a building is remembered. A building which offers a very comfortable indoor environment, which has extraordinary structural benefits etc. but does not do well from the aesthetic point of view may not be preferred by occupants. The appearance of the façade is the selling point of a building in the market. It is for this reason that the aesthetic value of the facade is sometimes as important as its performance.

Facades should be able to connect to the traditional building culture of the region. Post industrialization and globalization, the buildings in India have started aping the West. Time tested indigenous practices are given up to 'fit in' in the international scene. In the process cities are slowly losing their identity.

Another aspect from the aesthetic perspective is the compatibility of the material of the façade with the other materials with which the façade interacts. That is, either of them should not pose a threat to the other.

5.5 Costs

The initial costs and the operational costs involved in the running of the building, including repair and maintenance decide the ultimate affordability of the façade. As discussed in the introduction chapter, the operational cost of a building is directly influenced by the efficiency of the façade in responding to the external climate.

If the expenses in developing and/or maintaining an efficient façade are high, its performance will be overlooked and it will eventually not do well in the market. On the other hand, a cheap and highly durable façade, but one that functions poorly with respect to controlling the climate might result in high operational costs. A façade which is affordable and at the same time has a good functional value is ideally preferred.

The requirements of the façade for buildings hosting different kinds of functions are compared for the above discussed criteria. Their relative performance is rated and displayed in the form of a matrix. (The darkness of the shade increases based on the level of importance.)

Façade Vs Functionality					
	Residential	**Offices**	**Schools/ Colleges**	**Hotels/ Resorts**	**Hospitals**
Shelter					
Climate: Sun, wind, rain	Flexible	Less Flexible	Less Flexible	Of high importance	Of high importance
Fire Safety	To a large extent the probability of a fire depends on the user.	Important - Although the people occupying the space will be alert, considerable damage could occur to the valuable documents/ equipments, etc.	Chances of fire are less. However, it is of importance due to the huge number of students involved. An advantage is the faster detection of fire as the occupants will be active at all times.	Chances of fire are high as it is difficult to predict or identify the activities of the occupants involved. Evacuation of people can also be a problem.	Crucial as patients are involved.
Safety against Burglary	Important factor- Thefts in apartments quite common.	Important factor- Contains Valuable documents/ equipments. Buildings are provided with tight security.	Classrooms hardly contain any valuables- not of interest to burglars as well.	Hotel Buildings are provided with tight security.	Buildings are provided with security. Generally not of interest to thieves.
Accessibility of Insects/ pests	Important	Important	Important	Important	Important
Structural Factors					
Loads - Dead load, Wind Load, Impact Load	Important	Important	A façade with poor impact resistance can be crucial particularly in a building with children.	Important	Important
Repair and Maintenance	Flexible	Less flexible- offices cannot be closed during repairs.	Less flexible- schools cannot be closed during repairs. But if not critical, repairs can be carried out during holidays.	Less flexible- Can be carried out in phases. Therefore not closing it completely.	Difficult- Cannot be closed for a certain period.

	Residential	Offices	Schools/ Colleges	Hotels/ Resorts	Hospitals
Microclimate and Physical Comfort					
Internal temperature	More flexible	Less flexible	Less flexible	Less flexible	Strict requirements
Humidity	More flexible	Less flexible	Less flexible	Less flexible	Strict requirements
Ventilation (Air change per hour)	More flexible	Less flexible	Higher air exchange rates required. Large population.	More flexible	Strict requirements
Air Quality	Important	Important	Important	Important	Crucial
Daylight and visual comfort	Important	Crucial	Crucial	Less demand	Less demand
Acoustics- External noise + Internal transmission	Important- more easily achievable if apartments are located in Residential areas.	Can be important when situated along highways/ main roads.	Flexible- generally noise producing regions. Noise has to be kept within the individual rooms.	Important	Crucial
Ease of User Control	Not a problem	Flexible to some extent- however it depends on the unanimity in everyone's preference.	Flexible to some extent- depending on everyone's preference.	Not a problem	Difficult
Aesthetics, Cultural Aspects/ Tradition					
Compatibility with other building materials	Less important- user's preference.	Important	Less important	Important- Often a landmark.	Appearance can be important.
Acceptance among people using the building	Less important- user's preference.	Important- but not in user's control.	Less important	Important	Important
Impact on the urban fabric- acceptance among neighbours	Less important	Less important	Less important	Important- Often a landmark	Can be a criteria to determine the quality of service offered.
Maintenance Costs	Can be a constraint	Can be a constraint depending on the budget allocated	Can be a constraint depending on the budget allocated	Often not a problem	Often not a problem

Table 3 Façade Vs Function Specific Demands

5.6 Choice of Function

In the previous chapter, passive design strategies for a hot-humid climate were discussed. Continuous ventilation and a light construction which does not store heat to release it during the otherwise cooler part of the day were identified as the crucial design criteria. Keeping this as a basis and being aware of the problem of housing shortage in cities, an appropriate function is narrowed upon for further study.

Based on personal observation, in India, the design requirements for residential buildings and small self-run office spaces are less strict (and more flexible) as compared to other functions. The use of air-conditioners in apartment buildings and small office spaces is common among the economically sound class, however, not popular among the weaker sections which cannot afford it. Hotels and hospitals have very high standards to meet, especially with respect to the microclimate, which might be too ambitious for a start. Residential spaces are also eliminated for this study due to the relatively complex floor plan associated with it. Open plan, small office spaces and classrooms seem to be ideal for a start.

Classrooms of schools and colleges are generally not air conditioned. Although both classrooms and office spaces will ideally be occupied only during the day, in this study the space is assumed to be in use through the day. This was a conscious decision, made considering the shortage of built space to meet the housing needs of the entire urban population. Already several of these spaces are used in the late evenings for other purposes- mostly as coaching centres for co-curricular activities. A large population still lives in the platforms. These 'platform dwellers' typically are on the move all day long and rest on the platforms during the nights. If classrooms of schools/ colleges are allowed to be occupied by these platform dwellers, their housing needs can be met with to some extent. This is complex on many levels and has several problems associated with it, but it is only a suggestion. Assuming that this is a design requirement, thermal comfort during the night also becomes important.

5.7 Façade Design Regulations according to National Building Code of India (2005)

5.7.1 Openings

For hot humid climate, the minimum area of openings of windows should be at least 1/6th of the floor area. The maximum area of openings in the façade shall not exceed 3/4th of the total area of the external wall. If a window is partly fixed, the operable area is counted.

Openings should be protected with fire resisting assemblies or enclosures having a fire resistance equal to that of the wall in which the openings are situated. Louvers where provided should have a minimum half an hour fire resistance rating.

5.7.2 Daylighting

No portion of a room shall be assumed to be lighted if it is more than 7.5 m away from the opening which is assumed to light the portion.

5.7.3 Thermal Comfort

According to studies carried out in India and abroad, the limits of thermal comfort is said to vary considerably. The thermal comfort of a person is said to lie between 25 - 30˚C with optimum condition at 27.5˚C. Apart from this, no strict thermal requirement has been specified in the National Building Code. However, there is a mention about the need for air movement for body cooling in hot-humid climate zone.

Chapter 6: Performance of Different Types of Construction

The type of construction that works best has to be identified for the particular climate. For this reason, the performance of different possible existing constructions: light/ medium/ heavy weight, with and without insulation was studied. The calculations were done using DesignBuilder [2].

6.1 Description

A simple one room building (10m * 10m * 3.6m) with a wall opening area 1/6th of the floor area was considered. According to the National Building Code, this is the minimum opening ratio that a building in a hot-humid climate should have. In this case, openings are considered on all four facades. The site location (Chennai) and the function of the building (classroom, occupied through the day) were chosen based on the boundary conditions set in the previous chapters. Opening sizes, orientation of the building, internal heat loads etc., are kept constant for this particular study as the results will only be a comparative analysis of the construction types. The building is not subjected to artificial cooling, heating or mechanical ventilation. 'Calculated Natural Ventilation' is chosen. Design Builder calculates the ventilation rates using wind and buoyancy-driven pressure and the characteristics of the openings.

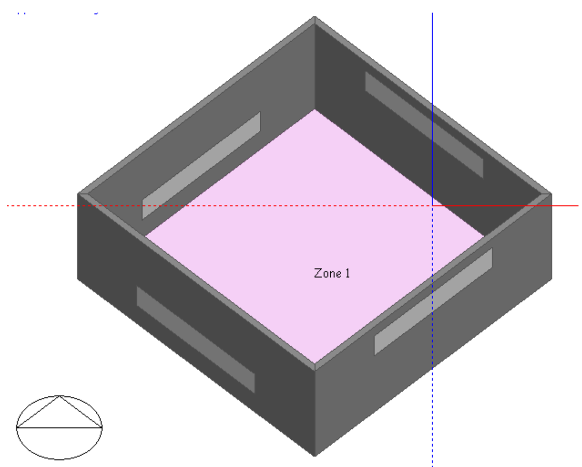


Figure 21 Test Building: Simple one zone building of dimensions 10m * 10m * 3.6m

Heat Loads Considered:

[2] DesignBuilder is considered a good tool for early-stage modelling of building designs. It provides a user-friendly modelling environment which allows the user to play with different parameters including not only the type of construction but also the kind of activity carried out within the building, the type of appliances used, the extent and duration of occupancy/ usage etc. A wide range of output data is generated based on detailed sub-hourly simulation time steps using the EnergyPlus simulation engine. This is particularly useful in understanding the cause and effects of various design decisions.

Solar Loads: DesignBuilder uses the values of solar loads which is present in the weather files.

Sensible loads of people and lighting loads are calculated based on the occupancy schedule. An occupancy rate of 2 persons/ m^2 is usually followed for classrooms. The building is assumed to be occupied throughout the year and holidays are not considered.

Sensible loads of people = 50W/m^2 = 5000W for a floor area of 100 sq.m

Lighting loads = 5W/m^2 per 100 lux. The minimum requirement is 280 lux.

Therefore total lighting loads = 5* 2.8 = 14 W/ m^2 or 1400W for a floor area of 100 m^2

Lighting loads are calculated based on the amount of daylight available and occupancy schedule.

The following different alternatives were considered for the external wall construction. The built up of the constructions are as shown in figure 34.

a) Insulated Heavy Weight Construction; U-value = 0.25 W/ m^2K
b) Insulated Light Weight Construction; U-value = 0.25 W/ m^2K
c) Uninsulated Heavy weight Construction; U-value = 1.50 W/ m^2K
d) Uninsulated Light weight Construction; U-value = 2.55 W/ m^2K
e) Uninsulated Medium weight Construction; U-value = 2.07 W/ m^2K

Figure 22 Built up of the different constructions

6.2 Observations

The week with the highest outdoor temperatures (22nd May- 29th May), lowest outdoor temperatures (22nd Dec – 29th Dec) and a week having an intermediate weather situation (22nd Sept – 29th Sept) were considered for the different constructions. The relative performance of the different constructions considered were analysed for Mean Radiant Temperature, Air Temperature and Indoor Operative Temperature. Additionally the interior and exterior surface temperature of the wall facing the South-West direction was also studied.

Thermal comfort depends on the operative temperature which is the average of the air temperature and the mean radiant temperature. The mean radiant temperature is calculated based on the interior surface temperatures of the walls, floor and ceiling which is directly dependant on the type of construction. Therefore it is good to study the variation in indoor surface temperatures through the day.

6.2.1 Summer Situation

During this period, the mean hourly outdoor dry bulb temperature ranges between 28˚C and 42˚C. The external surface temperatures of all alternatives considered are more or less the same during the day. In the night however, the surface of a light weight wall (metallic cladding) insulated/ uninsulated, cools down faster than the rest (Figure 23).

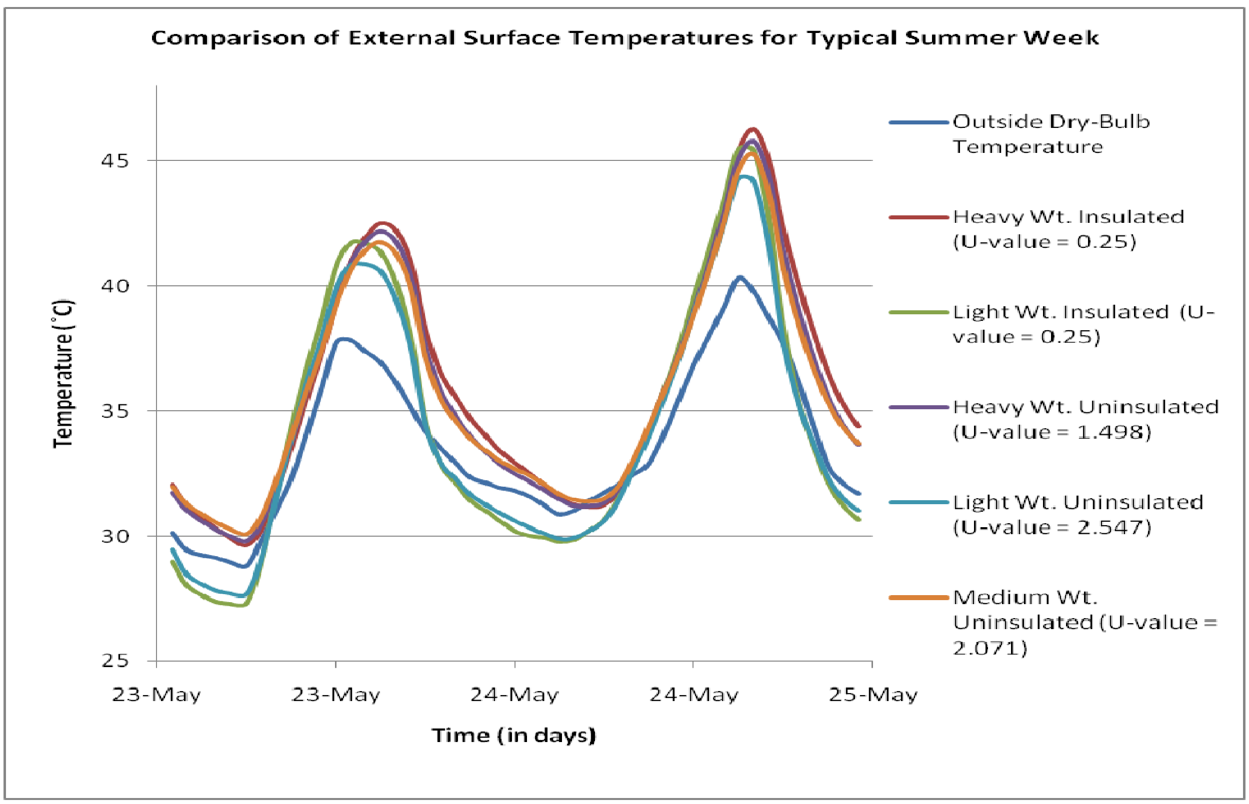


Figure 23 Comparison of Exterior Surface Temperatures- Typical Summer Week

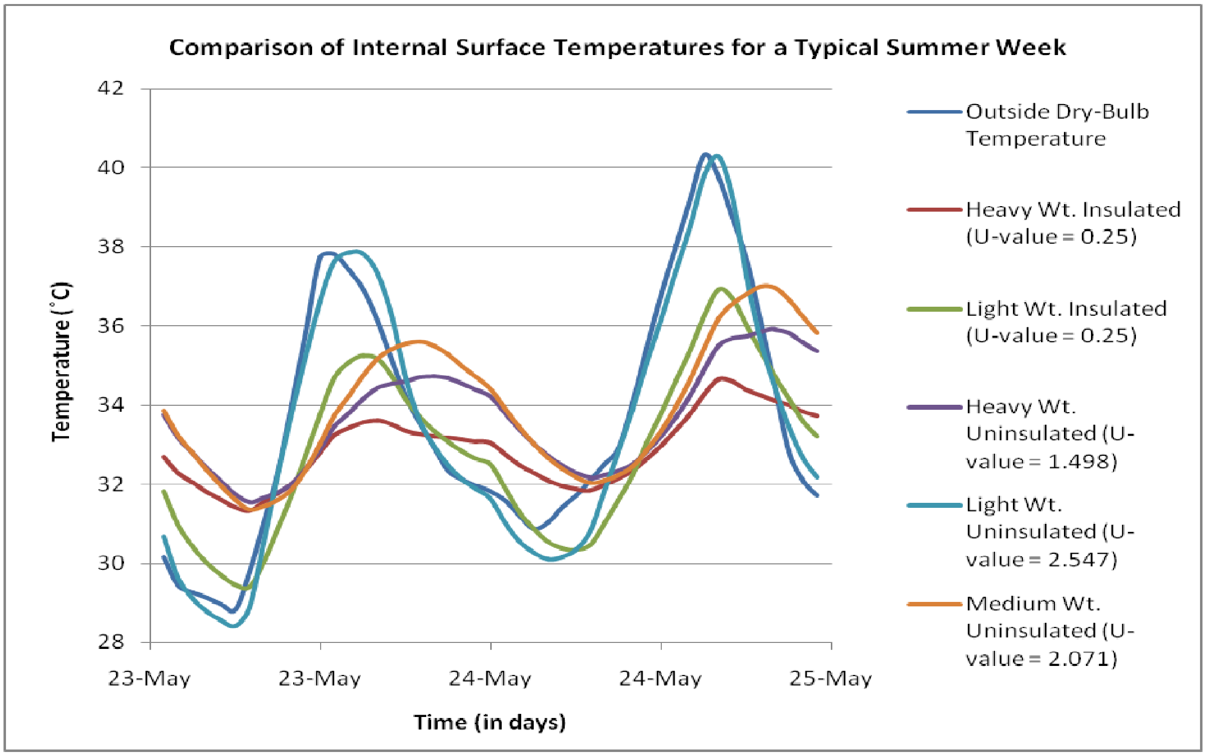


Figure 24 Comparison of Interior Surface Temperatures- Typical Summer Week

The combined effect of thermal mass and insulation value controls the heat flow through the construction, which directly affects the internal surface temperature. The internal surface temperature is highest in the case of a light weight uninsulated wall wherein it varies closely with the outdoor temperature (Figure 24). This can be attributed to two factors: low thermal mass and high U-value. Due to the low thermal mass, heat is not stored in the construction. Having a high U-value implies that there is high rate of flow of heat through the construction. During the day heat flows from the outside to the inside, whereas in the nights the heat is lost from the building to the cooler night sky. A light weight insulated wall (with a much lower U-value) however, has relatively lower temperatures during the day and relatively higher temperatures during the night. This is due to the presence of the insulation layer which lowers the heat transfer into and out of the construction. A heavy weight construction with insulation has the least interior surface temperatures during the day followed by a heavy weight uninsulated and a medium weight uninsulated construction. In the night the surface temperatures of the medium weight and heavy weight uninsulated walls are the highest. All three constructions display the effect of a thermal lag- that is the peak values of the exterior surface temperature and the interior surface temperature are obtained at a different time and this is due to the heat storage capacity of the construction.

Similar trend in behavior can be identified looking at the graphs of the mean radiant temperature and operative temperature (Figures 25 - 27).

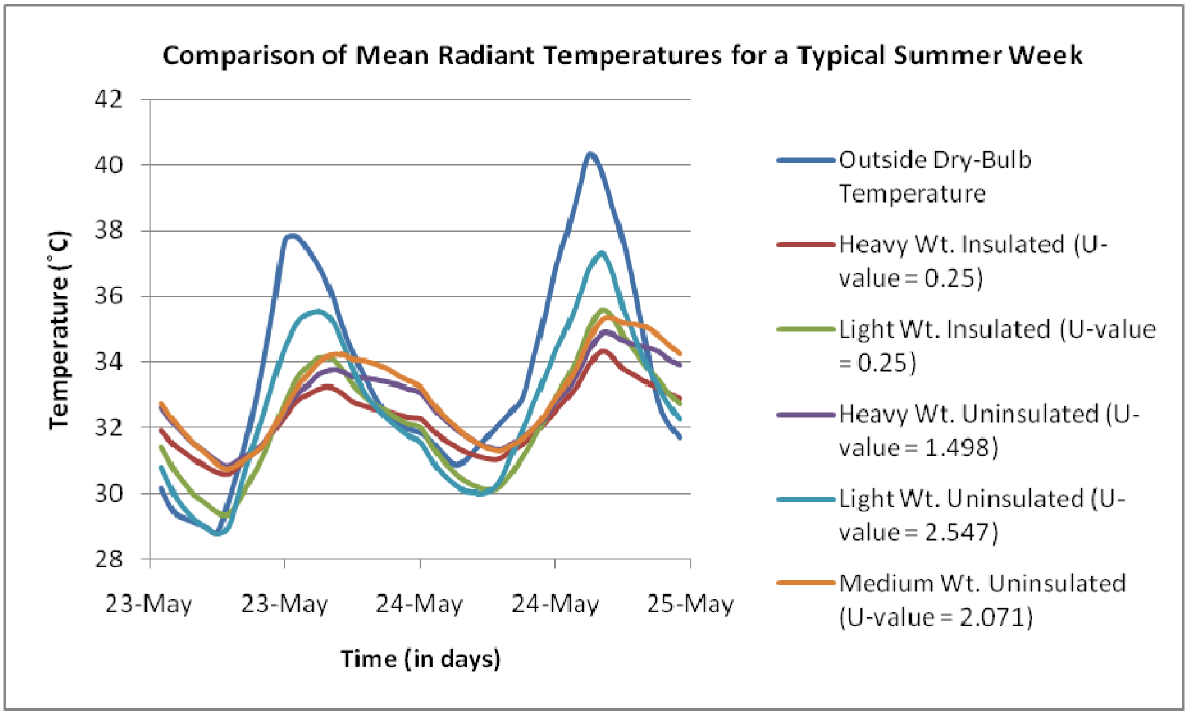


Figure 25 Comparison of Mean Radiant Temperatures- Typical Summer Week

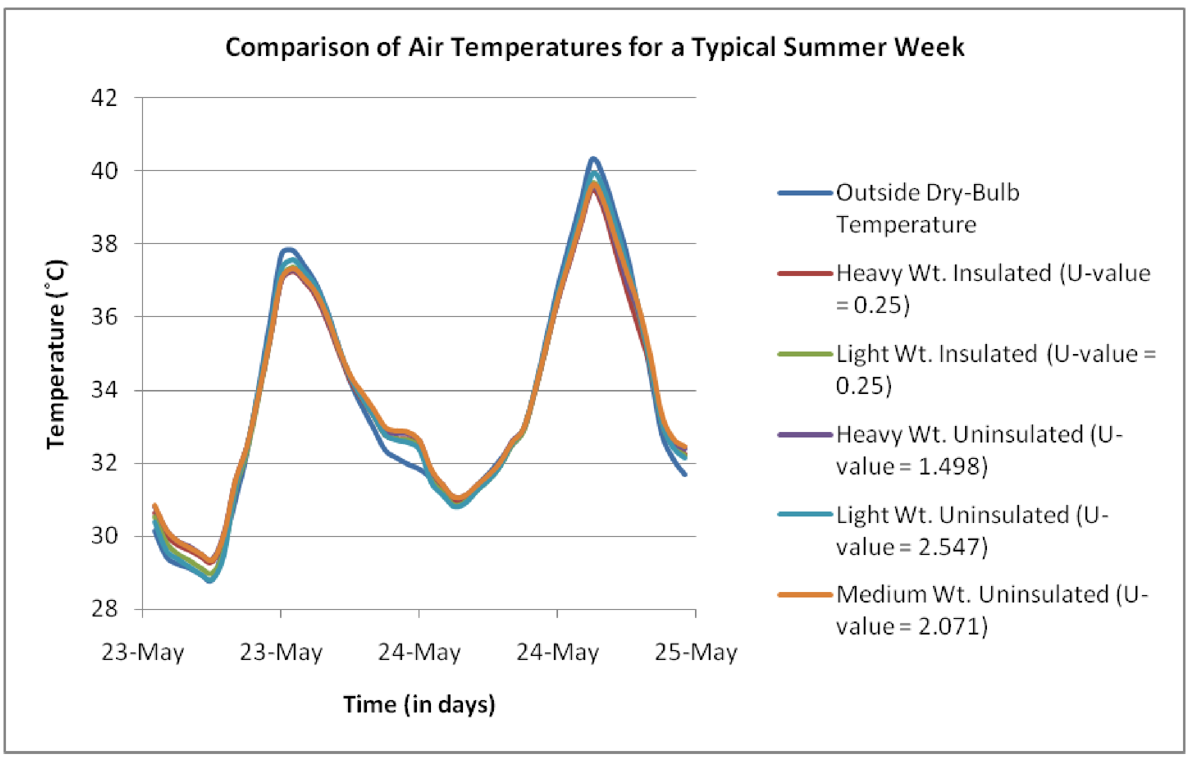


Figure 26 Comparison of Air Temperatures- Typical Summer Week

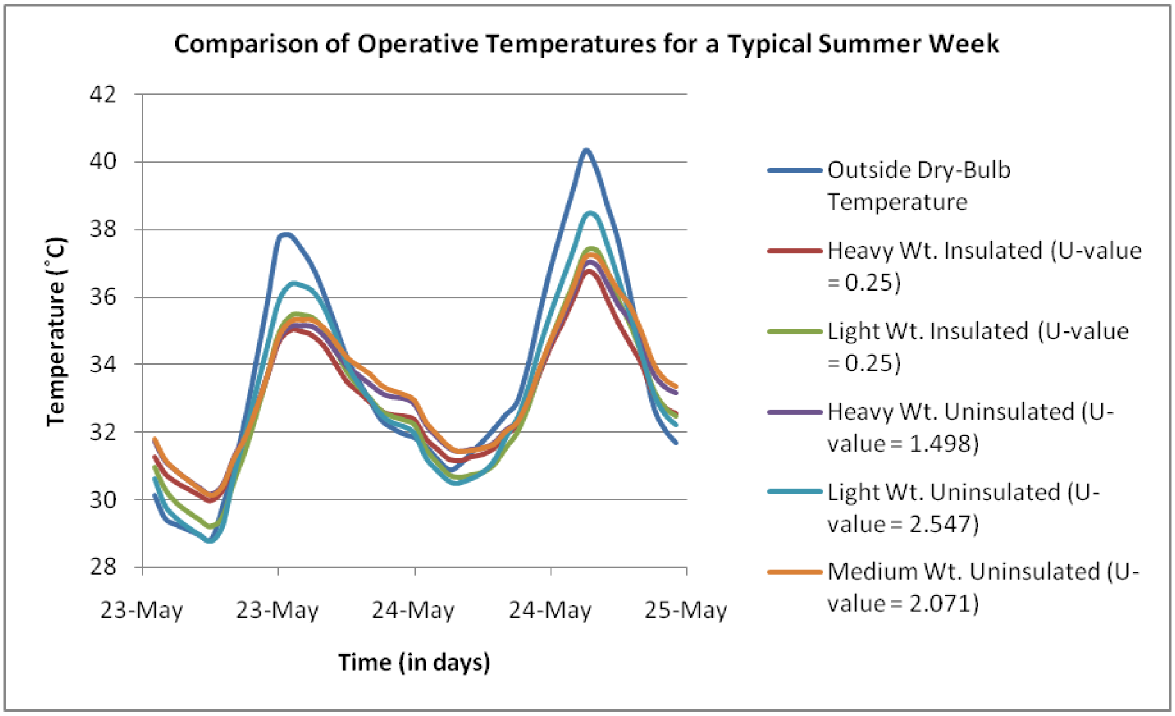


Figure 27 Comparison of Operative Temperatures- Typical Summer Week

6.2.2 Winter Situation

The relative behavior of the different constructions considered is similar to that in the summer (Figures 28 - 32). However the range of values with respect to the outdoor temperatures is different. In the winter situation, the indoor surface temperatures are for most part of the time higher than the outdoor air temperature. This can be due to a higher indoor air temperature which can cause heat flow from either sides of the construction.

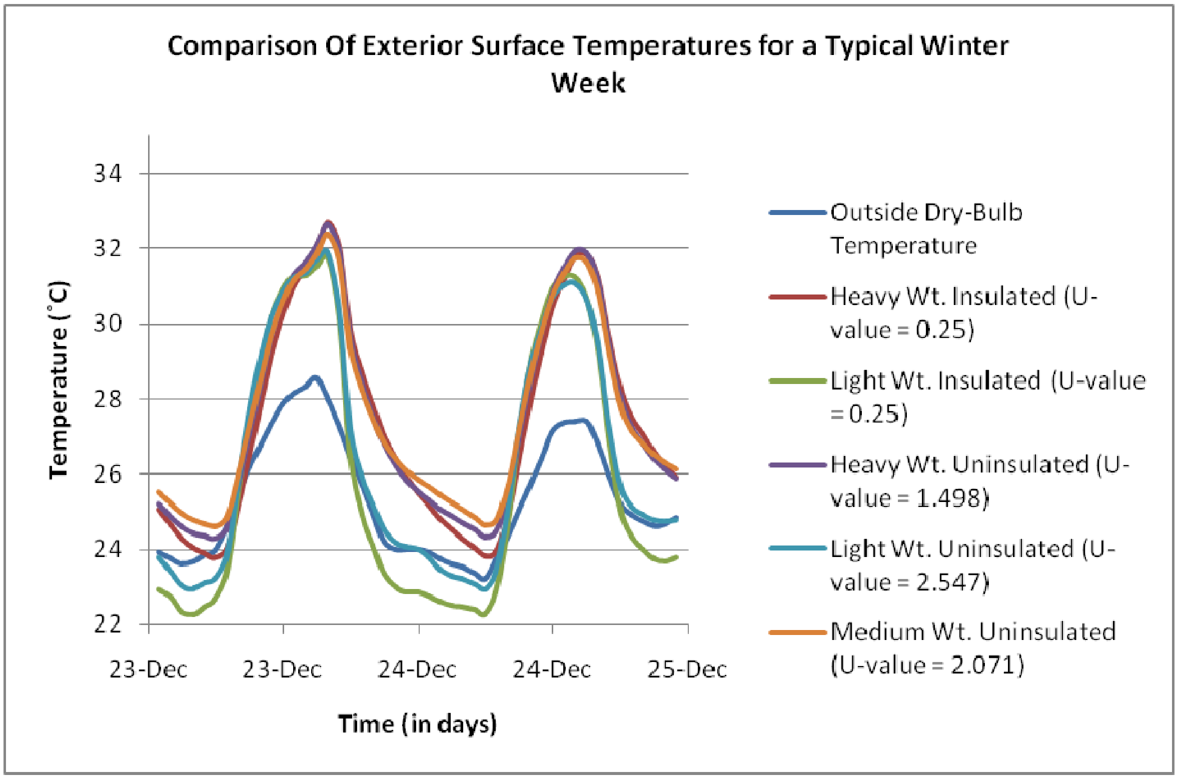


Figure 28 Comparison of Exterior Surface Temperatures- Typical Winter Week

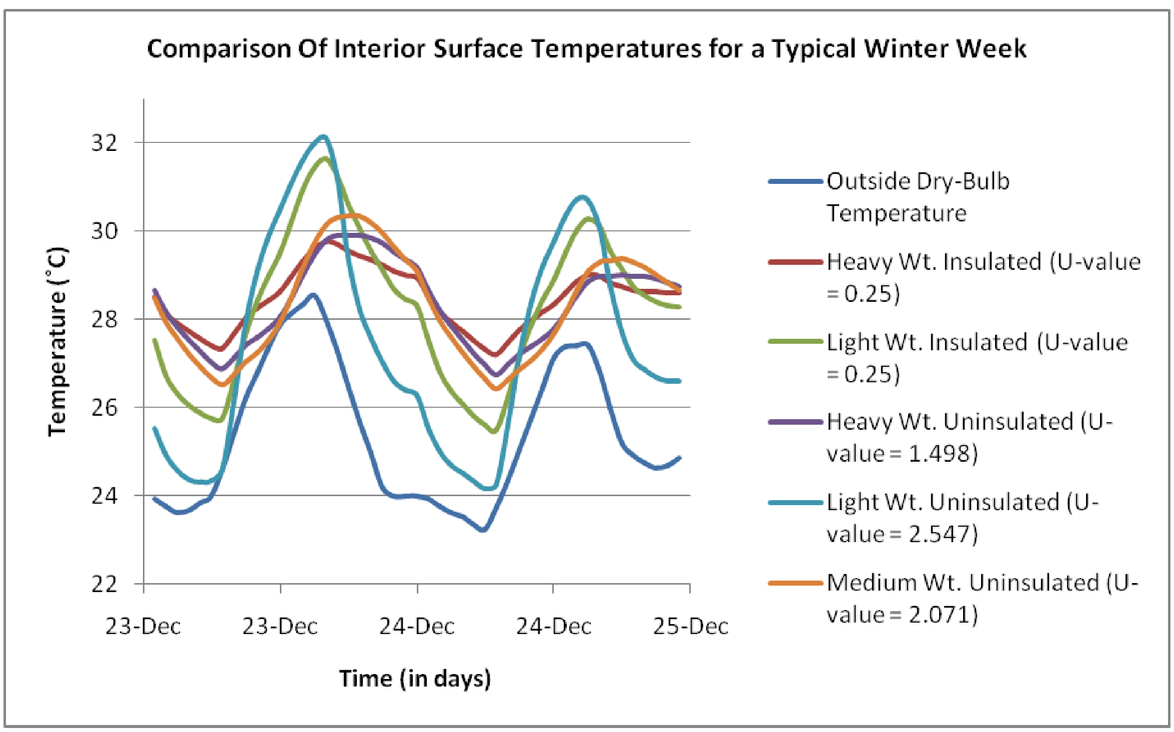


Figure 29 Comparison of Interior Surface Temperatures- Typical Winter Week

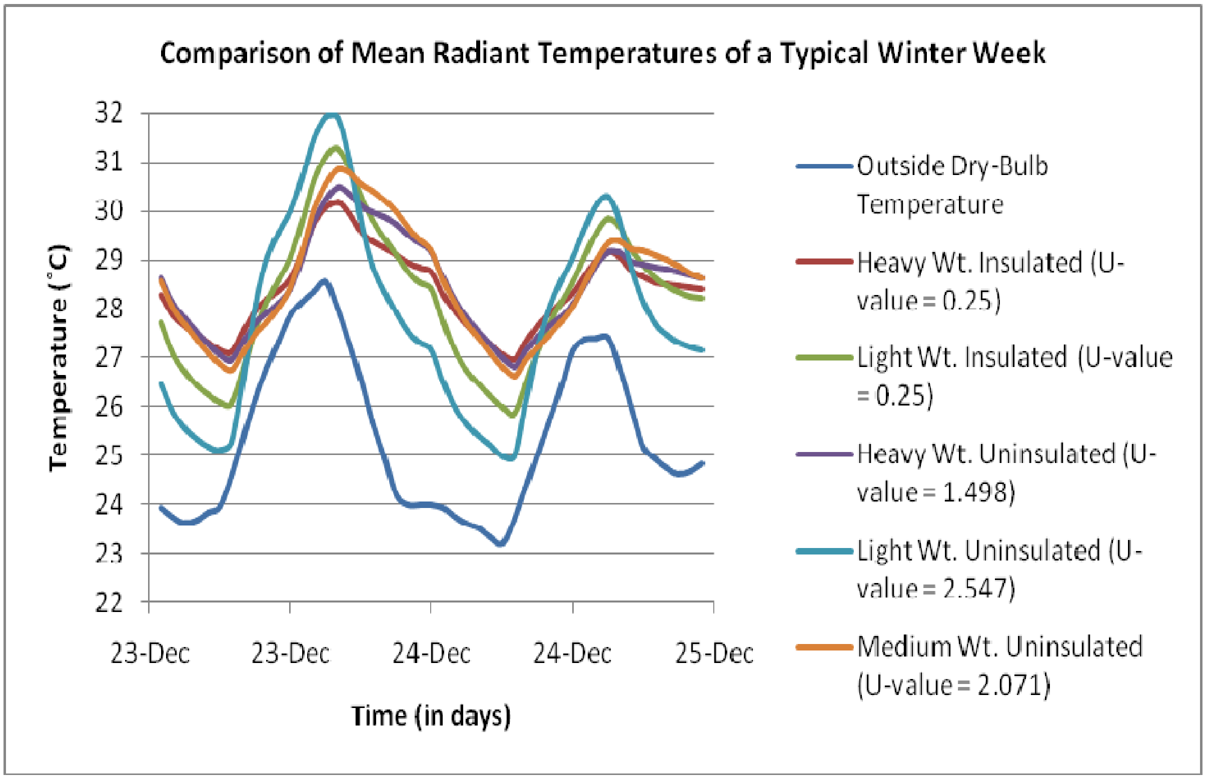


Figure 30 Comparison of Mean Radiant Temperatures- Typical Winter Week

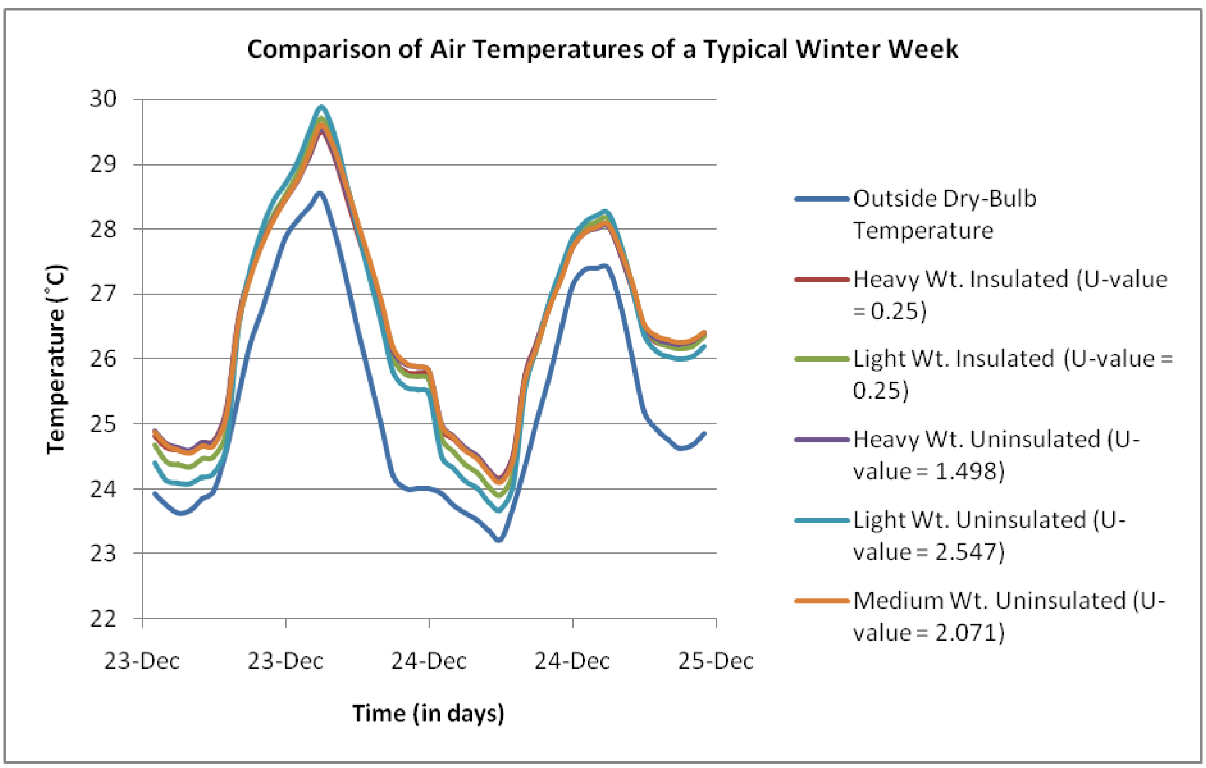


Figure 31 Comparison of Air Temperatures- Typical Winter Week

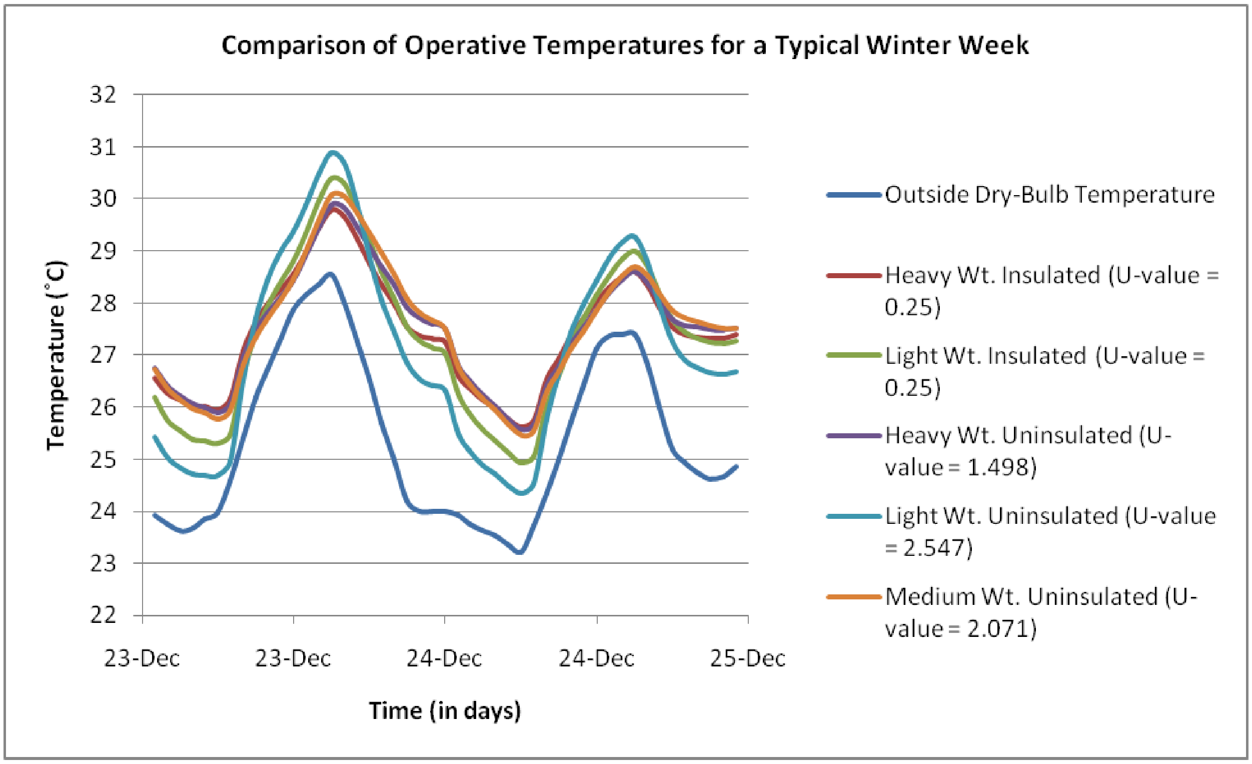


Figure 32 Comparison of Operative Temperatures- Typical Winter Week

6.2.3 Intermediate Situation

For the intermediate months as well, the trend among the different constructions is the same. However, during the day the temperature difference between the interior surfaces and the outdoor temperature is not considerably larger as in the summer situation (Figures 33 and 34). In the nights the interior surface temperature (and hence the mean radiant temperature and operative temperature) are much higher than the outdoor temperature (Figure 36). This can be attributed to the relatively cloudy skies/ moisture contentss in the air which reduces heat loss due to radiation. From the graph it can be seen that during the day, the indoor operative temperature for a construction having an external wall with a small U-value performs slightly better than the one with a higher U-value (close to the external temperature and ~2˚C lower than that obtained for a construction with a high U-value). In the absence of the solar loads this was found to be otherwise. That is, the construction with higher U-value results in an indoor temperature closer to the external temperature and that resulting from a construction with a low U- value is at least 2˚C higher than the external temperature (Figure 37).

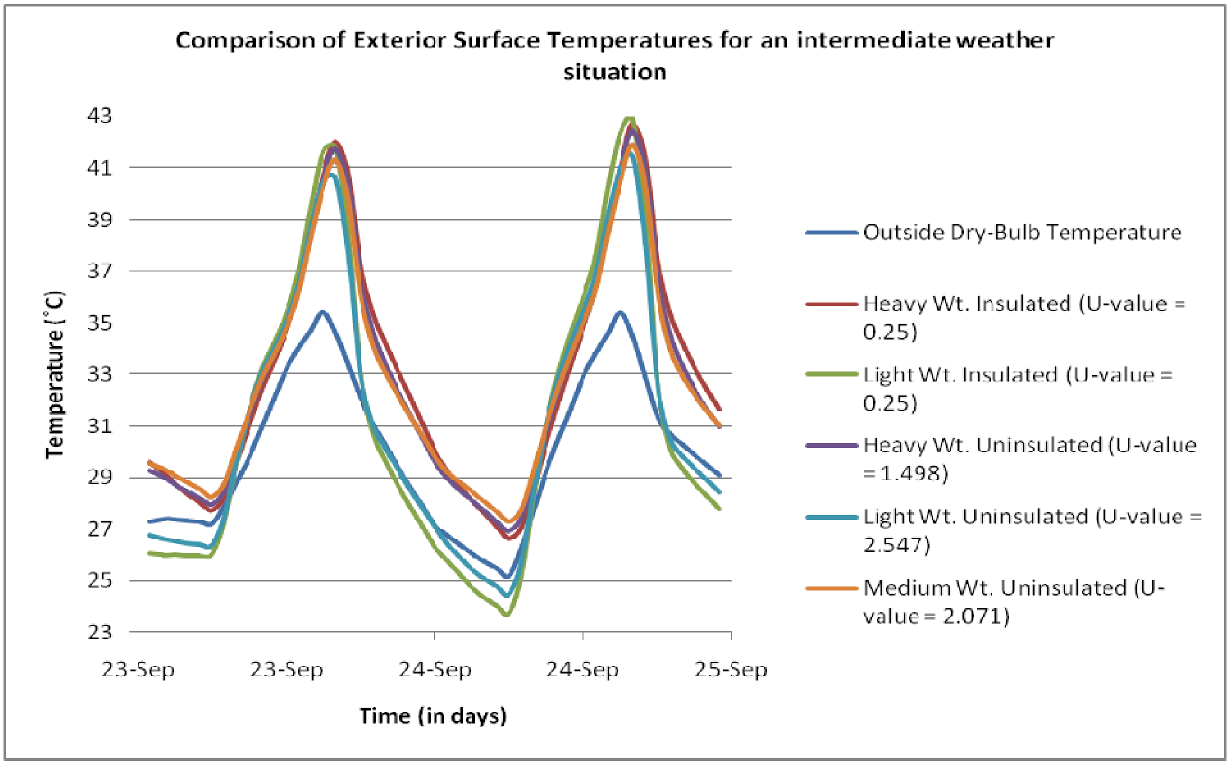


Figure 33 Comparison of Exterior Surface Temperatures- Intermediate Weather Situation

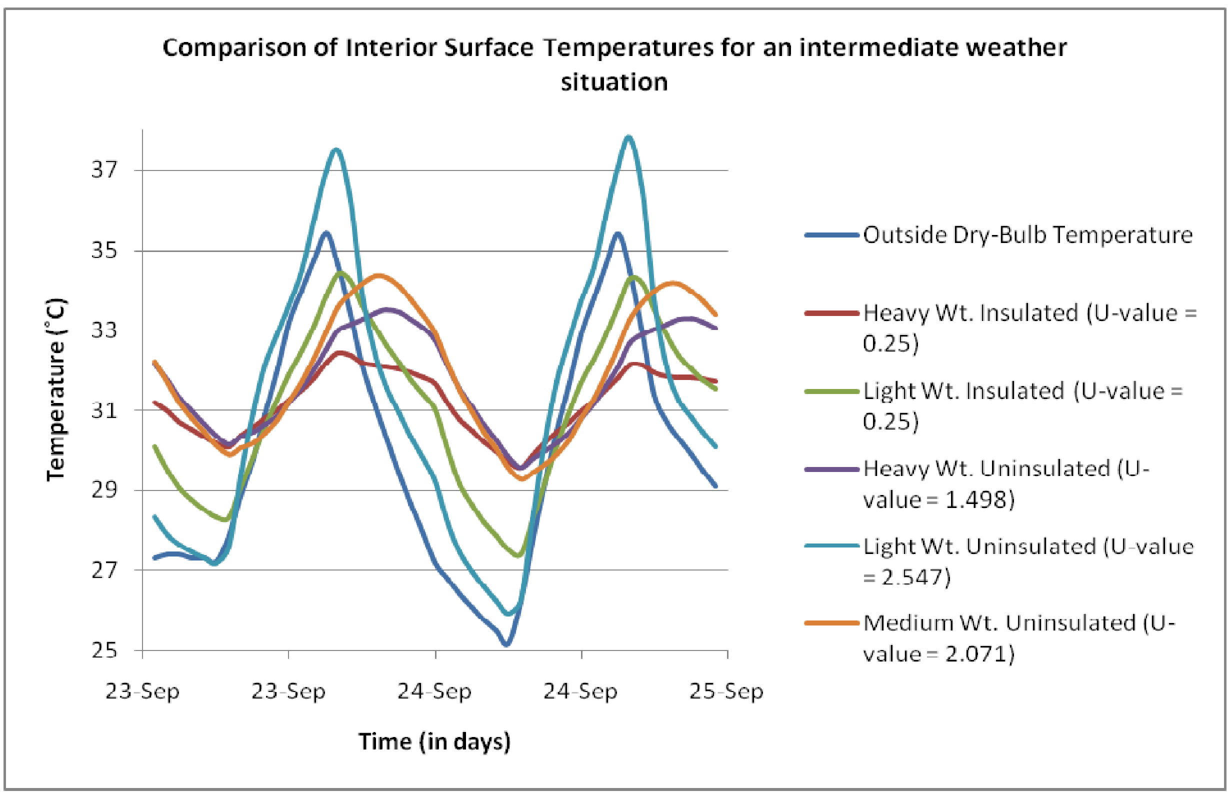


Figure 34 Comparison of Interior Surface Temperatures- Intermediate Weather Situation

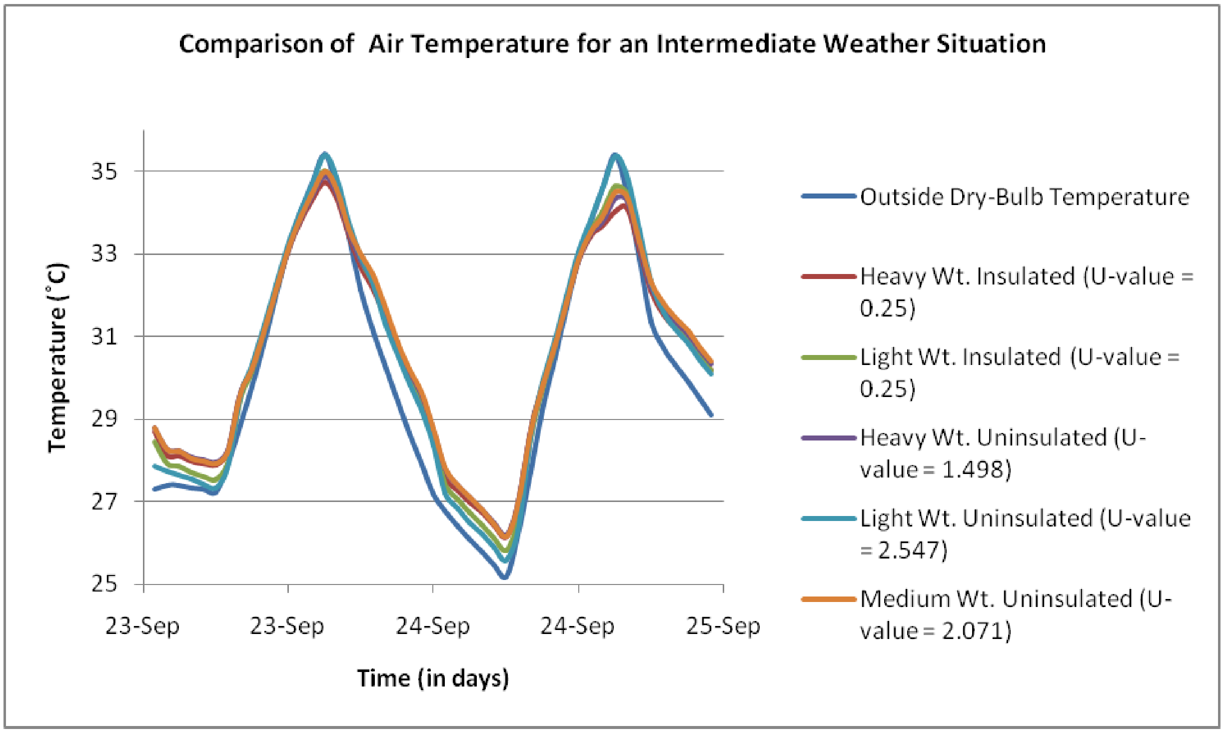


Figure 35 Comparison of Air Temperatures- Intermediate Weather Situation

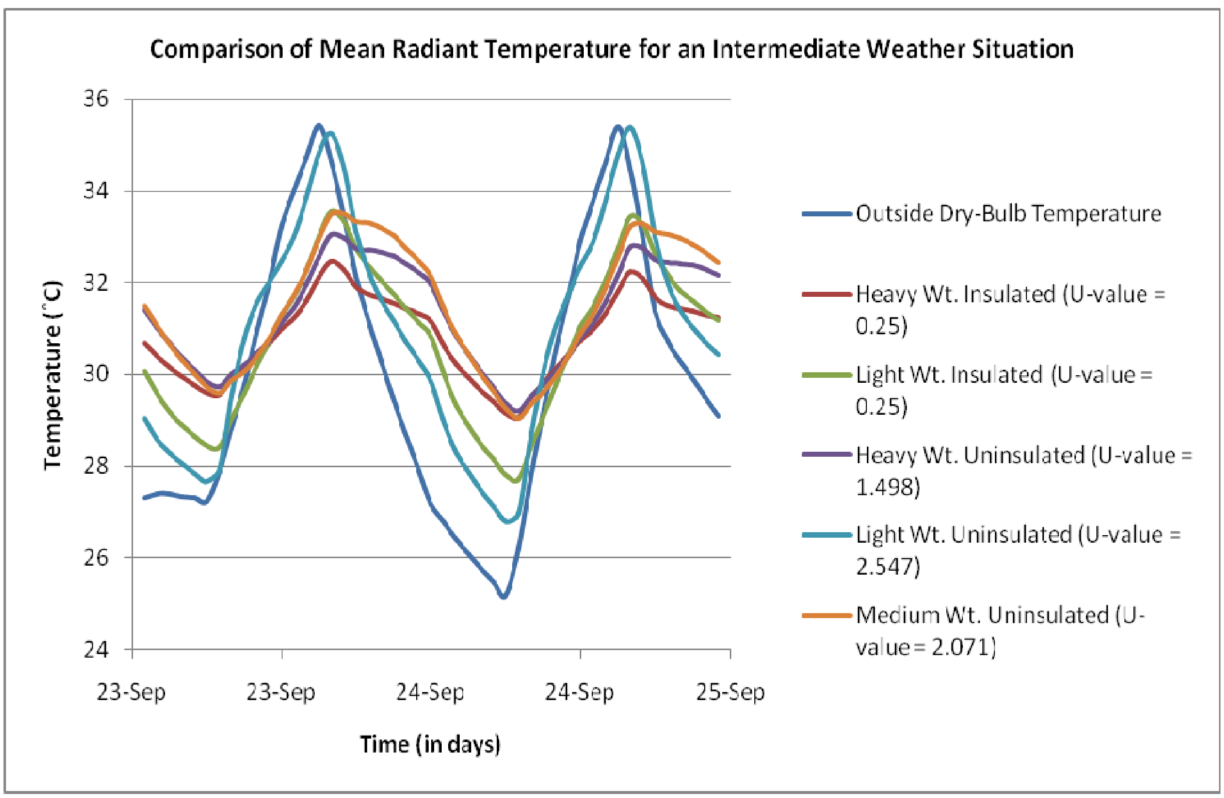


Figure 36 Comparison of Mean Radiant Temperatures- Intermediate Weather Situation

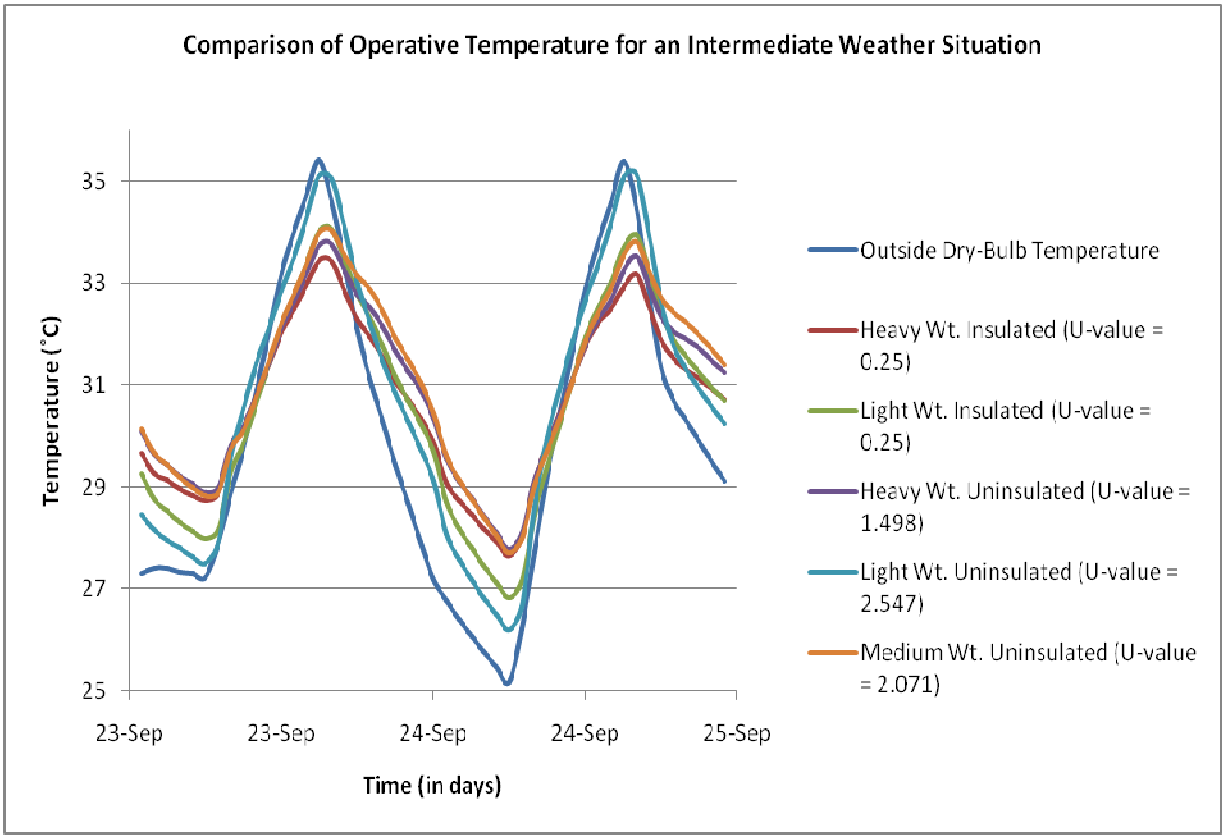
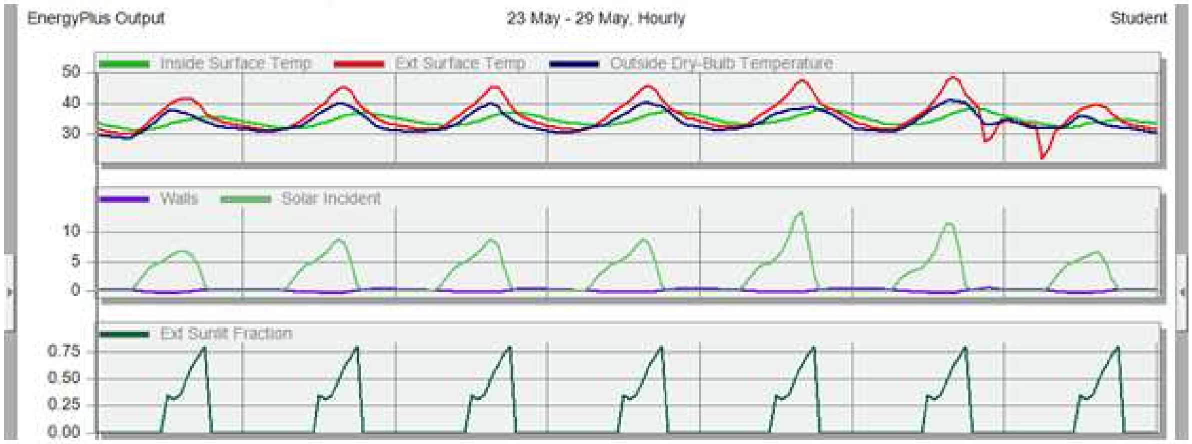


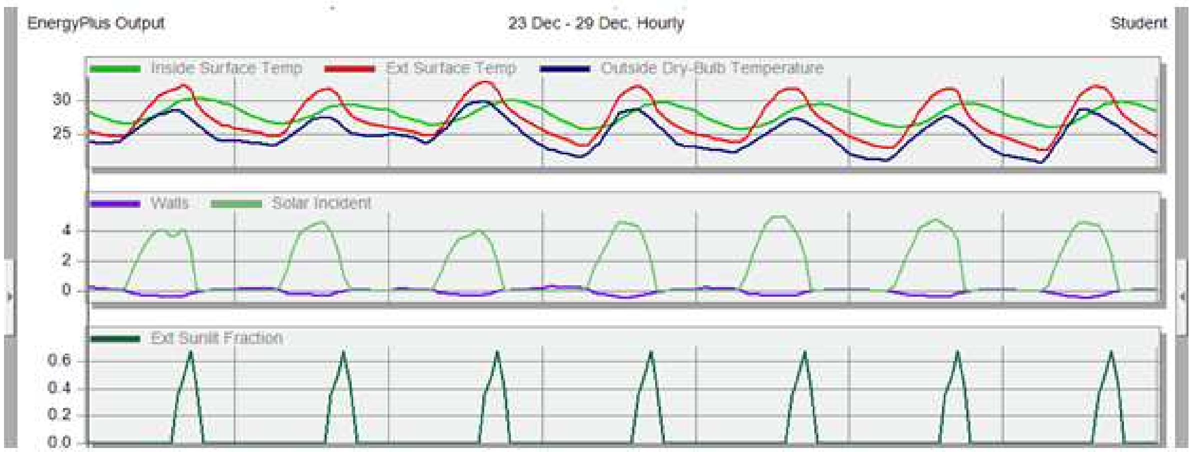
Figure 37 Comparison of Operative Temperatures- Intermediate Weather Situation

The difference in the reductions of the internal surface temperatures with respect to the outdoor temperature can be explained by the differences in solar intensity during the different periods (Figure 38). This is in also with Givoni's (1994) observation: "the depression of the indoor maximum below the outdoor's increased as the days became hotter."

Summer Situation



Winter Situation



Intermediate Situation

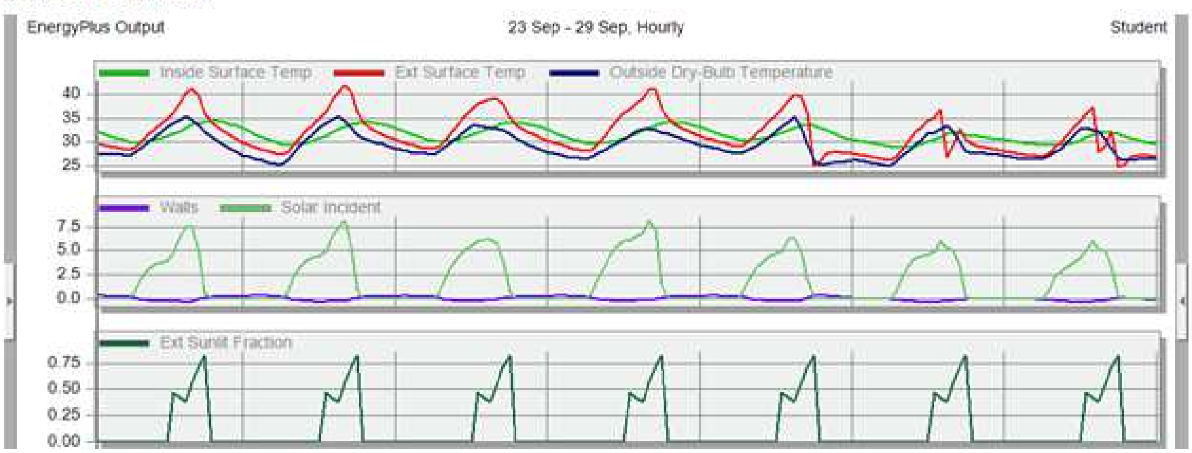


Figure 38 Variation of surface temperatures (exterior and interior) with respect to the solar intensity

The difference in the magnitudes of internal operative temperature and the outdoor temperature depends on several factors apart from just the type of construction. Orientation of the façade, amount of solar loads, wind speed and direction, etc., which vary across seasons are important factors that affect the air temperature greatly. With respect to the interior surface temperatures, two main conclusions can be drawn:

- During the day, an insulated wall performs better than an uninsulated wall. In the night however, an uninsulated wall is preferred to achieve low temperatures.
- Light-weight buildings (low thermal mass) are often considered as the appropriate construction type for hot humid regions where continuous ventilation is the main comfort strategy. But looking at the results above the following conclusion can be made: Thermal mass results in lower temperatures during the day and higher temperatures during the night. A heavier construction is therefore beneficial during the day and a lighter construction is preferred during the rest of the periods. The reason for higher temperatures in the heavier construction is due to the time lag in heat entering the structure at daytime and leaving the structure during the night.

Not much literature emphasizing the need for thermal mass in a hot-humid climate is available. One of the very few experimental studies proving the suitability of a high thermal mass building for a hot-humid climate is that of Givoni (1994-a). He has demonstrated that even when the buildings are continuously ventilated, thermal mass can significantly lower the indoor maximum temperatures. He suggests the possibility of night cooling by enhancing ventilation at night by a small exhaust fan.

6.3 Analyzing the current Trend

A medium weight, uninsulated construction is the most commonly used type of construction in urban India. Figure 39 represents the common built-up of an external wall.

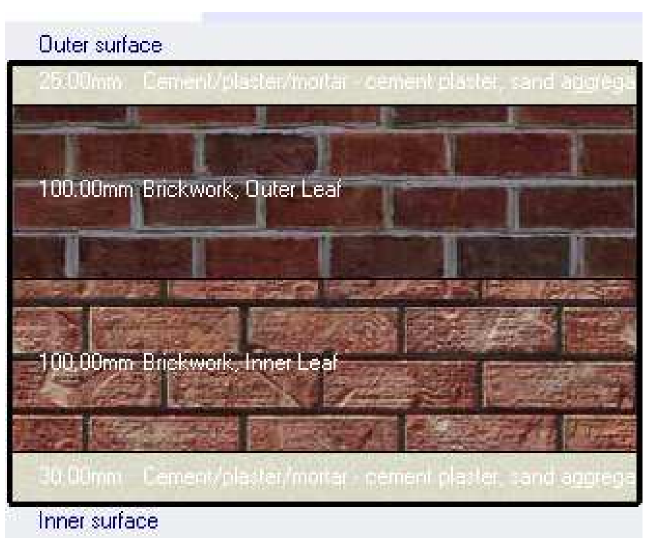


Figure 39 Common Built up in India

Figures 40 - 42 represents the performance for such a construction during different periods of a year. Studying the current trend will help understand the present situation and the requirements to be fulfilled by the new design.

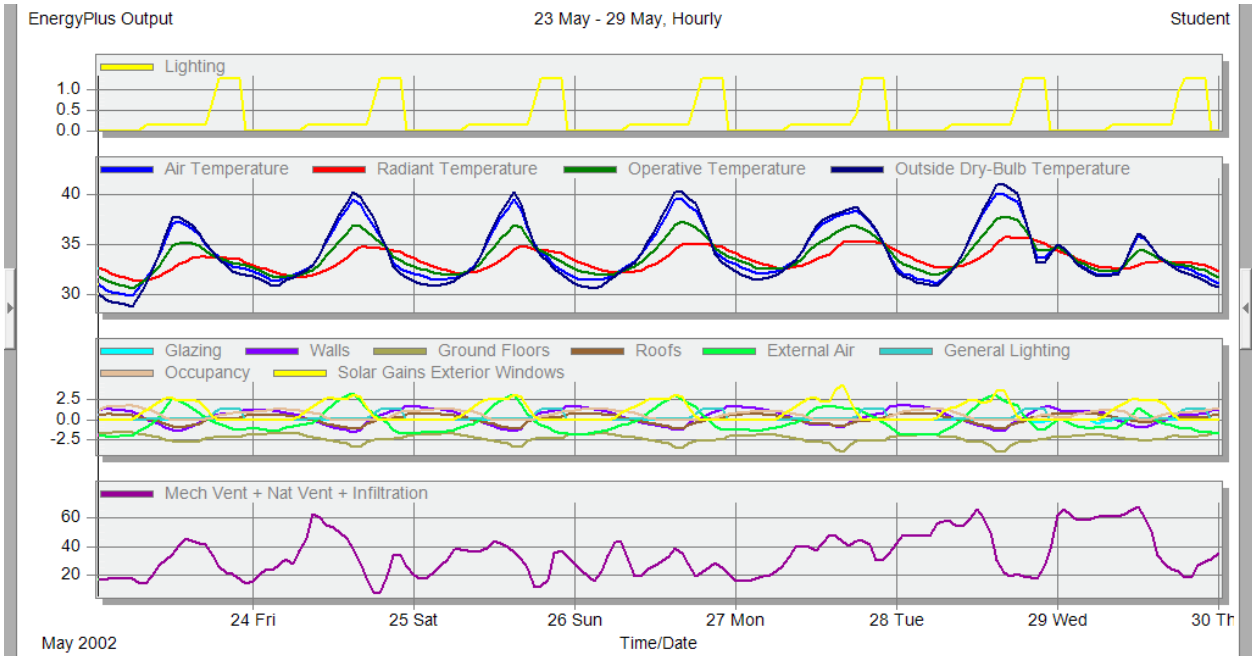


Figure 40 Current Trend: Summer Situation

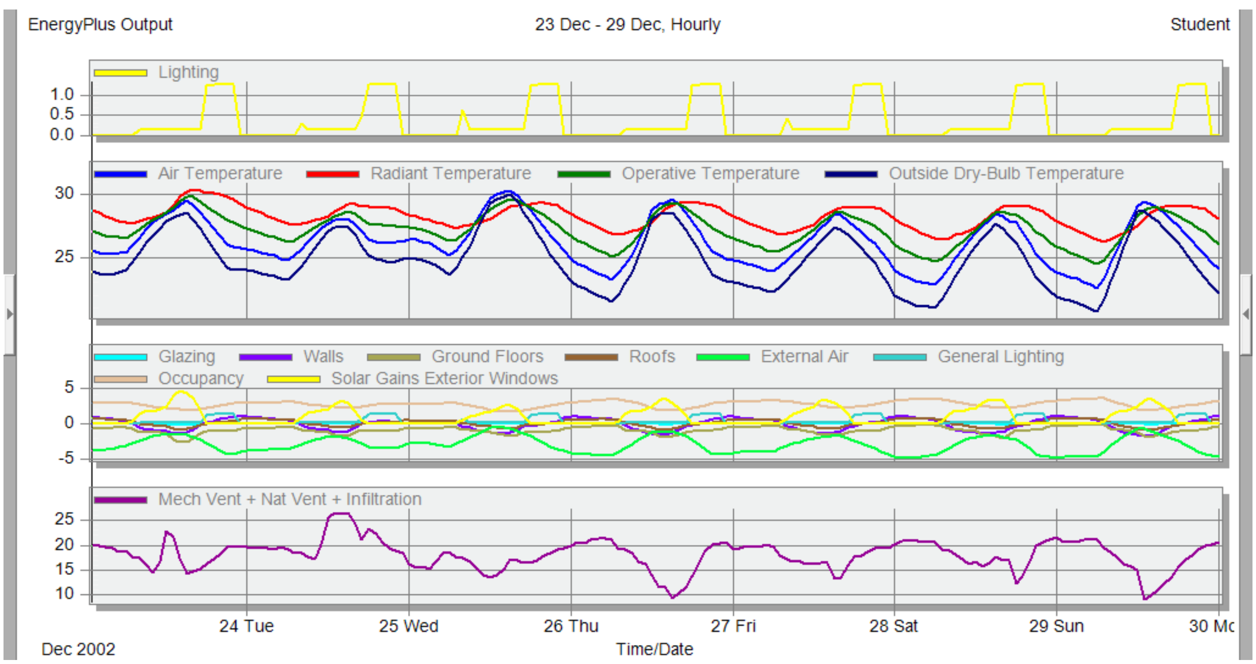


Figure 41 Current Trend: Winter Situation

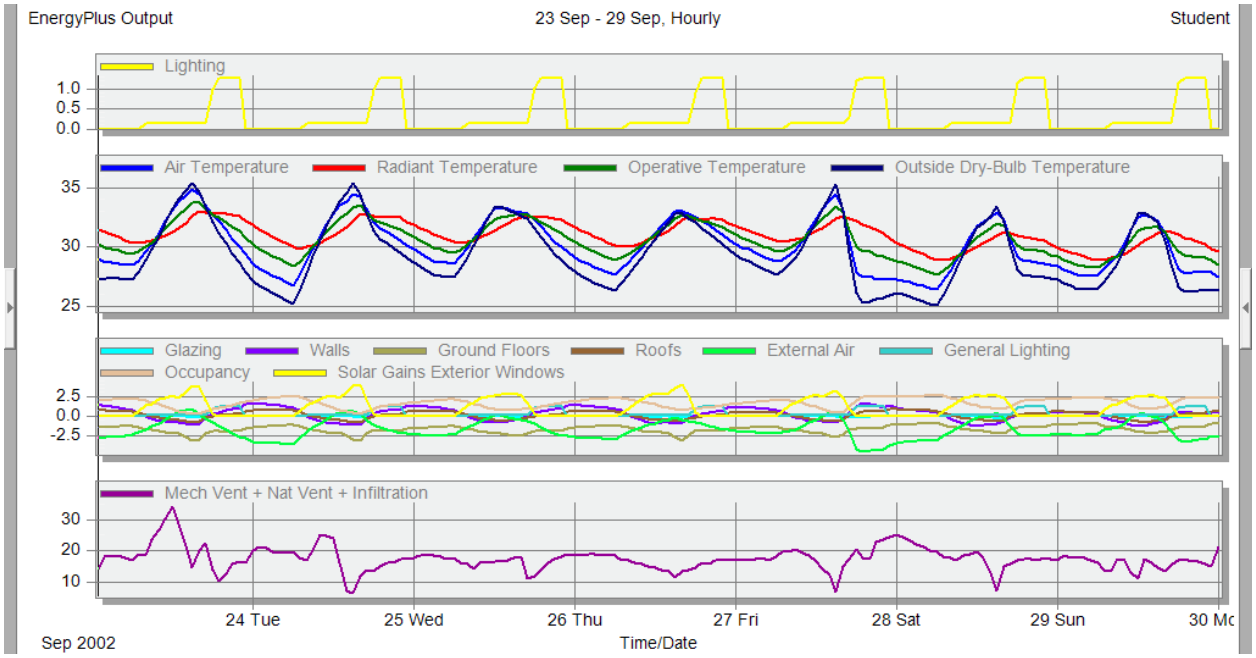


Figure 42 Current Trend: Intermediate Situation

6.3.1 Observations

The summer indoor temperatures are much lower than the external temperature during the day and slightly higher during the nights. Winter indoor temperatures are higher than the outdoor temperature through the day, with much larger differences in the night. During the intermediate months the indoor temperature during the afternoon hours is slightly lower than that outside and much higher in the nights. The typical range of values are depicted in table 6.

Time of the Year	Day time Temperature (˚C)		Night time Temperature (˚C)	
	Outdoor dry Bulb	Indoor Operative	Outdoor dry Bulb	Indoor Operative
Summer	37 - 41	35 - 38	29 - 31	30 - 32
Winter	27 - 30	27 – 30	20 - 24	24 – 27
Intermediate Months	33 – 35	32 – 34	25 – 28	28 - 30

Table 4 Summary- Current Trend

DesignBuilder uses Fanger's PMV model to calculate comfort. More about the model will be discussed in the next chapter. However it was found that it estimates that throughout the year, barring a few hours in January, the indoor climate will be uncomfortable (Figure 43).

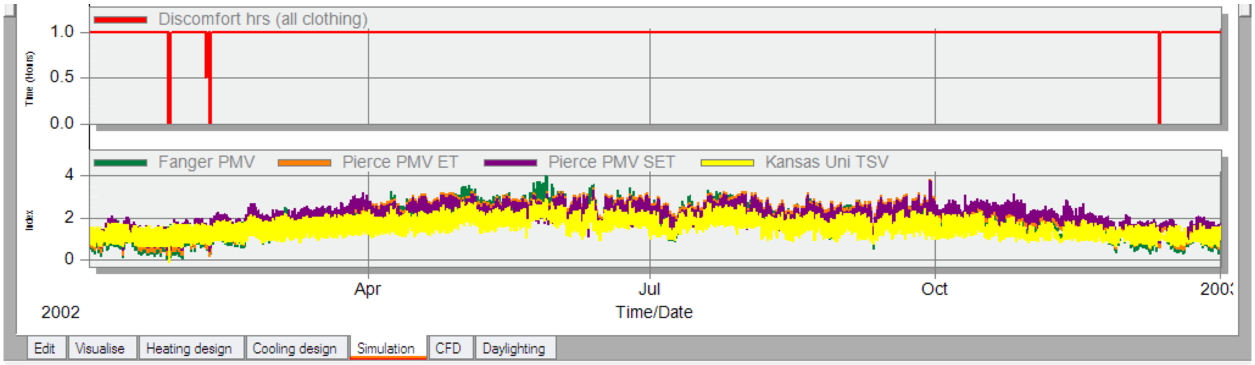


Figure 43 Thermal comfort based on PMV

Chapter 7: Adaptive Thermal Comfort

7.1 Choice of an appropriate Thermal Comfort Model

Thermal Comfort is defined as the condition of mind that expresses satisfaction with the thermal environment (ASHRAE, 2010).

Thermal Comfort models can be classified into two types: Standard and Adaptive. Standard models are based on the heat balance of the body with its surrounding environment and are based on uniform thermal environment. The Predicted Mean Value (PMV) model developed by Fanger (1972) is a popular example for a standard model. The PMV model is also used as an Fanger predicts that thermal comfort can be achieved when the rate of generation of heat and rate of heat loss in the body are balanced, and the average skin temperature and rate of sweating are within a certain range of values. The air temperature, air velocity, humidity, occupant clothing levels, mean radiant temperature and occupant metabolic level are the different parameters that are considered. Adaptive thermal models on the other hand, allow for variations in zonal temperatures and for diurnal or seasonal variations in the indoor thermal conditions. It is based on the principle that people tend to react to situations which cause discomfort and try to restore their comfort levels (Humphreys and Nicol, 1998).

The equations of Fanger's model were arrived based on subjective response to the thermal environment and were voted on the ASHRAE scale. The results of the field experiments conducted in tropical regions by several others, also based on voting according to the ASHRAE scale, resulted in discrepancies in the findings. Fanger's model, especially for free running buildings in the hot-humid climate has been found to underestimate the temperature range in which people feel comfortable. That is, for several occasions during which the participants felt comfortable, when calculated by the PMV model would state otherwise (Nicol, 2004). Another drawback of the Fanger's model is that it considers 30˚C and 1 m/s as the upper limit to the indoor air temperature and wind speed, however in reality much higher values can be obtained. The current usage of Fanger's model as a basis to classify thermal comfort in several building codes including the National Building code of India is being debated for these reasons. On the other hand, use of an adaptive model has been proven to be more appropriate especially for naturally ventilated buildings as it provides greater flexibility in matching optimal indoor temperatures with outdoor climate (de Dear and Brager, 2002; Deuble and de Dear, 2012; Humphreys, 1981; Nicol and Humphreys, 2010).

Based on the adaptive comfort model, a study conducted by Toe and Kubota (2013) led them to the following conclusions:

- "People living in hot climates, particularly regions with daily mean outdoor air temperatures higher than 20◦C, adapt to a wider and higher range of indoor operative temperatures relative to the same magnitude of outdoor air temperature increases than those living in colder climates.

- A thermal comfort standard for naturally ventilated buildings in hot–humid climate should consider occupants' thermal adaptation to various indoor air speeds."

They have also proposed an equation to calculate the indoor operative temperature for hot humid climate.

$T_{neutop} = 0.57\ T_{outdm} + 13.8$

Where, T_{neutop}: Indoor neutral operative temperature (˚C)
T_{outdm}: Daily mean outdoor air temperature (˚C)

No.	Aspect	Criterion	Note
(i)	Climate type	All A climate types; and Summer season of Cfa climate type.	Climate type refers to the Köppen-Geiger climate classification system.
(ii)	Neutral operative temperature, T_{neutop} (°C)	$T_{neutop}=0.57T_{outdm}+13.8$	T_{outdm} is daily mean outdoor air temperature (°C), i.e., the 24-h arithmetic mean for the day in question.
(iii)	Daily mean outdoor air temperature, T_{outdm} (°C)	Range from 19.4 to 30.5.	Recommended applicable range for criterion no. (ii).
(iv)	Lower comfort operative temperature limit, T_{lower} (°C)	No required limit.	-
(v)	Upper comfort operative temperature limit, T_{upper} (°C)	$T_{upper}=T_{neutop}-0.7$ for 80% comfortable thermal sensation votes.	Graphical representation can be referred in Fig. 3a (continuous line in the right figure) for a different percentage of comfortable thermal sensation votes.
(vi)	Indoor air speed, v (m/s)	<0.65 at and below neutral operative temperature; ≥ 0.65 above neutral operative temperature.	Recommended to provide non-still air and occupants' control to adjust the indoor air speeds according to their preferences.
(vii)	Indoor humidity, RH (%)	No required limit.	-

Table 5 Proposed adaptive thermal comfort equation and related criteria for naturally ventilated buildings in hot-humid climate [Source: Toe and Kubota, 2013]

This formula however, is valid only for an outdoor temperature range between 19.4 – 30.5˚C. Further a minimum indoor air speed of 0.65 m/s is required to increase the neutral operative temperature predicted by this equation. Due to the lack of a suitable formula for temperatures outside this range, periods having temperatures below 19.4˚C and above 30.5˚C (26% of the year) were not counted. Assuming that the minimum air speed within the room is 0.65 m/s, the indoor neutral operative temperature is calculated for the existing situation. During the remaining 74% of the year, going by this formula, thermal comfort can be achieved for 47.2 % of the year).

7.2 Air speed and evaporative cooling

"The rate of metabolic heat production depends upon the physical activity of the person" (Givoni and Goldman, 1971). Convection and radiation govern the heat transfer process between the human body and the surrounding environment.

Convection heat flow is proportional to the temperature difference between the skin and the air and speed of the surrounding air. Radiation heat flow is proportional to the temperature difference between the skin and the surrounding surfaces. Under comfortable conditions, skin temperature is about 32°C to 33°C. Under hot conditions, the temperature of the skin increases due to more blood being is directed towards the skin. With an increase in the skin temperature, the difference between the skin and the surrounding air/surfaces falls, eventually lowering the heat gain by convection and radiation (Givoni, 2010).

Every gram of water or sweat that is evaporated consumes in the process about 0.68Wh of heat, thus resulting in a cooling sensation. Evaporative cooling of the skin is closely related to the ambient air temperature. One sweats at temperatures above the comfort zone. But some minor amounts of water diffuse from the skin even under thermal comfort conditions, when the sweat glands are not activated. At air temperatures above the comfort zone temperature, the body maintains its thermal balance mainly by sweat evaporation. The increased air speed over the body enhances sweat evaporation which in turn reduces discomfort resulting from moist and wet skin (Givoni, 1971).

Experimental studies in non-air conditioned buildings were carried out in regions with a hot-humid climate: Fong et al., (2008) in Hong Kong, Khedari et al., (2001 and 2003) in Thailand and Wong and Tanamas, (2002) in Singapore. All of them involved the participation of common people and took into account their subjective score for thermal comfort.

In the experiment conducted by Fong et al in Hong Kong, participants were made to sit in an environmental chamber with varying temperature (between 25 - 30˚C) and relative humidity (50, 65 and 80%). Participants were given a tower fan each, and their task was to set its air speed (beween 0.5 m/s to 3 m/s) to suit their comfort according to varying indoor air temperature and relative humidity. Based on this experiment, Fong et al., (2008) have demonstrated a significant upward shift of the comfort temperature and relative humidity levels with higher air speed.

In the climate chamber research in Singapore, air conditioning was used to control the air temperature and humidity levels. Wind speeds of varying degrees between 0 m/s and 4.0 m/s were generated by wind-tunnel fans. The air temperature ranged between 22 - 29˚C and the relative humidity ranged between 45 – 75%. Subjects had no control over any of the parameters. Based on their rating of thermal sensation, it was again concluded that a high air speed has a positive effect on thermal comfort at high temperatures and relative humidity. Air speed of 2 to 3 m/s at 29˚C was proven to achieve a thermal comfort level equivalent to that at a speed of 0.2 m/s at 22˚C. Similarly, a reduction of 1 m/s of air speed had a bigger effect than an increase of humidity ratio from 8 g/kg to 19 g/kg, clearly signifying the effect of a higher air speed (Wong and Tanamas, 2002).

The conclusion of the study carried out at Thailand by Khedari et al., (2001 and 2003) is no different from that arrived by the others: the effect of changes in temperature reduces with increase in wind speed.

7.3 Effect of Humidity on Thermal Comfort in hot-humid regions

Experimental data from previous comfort studies conducted in Thailand, Singapore, Indonesia and Japan were analyzed to examine the effect of humidity on the perceived levels of comfort. The study concluded that the effect of humidity, expressed as the humidity ratio (g/kg) on the thermal sensations, was very small to negligible. This contradictory behavior was identified as an "insensitivity of the acclimatized subjects to the humidity level within the range encountered in the countries where the studies were conducted" (B.Givoni et al., 2006). In another study conducted by Toe and Kubota (2013) it was again proved that humidity does not influence the predicted neutral temperature in hot–humid climate. However, not all studies lead to the same conclusion. X.Su et al. (2009) propose that for relative humidities beyond 70%, with every 10% increase in the relative humidity the comfort temperature reduces by 0.4˚C.

7.4 Problems associated with Natural Ventilation in high-density cities

Due to the urban heat island effect, temperatures in dense cities are higher than its surrounding sub-urban or rural areas. From the previous section it is clear that a high indoor air speed can improve thermal comfort levels in non- air conditioned buildings. However, to achieve good air speed in high-density cities is often very difficult, mainly because of the lower outdoor air speed. Higher outdoor temperature elevates the indoor temperatures of buildings, which is accumulated within the indoor space due to poor ventilation. "The likelihood and severity of indoor thermal discomfort is therefore higher in high-density cities located in a hot humid climate" (Givoni, 2010). This, however can be partly improved by appropriate urban planning. The concentration of buildings in the urban area have been proven to generate local air currents as a result of micro-scale temperature differences. "Suitable placement of high-rise buildings can help create zones of high and low pressures above the built-up area, and thus generate vertical air currents stirring the urban air mass" (Givoni, 1974). A part of these wind currents may get diverted downwards towards the ground, increasing the average wind speed at street level (Wise, Sexton and Lillywhite, 1965; Givoni and Paciuk, 1971).

7.5 Conclusion

Based on the literature, we can conclude that an approach different from Fanger's PMV model is required to predict the range of comfort temperatures. The Adaptive Thermal comfort model which has been proven to be appropriate for free running buildings in hot-humid climates will be chosen for this study.

Further, the need for high indoor air velocities as a facilitator for thermal comfort has been emphasized by various studies.

Chapter 8: Design for Ventilation

Ventilation forms the basis for thermal comfort for hot-humid regions. In this chapter the basic principles behind ventilation and the ways to achieve good air flow and air speed within the building will be discussed. Results from CFD simulations of a combination of the several principles will be simultaneously presented.

8.1 Theory

Air flow into a building can occur by two means: ventilation through openings such as windows or infiltration through cracks or pores in the material fabric. The former is purpose-provided whereas the latter occurs due to faulty design. Air flow through infiltration is difficult to control. However, it is not a problem in free running buildings in the hot-humid climates where high rate of ventilation is anyway preferred. Air flow through openings can be designed in such a way that it is favourable for thermal comfort.

The type of opening and the pressure distribution on the building envelope directly determine the amount and nature of the airflow. The characteristics of the opening (dimensions, shape, presence of obstructions etc.,) determines the resistance to flow whereas the pressure distribution causes ventilation to occur. Pressure here can be classified into two types: wind induced pressure and temperature induced pressure.

Wind induced pressures are dependent on the geometry of the building, the orientation of the building with respect to the wind direction, the wind speed in the locality and the nature of the terrain surrounding the building. Temperature induced pressure on the other hand, arises due to the difference in density between the indoor and outdoor air (caused due to difference in indoor-outdoor air temperatures) as well as the temperature differences at different regions within the building.

The position of the neutral pressure plane determines the flow directions of the air. It sets itself in such a manner that there is a balance between the airflow rates entering and leaving a building. Its location is dependant not only upon the size and location of the openings, but also on the indoor-outdoor temperatures and wind. The neutral plane generally tends to place itself closer to the largest openings.
Air enters an opening at a level below the neutral pressure plane and leaves above the neutral pressure plane. Warm and humid air tends to rise up as it is lighter than cold air. Provision of outlet openings at higher levels ensures removal of the hot air. This air is subsequently replaced by colder air entering through the lower openings. The air flow rates increase with increasing indoor-outdoor temperature difference and the vertical distance between the openings. The outlet opening should be as large and as high as possible in order to place the neutral plane at the highest possible level with respect to the floor. By doing so, provision of fresh air to a large part of the zone can be ensured. This is important in purely stack driven ventilation where it is not possible to pass fresh air through openings placed above the

neutral plane. It is also important to place the outlet openings in the low-pressure façade of the building so that wind and stack pressure work in the same direction.

As outdoor temperatures approach indoor air temperatures, the stack pressure differences become negligible compared to typical wind-driven pressure differences.

Figure 44 compares the indoor air velocity and distribution of three different cases:
A. Position of both windward and leeward openings at the same level
B. Position of windward opening closer to the sill level and leeward opening closer to the ceiling.
C. Position of windward opening closer to the sill level and a large leeward opening that extends from the sill till the ceiling.

Results are based on simulations run for May 23rd at 12.00 hours. The direction of wind is along the West (270˚ from the North) and has a magnitude of 4.9 m/s when measured at 10 m from ground level. Among the three cases, case B has the highest indoor air velocity as well as distribution across the room. Therefore, the results seen in the image complies with the theory.

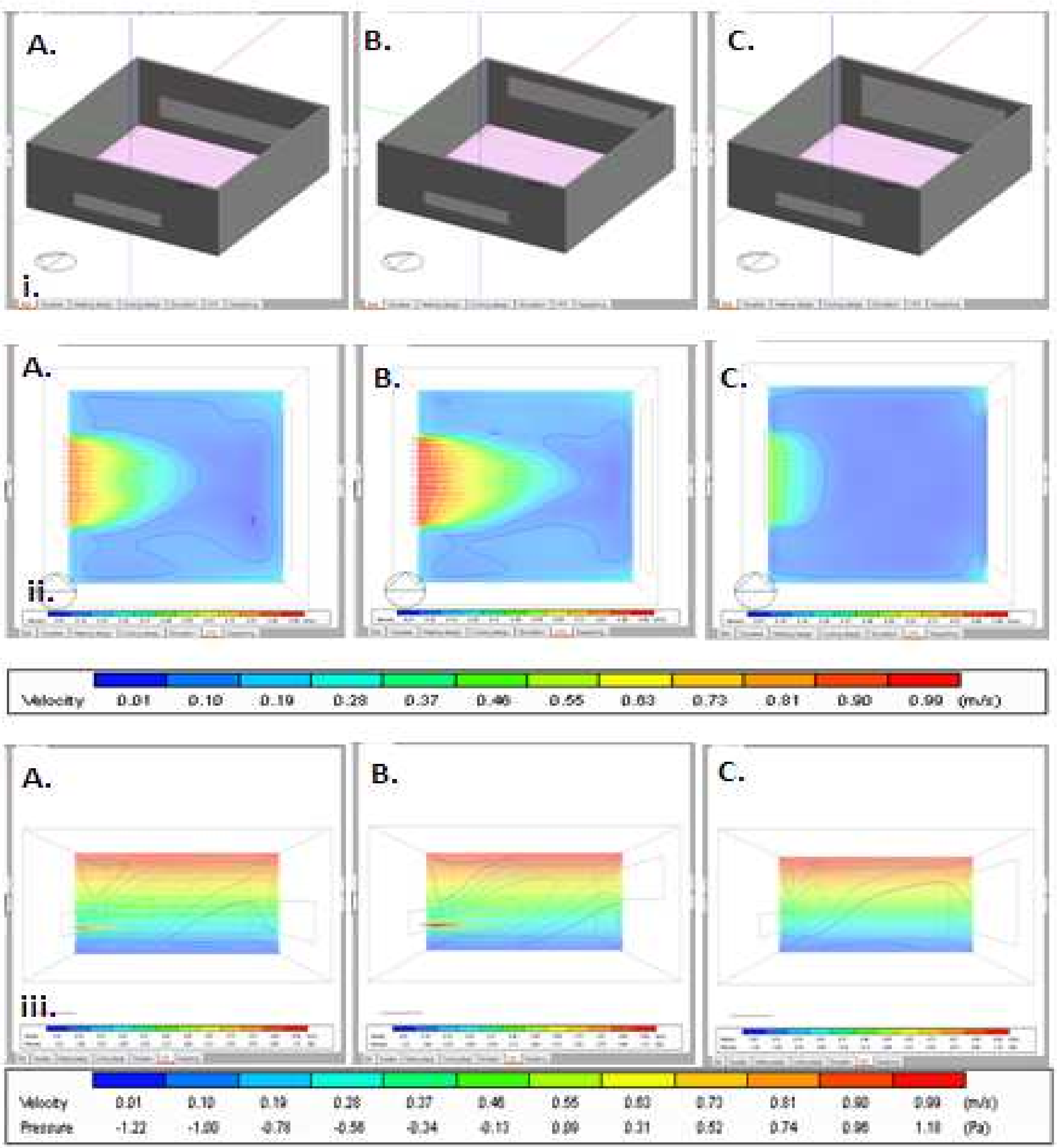


Figure 44 Effect of Neutral Plane on indoor air velocity and distribution. i) Position of Openings; ii) Velocity Distribution at the activity zone; iii) Section at the middle of the room – the contour lines depict the air velocity and the filled contour represents the pressure distribution and hence the position of the Neutral Axis (pressure at the neutral axis is zero).

8.2 Combined Wind and Buoyancy driven Ventilation

In a hot-humid climate zone, indoor air is often warmer than outdoor air and the temperatures are especially high at the occupancy zone. However the stack effect is instrumental in driving the airflow from bottom to top. The wind, on the other hand, drives the airflow from the windward to the leeward side of the building. If the ventilation openings are located in an appropriate manner (inlet openings below the neutral plane in the windward side and outlet openings above the neutral plane in the leeward side), the wind pressure is added to the stack effect and the ventilation is reinforced.

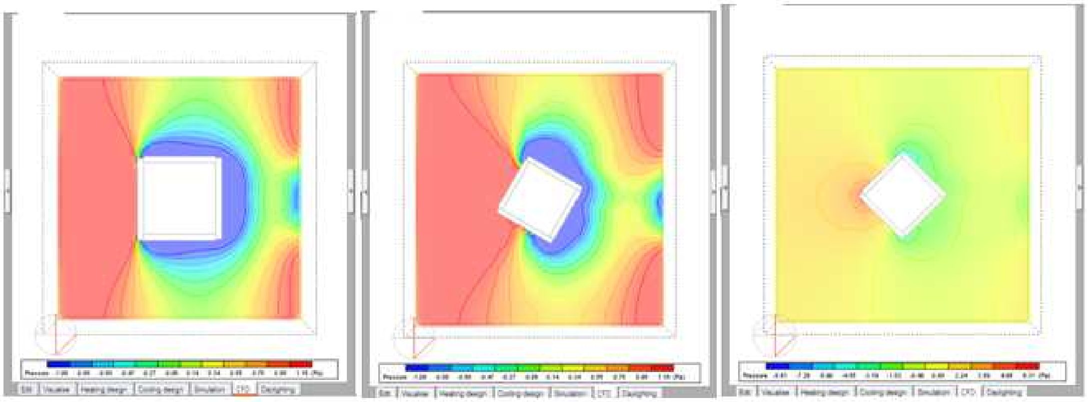
On the contrary, if openings at the windward side are on the top and those at the leeward side are at the bottom, the wind acts against the stack effect leading to suppressed ventilation. Ventilation openings in naturally ventilated buildings should therefore be located according to the predominant wind direction.

8.3 Other physical Parameters

8.3.1 Orientation of the Building

Orientation of a building in a hot-humid climate should be aimed at maximizing the ventilation, and therefore the direction of the prevailing winds should be given due consideration while deciding the orientation of the building. Contrary to common belief, an opening that is perpendicular to the wind direction is not the best suited for maximizing ventilation. On the other hand, satisfactory ventilation can be achieved at angles of up to 50˚ on either side of the wind direction. An angle of 45˚ is observed to be the ideal direction for increasing the air velocity within the building.

Figure 45 explains the effect of orientation on the building envelope. The prevailing wind direction is Westerly (indicated by the red arrow). The windward part of the envelope is governed by the region with positive pressure. For the 3 orientations considered (North at 0˚, 30˚ and 45˚ to the wind), building with the 45˚ orientation has more surface area in the positive pressure zone.



Description (clockwise from the left)	Legend
Case A: Orientation at 0˚	Pressure -1.09 -0.88 -0.68 -0.47 -0.27 -0.06 0.14 0.34 0.55 0.75 0.95 1.16 (Pa)
Case B: Orientation at 30˚	Pressure -1.09 -0.88 -0.68 -0.47 -0.27 -0.06 0.14 0.34 0.55 0.75 0.95 1.16 (Pa)
Case C: Orientation at 45˚	Pressure -8.61 -7.26 -5.90 -4.55 -3.19 -1.83 -0.48 0.88 2.24 3.59 4.95 6.31 (Pa)

Figure 45 Effect of Orientation - Pressure distribution on the building envelope

The indoor air speed and uniformity in distribution is assessed for openings oriented perpendicular to the wind direction and oblique to the wind direction (at an angle 45˚ in this case). Two different cases are considered for each orientation (Figure 46).

I. Narrow openings (2.6 m x 0.5 m) distributed along West and East walls; spacing between openings: 0.5 m.
II. Narrow openings (2.6 m x 0.5 m) distributed along all four walls; spacing between openings: 0.5 m.

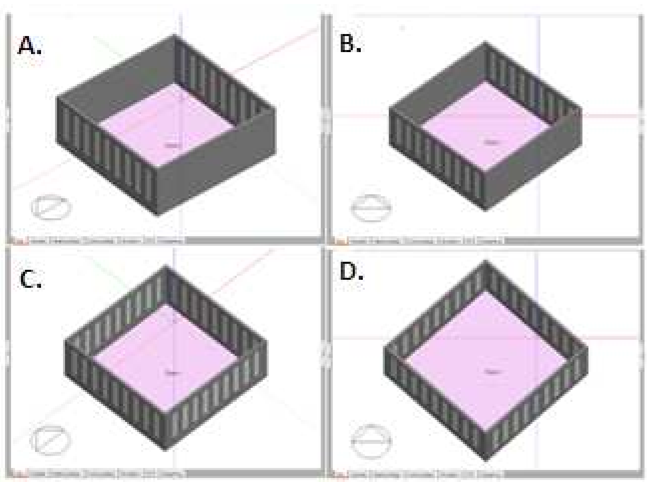
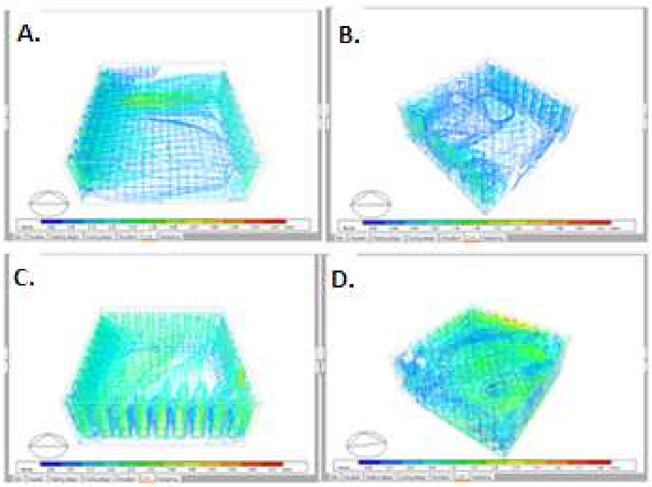


Figure 46 Representation of the various cases considered

Simulations were run for May 23rd at 12.00 hours. The outdoor temperature is 37.8˚C. The direction of wind is along the West (270˚ from the North) and has a magnitude of 4.9 m/s when measured at 10 m from ground level. The following observations can be drawn.

Overall Velocity Distribution



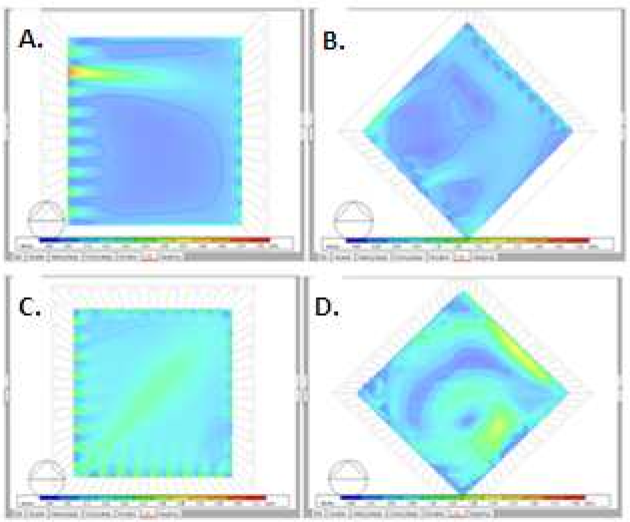
	Legend													
Case I - 0˚ orientation	Velocity	0.00	0.08	0.15	0.23	0.30	0.38	0.45	0.53	0.60	0.68	0.75	0.83	(m/s)
Case I - 45˚ orientation	Velocity	0.00	0.29	0.58	0.87	1.16	1.45	1.74	2.02	2.31	2.60	2.89	3.18	(m/s)
Case II - 0˚ orientation	Velocity	0.00	0.07	0.13	0.20	0.26	0.33	0.40	0.46	0.53	0.59	0.66	0.72	(m/s)
Case II - 45˚ orientation	Velocity	0.00	0.31	0.63	0.94	1.25	1.57	1.88	2.19	2.51	2.82	3.13	3.45	(m/s)

Figure 47 Effect of Orientation on Overall velocity distribution

There is an obvious improvement in the wind speeds when the orientation of the wind is oblique to the opening. This increase is about 270% in the first case, where openings are only along two walls and nearly 380 % in the second case where openings are provided in all the walls.

It has to be noted that providing openings in all walls when the building is oriented at an oblique direction results in two of the walls facing the wind instead of just one as in the case of a building which has openings perpendicular to the direction of wind.

Air Velocity at activity level



	Legend												
Case I - 0˚ orientation	Velocity	0.00	0.08	0.15	0.23	0.30	0.38	0.45	0.53	0.60	0.68	0.75	0.83 (m/s)
Case I - 45˚ orientation	Velocity	0.00	0.29	0.58	0.87	1.16	1.45	1.74	2.02	2.31	2.60	2.89	3.18 (m/s)
Case II - 0˚ orientation	Velocity	0.00	0.07	0.13	0.20	0.26	0.33	0.40	0.46	0.53	0.59	0.66	0.72 (m/s)
Case II - 45˚ orientation	Velocity	0.00	0.31	0.63	0.94	1.25	1.57	1.88	2.19	2.51	2.82	3.13	3.46 (m/s)

Figure 48 Air Velocity at activity level

In case I, for both situations the uniformity in the distribution of air across the room is low. There are large areas where the air speed is lower than its surrounding regions. However, among the two, situation two has an overall much higher air speed than situation one.

In case II, under both orientations, the distribution of the wind is more or less uniform. The wind speeds however are much higher (~ 4 times) when the building is oriented at a 45˚ inclination.

Age of Air at activity level

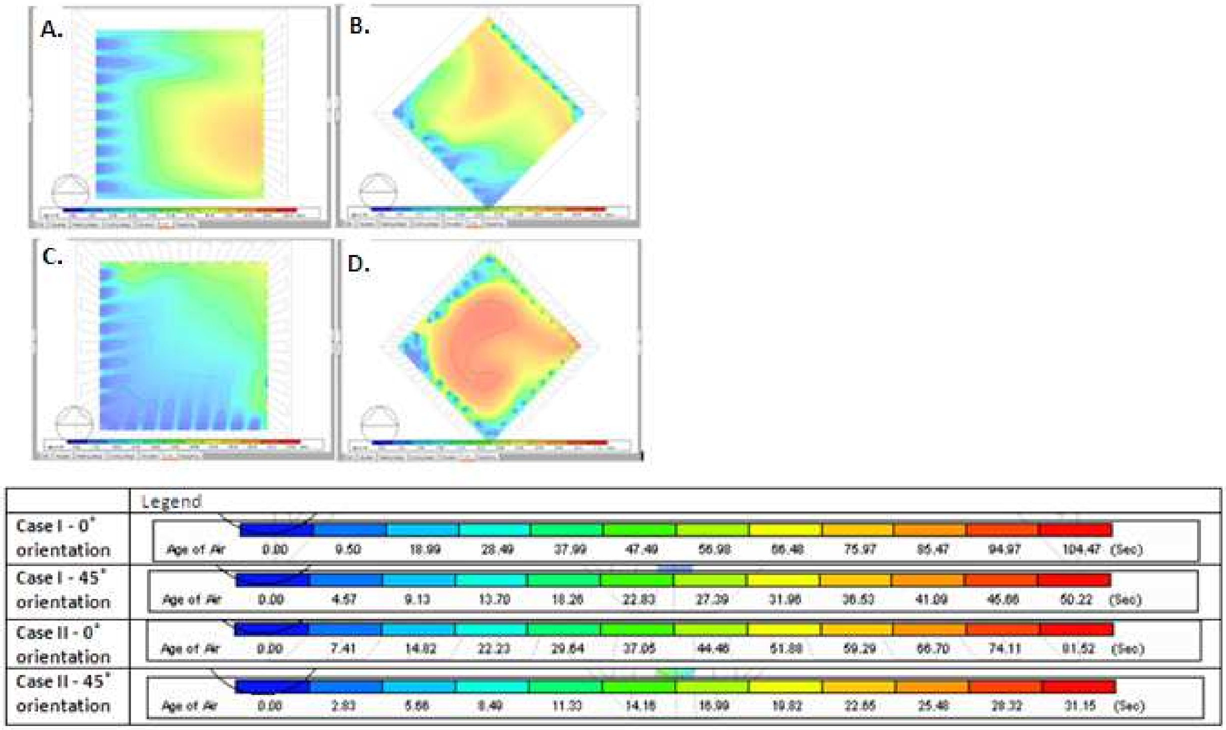


Figure 49 Effect of Orientation on air movement at activity level

The 'age of air' at a particular location is the average time elapsed since molecules of air at that location entered the building. Better distribution and higher air speeds within the room leads to faster exchange of air. Yet, when the orientation is oblique, there seems to be some amount of stagnation of air in the centre of the room, as compared to that along the boundary. This could be because of the proximity of the openings. Nevertheless, the lag between the two regions is less than 10 seconds. Therefore there is almost no stagnation of air within the room. This continuous movement of air is beneficial in hot humid climates, as it not only prevents the storage of the heat from the incoming outdoor air, but it also prevents the accumulation of moisture.

Looking at the regions with the 'oldest' age of the air, in case I, the second situation seems to perform twice as better than the first situation. In case II, the performance is more or less the same, with the second situation slightly better than the first.

From the results, it can be concluded that an oblique orientation of the building (and hence the opening) does improve indoor air velocity as well as air movement. But the wind direction is not always constant, especially for a city like Chennai, the direction of the wind is quite erratic and wind is oriented along the predominant wind direction for only 60% of the year. In such cases additional structures such as vertical louvers can be used to effectively change the orientation of the wind entering the opening. This will be discussed more in detail later in this chapter.

8.3.2 Size of Openings

Increased air speeds can be achieved by providing smaller inlets than outlets. When a large volume of air is removed from a zone, an equal amount of air has to be replaced. As the flow rate remains constant, a smaller inlet opening area results in an increased air velocity. However, it has the disadvantage of an unequal velocity distribution which may not be preferred for zones where a large part of the floor area is to be occupied. For such situations it is preferable to have inlets and outlets of similar size.

Increased opening areas in hot-humid climates not only have the advantage of improved ventilation, but it also results in reducing the heat capacity in case of a heavy mass construction. This however can only be effective if the openings are adequately shaded. If proper measures for solar protection are not taken, it will worsen the situation.

8.3.3 Position of Openings

The most effective position of openings from the comfort point of view is 0.5 – 1.5 m, that is, at the level of the occupied zone. A low sill level is preferred for bedrooms or other regions where the occupant's body lies close to the floor. When windows need to be provided at a higher level for some reason, horizontally pivoted windows which guide the wind towards the level of the occupants seem efficient. Large sliding walls which provide the possibility to open or close are particularly of use in regions with conflicting requirements.

The effect of the size and position (distribution) of openings and performance of different types of openings on air speed and distribution were studied. Additionally the resulting indoor operative temperatures were also compared. Simulations were run for September 23rd at 12 hours. The outdoor temperature is 37.8˚C. The direction of wind is along the West (270˚) and has a magnitude of 4.95 m/s when measured at 10 m from ground level. The building is oriented in such a way that the facades make 45˚ with the cardinal directions. Except for case A and C, in all other cases the openings at the windward side are placed closer to the sill level and that at the leeward side are placed closer to the ceiling. The following cases are considered (Figure 50):

A. Large openings on all four facades.
B. Openings of 4.5 m^2 all four facades.
C. Narrow openings (2.8m x 0.5m) distributed along all 4 facades (spacing between openings: 0.5m; total area of openings: 12.6 m^2 per facade).
D. Narrow openings (1.3m x 0.5m) distributed along all four facades (spacing between openings: 0.5m; total area of 5.85 m^2 per facade).
E. Narrow openings (1.3m x 0.5m) distributed along three facades: two windward and one leeward; (spacing between openings: 0.5m; total area of 5.85 m^2 per facade).
F. Narrow openings (1.3m x 0.5m) distributed along three facades: one windward and two leeward; (spacing between openings: 0.5m; total area of 5.85 m^2 per facade).

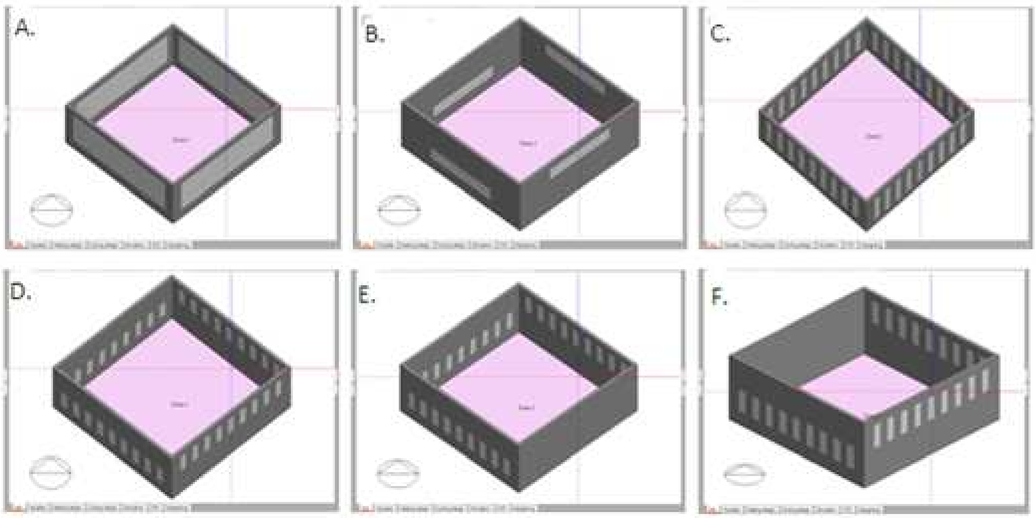


Figure 50 Various Position of Openings studied

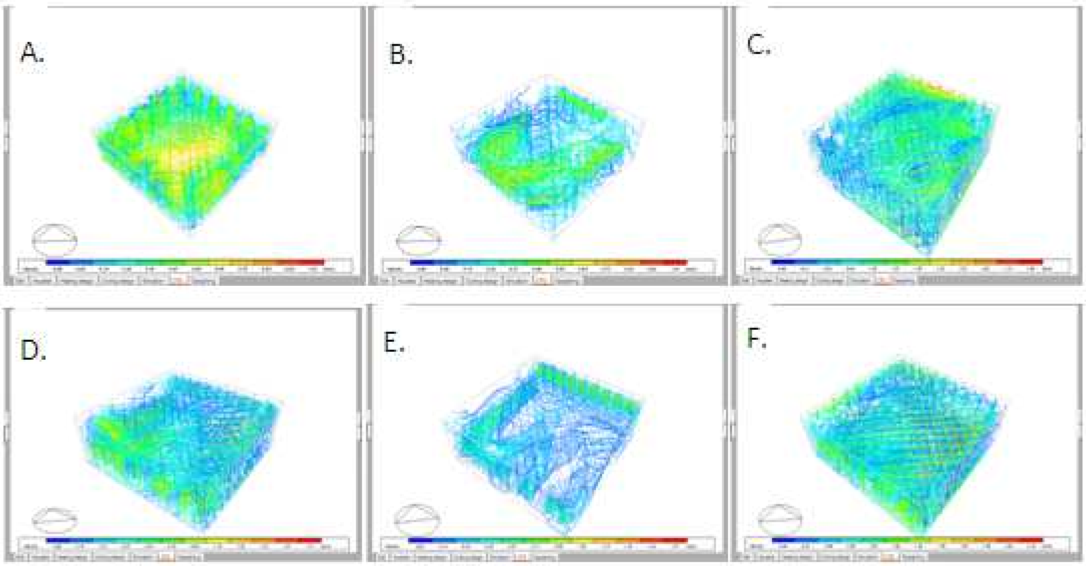
The average values for the various parameters in the entire zone is as given in Table 6.

Results from Simulation (Average values for the entire zone)				
Type	Operative Temperature (˚C)	Air Change/ Hour	Solar Gains (kWh)	Heat Gain from External Air (kWh)
Case A	38.02	165.50	13.25	0.047
Case B	34.90	35.00	2.65	2.51
Case C	36.40	89.50	6.98	1.05
Case D	35.23	47.00	3.70	2.27
Case E	34.90	28.60	2.91	2.34
Case F	34.80	30.15	2.72	2.42

Table 6 Results from Simulation (Average values for the entire zone)

It has to be noted that in most cases the outdoor temperature is high compared to the average indoor operative temperature. The general notion is that in such scenarios, a high ventilation rate will only increase the indoor temperatures further. However, "unlike space or structural cooling, direct occupant cooling can be achieved with outdoor temperatures that are near or higher than indoor temperature, provided it is lower than body temperature and the air velocity is high" (Hildebrand, 2011).

Overall Velocity Distribution:



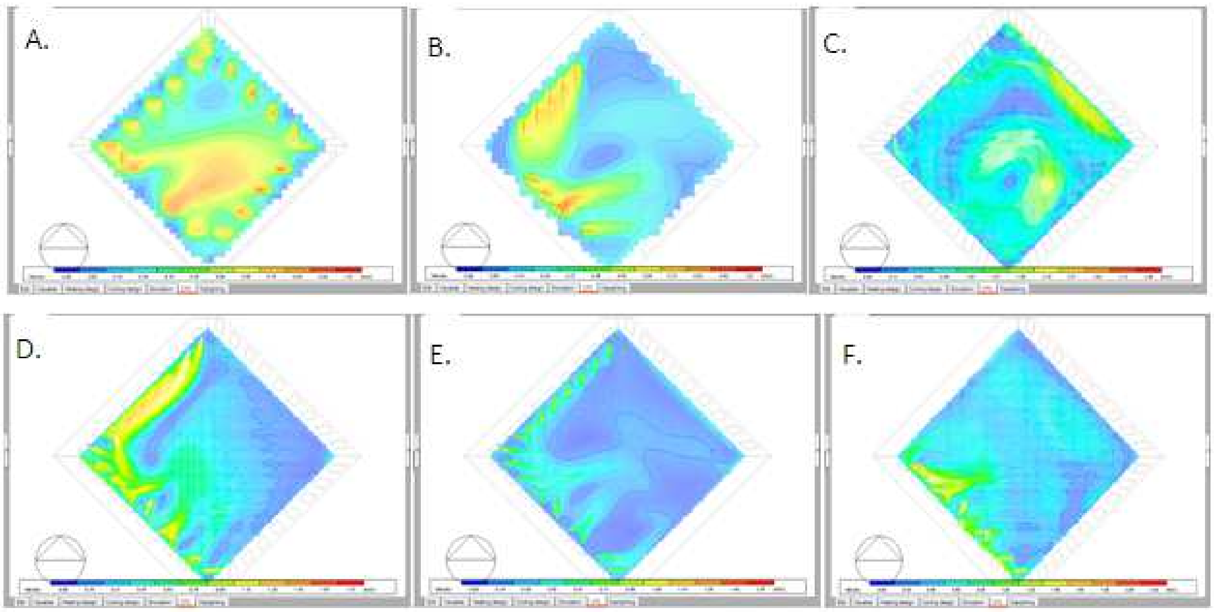
Case A	Velocity	0.00	0.09	0.19	0.28	0.38	0.47	0.56	0.65	0.75	0.84	0.94	1.03 (m/s)
Case B	Velocity	0.00	0.09	0.19	0.28	0.38	0.47	0.57	0.66	0.76	0.85	0.95	1.04 (m/s)
Case C	Velocity	0.00	0.31	0.63	0.94	1.25	1.57	1.88	2.19	2.51	2.82	3.13	3.46 (m/s)
Case D	Velocity	0.00	0.16	0.31	0.47	0.63	0.79	0.94	1.10	1.26	1.41	1.57	1.73 (m/s)
Case E	Velocity	0.00	0.14	0.29	0.43	0.57	0.71	0.86	1.00	1.14	1.29	1.43	1.57 (m/s)
Case F	Velocity	0.00	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20 (m/s)

Figure 51 Overall Indoor Air Velocity Distribution

An almost completely open building (case A) has a reasonable spread of air movement, however the wind speeds are quite low as compared to the others. Case B, with lumped openings on all four facades, which is one of the most commonly found type of opening found in the region, results in improper distribution as well as low indoor air velocities. About 25% of the space has little or no air movement with velocities close to 0 m/s.

The indoor air velocity is found to be the highest in case C, where openings are distributed in all four facades for the entire height. The velocities are not only better than the other types, but it also results in a uniform spread which is desirable for an open plan space with every region occupied. The predominant wind velocity in the room ranges between 0.63 – 0.94 m/s (which is 12.8 – 19.2% of the outdoor wind velocity). Case F, where the ratio of the windward openings to the leeward openings is 1:2, also has comparable distribution, although the velocities are slightly lower (12.2% of the outdoor wind velocity). When the ratio of the windward openings to the leeward openings is reversed (2:1) as in case E, not only are the velocities very low, but the distribution is also very poor – with almost 50% of the space having velocities lesser than 0.15 m/s (3% of the outdoor wind velocity). A windward to leeward opening ratio of 1:1 (case D) also does not result in a satisfactory situation- as it has quite large pockets where the wind speed is zero or close to zero.

Air Velocity at activity level



Case A	Velocity	0.00	0.09	0.19	0.28	0.38	0.47	0.56	0.65	0.75	0.84	0.94	1.03 (m/s)
Case B	Velocity	0.00	0.09	0.18	0.28	0.37	0.46	0.55	0.64	0.73	0.82	0.92	1.01 (m/s)
Case C	Velocity	0.00	0.31	0.63	0.94	1.25	1.57	1.88	2.19	2.51	2.82	3.13	3.45 (m/s)
Case D	Velocity	0.00	0.16	0.31	0.47	0.63	0.79	0.94	1.10	1.26	1.41	1.57	1.73 (m/s)
Case E	Velocity	0.00	0.14	0.29	0.43	0.57	0.71	0.86	1.00	1.14	1.28	1.43	1.57 (m/s)
Case F	Velocity	0.00	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20 (m/s)

Figure 52 Air Velocity at activity level

The velocity distribution and speed at a height of 1m (where the human body rests) is more or less similar to the overall trend as seen above. Looking at the images it is clear that the velocity is maximum for case C (~0.94 m/s). Case F has the next highest velocity ranging between 0.60 – 0.80 m/s. The velocity is uniformly distributed in both cases. Wind velocity in all other cases is poor.

Operative Temperature

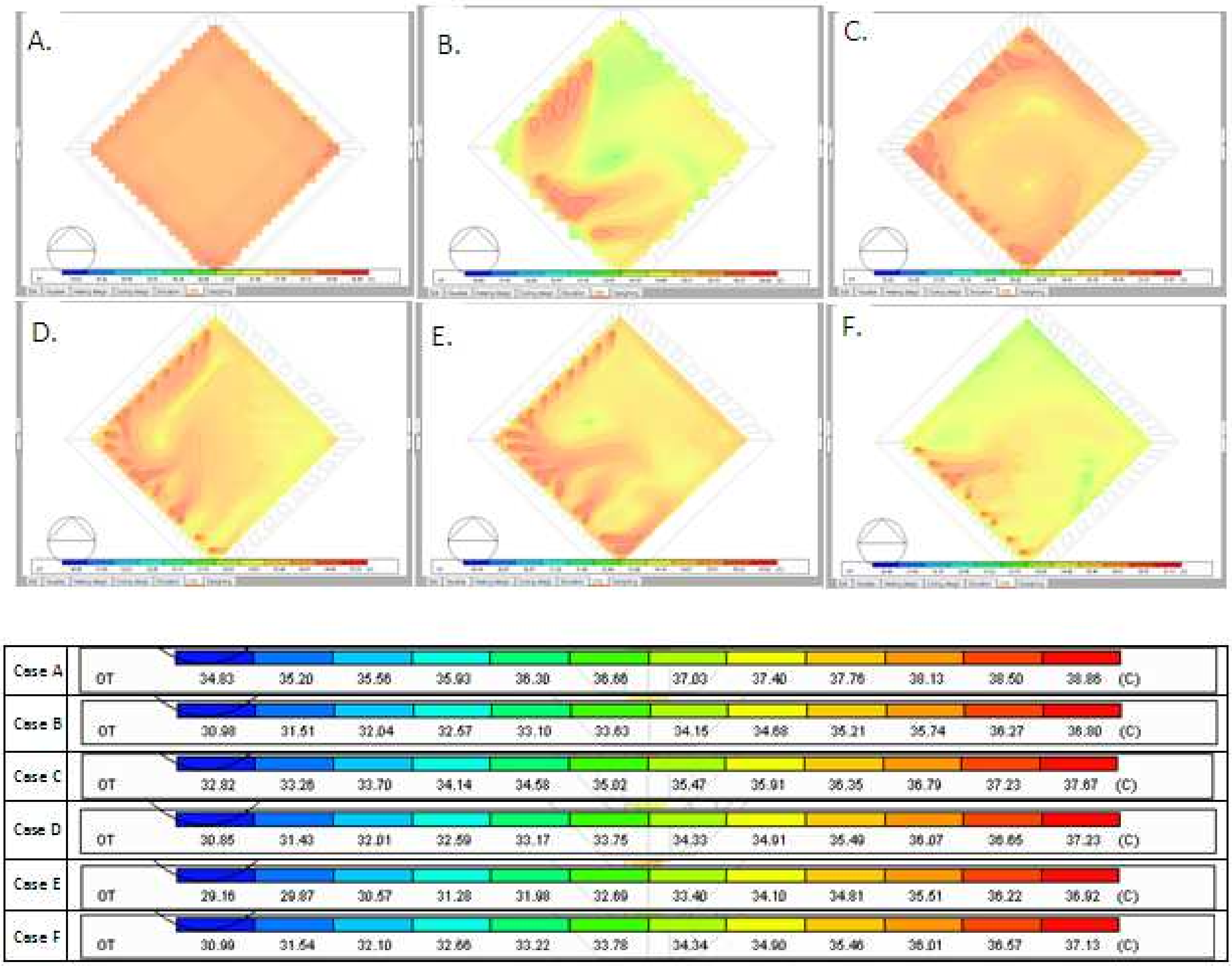


Figure 53 Operative Temperature at activity level

Comparing the images of the operative temperature with their respective images for the indoor air velocity, it can be noticed that a position with high velocity also has the highest operative temperature. This can correspond to the comparatively hotter air entering the room. Among the six cases considered the operative temperature is found to be the highest in case A, with values almost the same as that outside. Case E has the lowest operative temperatures (~34.10˚C as opposed to 37.8˚C outside) followed by case F (34.9˚C). A not so uniform temperature distribution can be observed in case E while similar to the velocity profile, cases A, C and F all have a uniform distribution throughout the room. However, comparatively case F has the lowest operative temperature among the three.

Age of Air at activity level

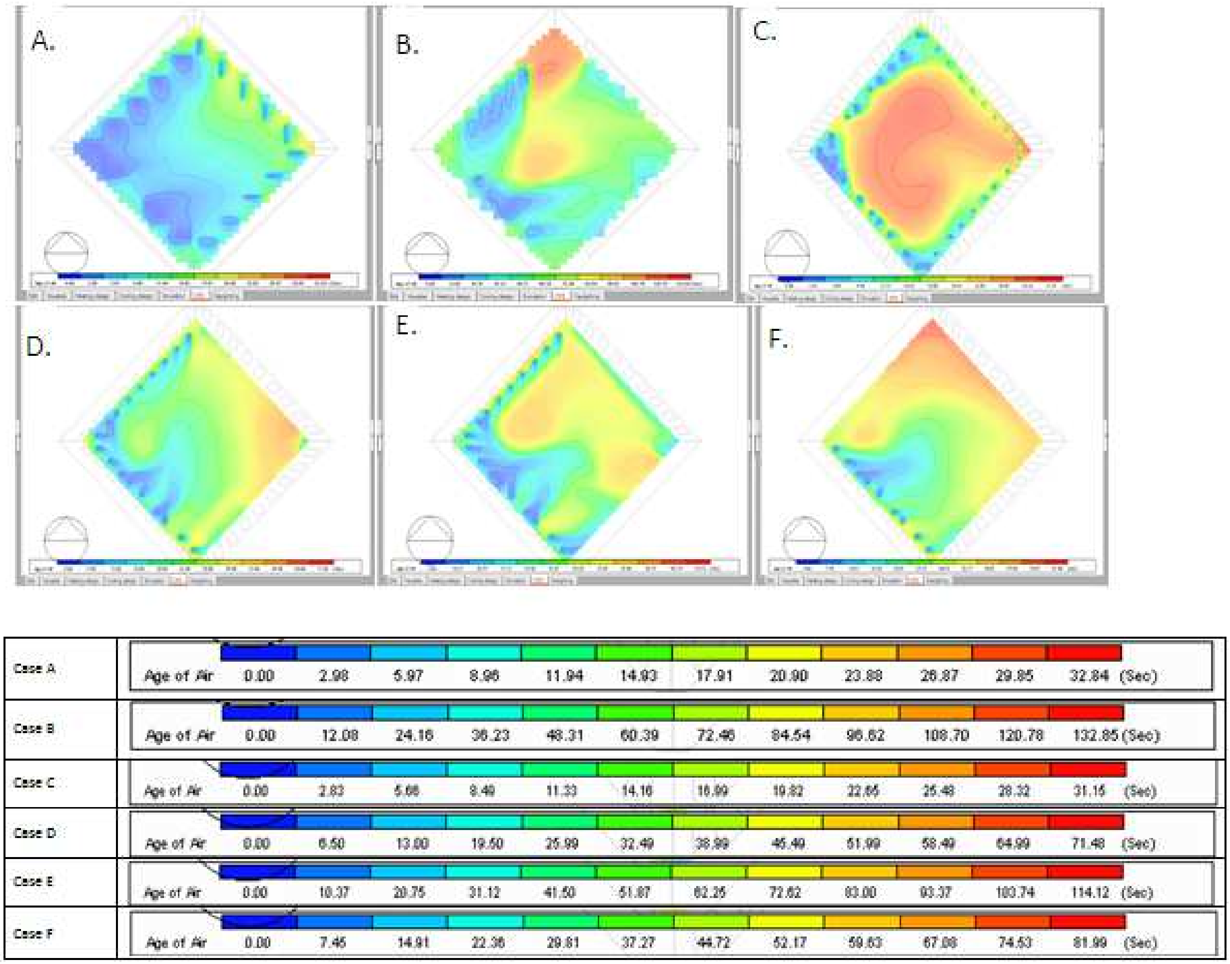


Figure 54 Air movement at activity level

The age of air at a certain location determines how good the air movement at that location is. All cases considered have reasonably good air movement- that is the values of the age of air are quite low. Case A has the lowest value (2.98 – 14.93 s) indicating an almost continuous air flow. Age of air is found to be oldest in cases E and F with large regions at 72.62 s and 80 s respectively. This is because a high windward to leeward opening ratio (as in case E) results in less air being drawn out by the leeward opening and consequently a slower rate of airflow entering through the windward openings.

The combination of operative temperature and velocity has to be considered to decide the best situation. Although case C results in the highest indoor air velocity, it also has very high operative temperatures (35.9 – 36.8 ˚C). Case F on the other hand has the next best velocity profile as well as a relatively much lower operative temperature (34.9 ˚C). Therefore this seems to be the ideal configuration among the six cases that were studied.

Here the inlet to outlet opening ratio was assumed to be 1:2. This can be varied further to identify the optimum opening area ratio. Further, all the inlet openings were provided on just one of the two facades facing the windward direction. The effect of having openings on both windward sides was already studied in case D. However, in that situation the inlet to outlet opening area was 1:1. Therefore the effect of distributing the inlet openings on both the windward facades and still maintaining a low inlet to outlet opening area ratio has to be further studied. This could not be done in the current study due to the large computational time involved with the CFD calculations.

Variation in Velocity at Different Elevations

The calculations for all the above simulations were carried out for a building located at the ground level. As we go higher up in the elevation, the external obstructions to wind flow are lesser in urban areas, hence leading to higher indoor air velocities.

Remarks:

Some problems were observed while working with the CFD models using DesignBuilder, especially when the main axes of the building were oblique to the cardinal axes. Although complete or reasonable amount of convergence of the different residuals occurred after running the simulations for a while, initial behavior of the residual curves were found to be quite erratic. Choosing a different turbulence model or discretisation scheme also did not prove to be suitable. So wasn't modifying the grid size (by making the grids more fine). Therefore use of a more advanced CFD tool to verify the results is recommended.

8.4 Effect of Shading Devices on Airflow

In hot humid climates, openings often demand to be closed partially or completely during times of heavy rains or storms. Adjustable louvers are effective options for such purposes provided they are able to withstand the intensity of the wind. Shading devices should be designed in such a way that they cause minimum restriction to air movement and reduction of air velocity within the occupied zone. Louvers are usually used for this purpose. In the North and the South façade horizontal louvers are effective in blocking the sun while vertical louvers are more appropriate for the West and the East façade as the afternoon low angle sun can easily make its way in, in case of horizontal louvers. The influence of the louvers on ventilation should be studied in order to choose the ideal one for optimizing indoor wind speed and movement.

Most types of louvers are found to reduce the indoor air speed by a considerable amount. The change in velocity as a percentage of the original indoor velocity is given for two types of orientation of the wind: 0˚ and 45˚ for different types of louvers in the table 7 below:

Type of Louver	% Change of velocity	
	0˚	45˚
Horizontal (Sunshade)	-20	-20
L-type (Semi-Box type)	+5	+10
Box Type		
Contraction Ratio 1:1	0	-25
Contraction Ratio 2:1	0	0
Multiple Horizontal	-10	-13
Multiple Vertical	-15	-25

Table 7 Effect of different types of louvers on wind velocity [Source: Bansal et al., 1994]

8.4.1 Horizontal Louvers

Horizontal adjustable louvers making an angle of approximately 120˚ - 135˚ with the plane of the wall is proven to be effective in directing the air flow downwards towards the occupied zone (Givoni, 1974; Chiang et al., 2005). This however will be disadvantageous from the shading point of view as such an orientation will only increase the solar loads.

Chiang et al. (2005) arrived at a correlation between air change and the effective depth of louver. The efficiency of air change with respect to different wind velocities was also analyzed. Air flow rates were found to increase with increasing depth and an increasing linear trend was observed with the increase in the square of wind velocity. Chiang et al. also studied the effect of a horizontal louver on the indoor air temperature at zones between 0.6 m to 0.9 m where the human body rests. As the depth of horizontal air-ducting louvers increases, outdoor cool air is found to be effectively ducted into the lower indoor space, which subsequently pushes the warm air in the region upwards. For wind velocities less than 0.5 m/s, it was found that the warm indoor air cannot be effectively removed if the opening is without installing louvers, and temperatures were found to accumulate especially around the resting site for the human body.

Louvers with low depths were found to be ineffective as they were not only unable to lower the temperature accumulation, but they lead to an increase of the same instead. This was attributed to limited air ducting performance of louvers with low depths. At very low outdoor wind velocities louvers with depth above 0.09 m were found to improve the indoor comfort. Depths between 0.36 m and 1.44 m were identified to be optimum dimensions for moving out hot air effectively especially when the wind velocities are found to be low. Increase in the depth also causes an increase in the draft rate. A depth of

1.44 m was found to keep the draft rate far above 25% which can have a significant impact on the human thermal comfort, but at the same time be unsuitable for certain activities. Further a high depth can also lead to losing a sizable area of the indoor floor space.

In a different study conducted by Chand and Krishak (1971), effect of a single as well as multiple horizontal louvers (perpendicular to the façade) on the indoor air speed and movement at different positions of a room was studied for different orientations of the wind. With respect to a single louver, it was seen that for all orientations, the presence of a louver caused a slight increase in the wind speed at the lintel level. At the mid-window level, a very low increase in the air velocity was observed for normally incident wind which gradually decreased as the orientation became more oblique. At the sill level presence of a louver did not seem favourable for any orientation as it caused a reduction in the air velocity for all orientations. With respect to the air movement at the sill level, it was observed that for the normally incident wind, total area over which addition of the louver caused a decrease in the air motion was higher than that with an increase in air motion. The situation reversed at higher levels. For the wind incident at 45 ° the air movement is again poor at the lower levels up to the mid-height. Above the mid-plane of the window, there was no improvement or reduction in the air movement. Multiple horizontal louvers were found to promote air motion at planes passing through the top and centre of the window for normally incident wind and had a negative effect for obliquely oriented wind. "The horizontal type of louver helps air motion at higher levels and reduces it at lower levels. This may be attributed to the horizontal projection disrupting the force component from the upper side of the window and allowing the force from the lower side to deflect the incident air stream in upward direction" (Chand and Krishak, 1971).

8.4.2 Vertical Louvers

In the same study conducted by Chand and Krishak (1971), multiple vertical louvers were also assessed for the same parameters and it was concluded that the reduction in the air movement as well as the indoor air velocity is much higher than the horizontal louvers. The louvers considered were perpendicular to the façade and extended outwards completely.

Although there are some texts claiming that the orientation of the louver can help in guiding the indoor air flow in a desired way, not much literature could be found on the effect of doing so on the indoor air velocity. In order to get a better understanding CFD analysis for two different orientations of the louvers were performed and compared with a base case with no louvers at all. Placing the louvers at the plane of the opening was not possible with DesignBuilder. Placing it just outside the opening caused instability in the calculations. Therefore the louvers here were placed completely within the room. Although the wind velocities may not be exactly the same, more or less similar effect can be expected to be caused by the obstruction of the louvers.

Figure 55 represents the top view of the velocity contour. The direction of the wind is 270˚ to the North. In case A the louvers are oriented parallel to the direction of the wind whereas in case B they are oblique to the direction of the wind. Case C is the base scenario without any louvers.

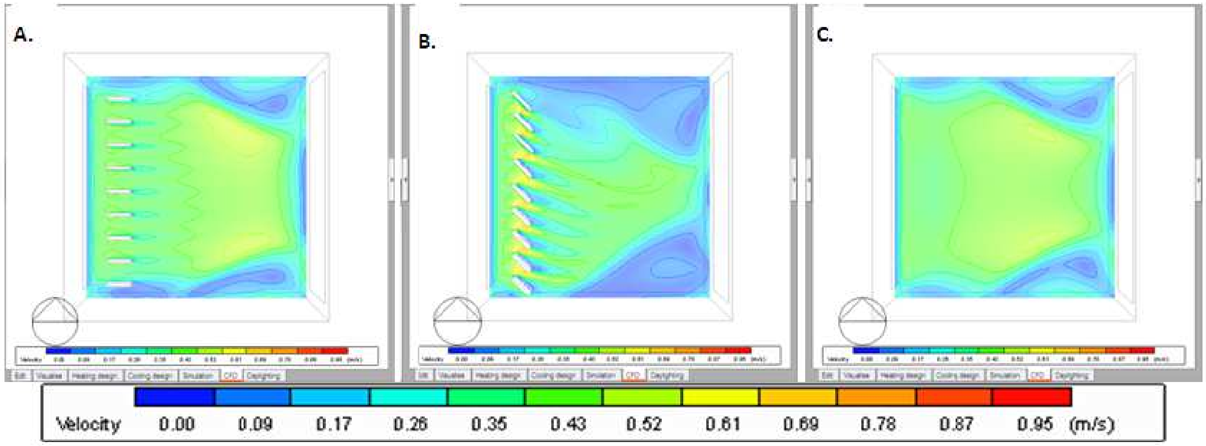


Figure 55 Effect of different orientations of vertical louvers on the indoor wind velocity

It can be observed that in case A, barring a little reduction in velocity just ahead on the other end of the louver, the velocity in the rest of the plane remains more or less unaffected. On the other hand, the velocity distribution changes quite drastically when the louvers are placed oblique to the wind direction (case B). The suction caused at the other end of the louver causing a dip in velocity is also evident. It also has to be noted that the velocity is increased at the inlet opening between two louvers. This is because the opening is now oblique to the incoming wind causing an increase in velocity. However the effect of the increased velocity diminishes quite quickly. Earlier in this chapter the possibility to use external louvers to change the orientation of the incoming wind in such a way that it causes an increase in indoor air velocity was discussed. That would ideally refer to a situation similar to case B. The results presented in this section are contrary to that notion.

Airfoil Shape

In figure 55 it can be noticed that the air velocity just ahead of the louver is lower than the regions adjacent to it. This is because of separation of flow caused by the pressure losses at the tip of the louver. “Airflow separation is a function of the prevailing airflow Reynolds number, the pressure drop through the void between two louver, louver geometry, any sharp edges on the louver, louver surface roughness and louver angle.. As the louvers are manufactured from the same material and of the same geometry, the louver geometry and in particular the louver angle is considered as the dominate factor in creating local flow separation” (Hughes, 2010).

An airfoil shape, due to its streamlined geometry is generally preferred in various fields to achieve a reasonably uniform flow and lesser reductions in velocity. NASA has extensive information on various configurations and their performance. For an effective performance, proper positioning of the airfoil with respect to the incoming wind direction is important. This section is only a brief introduction to other possibilities to improve the air flow pattern caused by louvers and will not be discussed any further in this report.

8.4.3 Pivoted Windows

Pivoted windows can in a sense be considered as louvers. The orientation of the pivoted window-upward/ downward and the effect of angle made by it with respect to the neutral position on indoor air movement were studied by Prianto and Depecker (2003). Pivoted windows in upward position were found to be better compared to those in the downward position. Maximum increase of air speed (19% at a height of 1m from the floor level) can be achieved at an angle of 45˚. This result is in line with that obtained by Givoni (1974) and Chiang et al. (2005) where the optimum angle of horizontal louvers was identified to be 135˚ (when measured from the plane of the wall).

When the orientation of the pivoted window has to be kept downwards, a 45˚ tilt was identified as the optimum position especially for comfort at levels above 1m (Prianto and Depecker, 2003).

Sun-shading Vs Effective Airflow

Positioning the shading devices according to the direction of the wind may not always result in an orientation that can best provide protection against the sun. It is difficult to prioritize one over the other as both sun-shading as well as air flow are of high importance. Studies by Hien and Istiadji (2003) proved that vertical shading devices when solely used are not effective in enhancing natural ventilation. A combination of vertical and horizontal shading devices is discussed below.

8.4.4 Box Type Louver

A box type louver is one having projections on all four sides of a window. The projections may be normal to the wall or at an inclination expanding outwards. The ratio of the size at the entry section of the louver to that at the point of actual entry is known as the contraction ratio. A box type louver with the projections inclined outwards has a contraction ratio higher than one. Chand and Krishak (1971) studied the performance for two different values of the contraction ratio- 1:1 and 2:1.

They concluded that the box type louver accelerates indoor air motion for wind that is normally incident whereas results in a reduction in the air motion for wind which is obliquely incident. The reason for this is attributed to the obstruction to the flow of outdoor wind caused by one of the vertical projection. They also claim that increasing the value of the contraction ratio of a box-type louver results in an increase in indoor air motion for a wider range of angles of incidence.

8.4.5 Semi-Box Type Louver

Following the analysis of a box-type louver, a semi-box type louver was assessed. These have one horizontal projection above the window and a vertical projection at one of the sides (positioned in such a way that it does not obstruct the incoming wind). Increasing wind velocity at different levels can be achieved using such a system. This is true for both normal as well as obliquely oriented winds. Prominent improvement in the air movement was also observed for all cases- with 70% increase at the lintel level (Chand and Krishak, 1971).

8.5 Conclusions

Several conclusions can be drawn based on the observations as well as literature study presented in this chapter.

- Wind entering an opening at an angle oblique to the plane of the opening results in high indoor air velocity, with the highest velocity for an angle of 45˚. For this reason, as far as possible the building should be oriented in such a way that the predominant wind direction is 45˚ to the opening.
- During other times when the direction of the wind is not oblique to the opening, literature suggests that additional structures such as vertical louvers or pivoted windows can be positioned in such a way that they change the orientation of the wind entering the opening. The extent to which this can improve the indoor air velocity should be studied further as this was not possible within the scope of the CFD tool in DesignBuilder.
- Distributed openings result in better distribution of air flow across the room. A small ratio of windward to leeward opening results in higher air flow. Further windward openings should be placed closer to the sill level and leeward openings should be placed closer to the ceiling in order to constantly remove the hot air out of the building.
- With respect to achieving high indoor air velocities for air flow through louvers, an inclination of 135˚ with the plane of the wall is considered ideal for horizontal louvers; whereas vertical louvers positioned parallel to the direction of wind flow is considered effective. The formation of separation at the tip of the louver can be reduced by choosing an appropriate geometry for the louver.
- Orientation of vertical shading devices with respect to the sun as well as the prevailing wind direction may sometimes result in conflicting demands. For such situations, a semi-box type louver should be considered as it not only provides protection against the sun but also results in an increase in indoor air velocity as well as movement for all orientations of wind. Horizontal louvers can be oriented at 90˚ when solar loads need to be blocked and at 135˚ during all other times.
- The provision of a ceiling fan, which is quite common in hot-humid regions was not considered so far. However, they are said to create a pressure drop that induces airflow inside the rooms and substantial increase in the internal air velocities (Priyadarsini et al., 2004).

Chapter 9: Thermal Mass

Bamboo is generally considered as a low thermal mass material, that is, it is not said to store any heat. This property is considered ideal for a building material in a hot-humid climate and it is for this reason that a hot-humid climate was chosen as an ideal climate which can benefit from bamboo. However, the analysis as discussed in the previous chapters proved that thermal mass is favourable during the daytime as it helps in controlling the indoor surface temperatures to a large extent. At the same time, the heat accumulated in the high mass is partially transferred to the interior surface during the night time leading to rise of interior temperature. This effect of this phase shift, which is typical of high rise buildings, is not desirable. This conclusion is important as it forms the design basis for this study. Looking at the principle behind the functioning of thermal mass can give more insight about how much thermal mass is possessed by bamboo and if it can in fact contribute in some way. If the material properties and the chosen climate do not go hand in hand an alternative climate has to be chosen.

9.1 Principle behind thermal mass

Diurnal variations in temperatures result in a 24 hour repetitive cycle of increasing and decreasing temperatures. This continuing cycle has the same effect in the heat flow through building materials as well. The amplitude of the heat flow curve of the material can be different from that of the outdoor temperatures and this depends on the thermal mass of the material or the ability of a material to store heat. Also, the thermal storage causes the peak values of both the curves to occur at different instances. That is, they are separated by a certain time lag. This periodic change in heat flow can therefore be characterized by two parameters: amplitude decrement factor and time lag.

The ability of a material to store heat depends on its density, thermal storage capacity and thermal conductivity. Thermal conductivity is the property of a material to conduct heat. Materials with low thermal conductivities are poor conductors of heat. The specific heat capacity of a material determines the amount of heat required to change the temperature of a unit mass of a material by 1˚C. A material with high specific heat capacity takes more time to be heated or cooled. Bamboo has a thermal conductivity much lower than other common building materials such as brick, concrete or steel and a specific heat capacity much higher than the same materials.

These thermal properties are used to define two other parameters namely: diffusivity and effusivity which in turn are used in determining the amplitude decrement factor and time lag.

Diffusivity

Thermal diffusivity ‘a’ represents the rate at which heat imposed at one side of a wall diffuses through the material and propagates through the other side. Larger the thermal diffusivity, the quicker is the heat transfer through the wall. It is given as:

Diffusivity (m^2/s) = $\frac{\lambda}{\rho.c}$

Where λ: Thermal Conductivity of the material in W/m.K

ρ: Density of the material in kg/m^3

c: Specific Heat Capacity of the material in J/kg.K

Effusivity

The thermal effusivity 'b' is related to the ability of a material's surface to absorb the energy received from the surrounding and impose this heat over other materials which are in physical contact with it.

Effusivity ($Ws^{1/2}/m^2K$) = $\sqrt{\lambda.\rho.c}$

For a construction of thickness 'x' (m) and diffusivity 'a' (m^2/s) the time lag, depth of penetration and amplitude decrement factor can be calculated for a diurnal variation as follows:

Time Lag:

The time lag (s) = $\frac{x}{\sqrt{2.a\omega}}$

$\omega = \frac{2.\pi}{86400}$ is the diurnal frequency. (s^{-1})

Depth of Penetration:

d (m) = $\sqrt{\frac{2a}{\omega}}$:

Amplitude Decrement Factor (μ) :

$\mu = \exp(-x.\sqrt{(\frac{\omega}{2.a})})$

The closer the decrement factor approaches zero, the greater is the effect of the construction element on attenuation. That is materials with smaller values of decrement factors are more effective at suppressing temperature swings.

Due to the ability of the materials to store heat, the heat flow is unsteady or transient. That is the heat flow into a material is not equal to the heat flow out of the material.

Thermal Properties of Bamboo

There is not much literature with respect to the thermal properties of the different commercially available engineered bamboo products. The density of a commercially produced bamboo is generally around 900 kg/m^3 hence the same value was assumed. The thermal conductivity increases with the increase in density. M.C. Kiran et al. (2012) arrived at a formula to express the thermal conductivity as a function of density:

$$\lambda = 0.328.\ \rho - 0.143$$

Where, λ : Thermal Conductivity of the material (W/m.K)

ρ: Density of the material (kg/m^3)

For ρ = 900 kg/m^3 , $\lambda = 0.152$ W/m.K

Specific Heat Capacity (c) of bamboo is normally assumed as 1680 J/kg.K

The values of diffusivity, effusivity, heat penetration depth and thermal lag are calculated and are compared with other common building materials (Table 8).

Material	Thermal Conductivity 'λ' (W/mK)	Density, 'ρ' (kg/m³)	Specific Heat Capacity, c (J/kg. K)	Diffusivity, 'a' (m²/s)	Effusivity, 'b' (Ws$^{1/2}$/m²K)	Depth of Heat Penetration (m)	Time lag (h) for thickness = 0.1 m	Amplitude Decrement Factor (µ)
Steel	15 - 17	7800 - 8000	490 - 530	39.2×10^{-7} - 40.1×10^{-7}	7570 - 8490	~ 0.33	1.15	0.74
Concrete	0.3 - 1.3	1400 - 2000	860 - 1100	2.5×10^{-7} - 5.9×10^{-7}	600 - 1690	0.083 – 0.13	3.00 – 4.60	0.30 – 0.45
Brick	0.6 - 0.8	1690 - 1950	750 - 850	4.7×10^{-7} – 4.8×10^{-7}	870 - 1150	0.11	3.30	0.42
Rammed Earth	0.8	1600	1000	5×10^{-7}	1130	0.12	3.25	0.43
Bamboo (transverse)	0.10 – 0.11	600 - 800	1660 - 1710	0.8×10^{-7} - 1.0×10^{-7}	315 - 385	0.05	7.30 – 8.10	0.12 – 0.15
Bamboo (longitudinal)	0.16 – 0.18	600 - 800	1660 - 1710	1.3×10^{-7} - 1.6×10^{-7}-	400 - 495	0.06	5.75 – 6.40	0.19 – 0.22
Bamboo (BMB)	0.15	900	1680	1.0×10^{-7}	476	0.05	7.30	0.15

Table 8 Comparison of Thermal properties of various materials

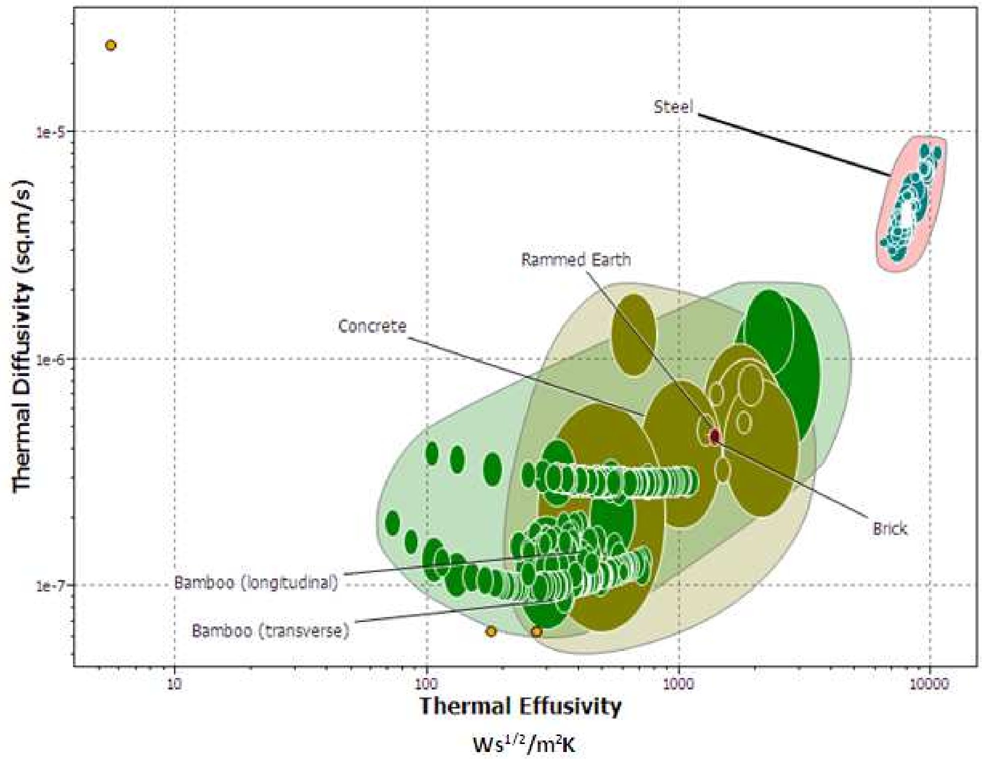


Figure 56 Comparison of Thermal Diffusivity & Thermal Effusivity of various materials [Source: CES EduPack 2013]

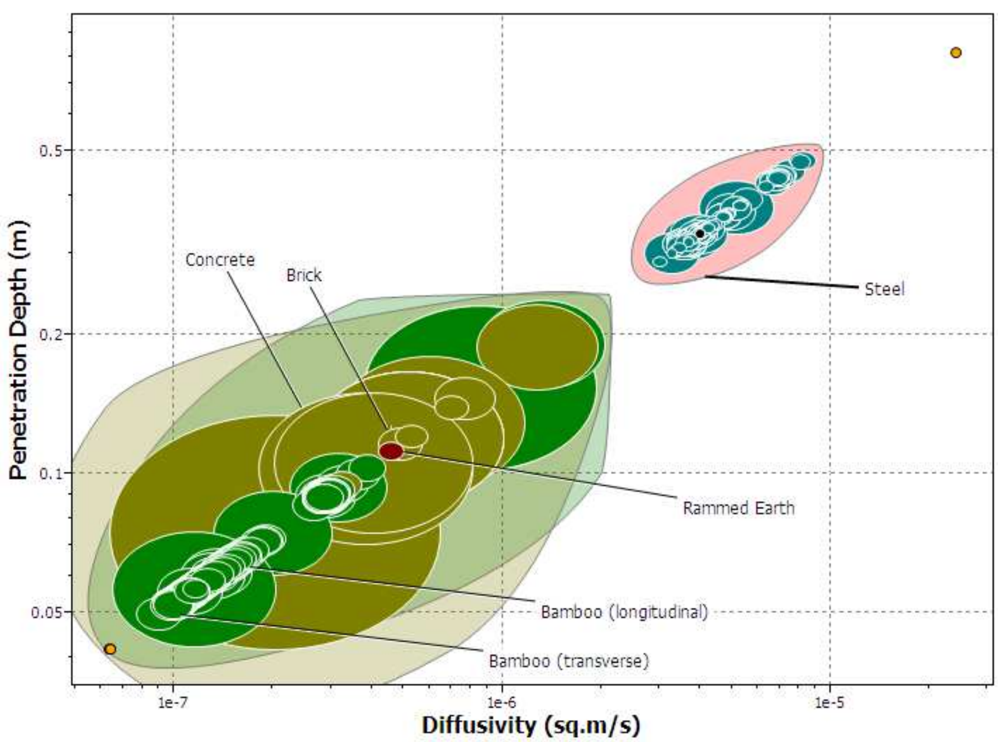


Figure 57 Comparison of Depth of Penetration of Heat for various materials [Source: CES EduPack 2013]

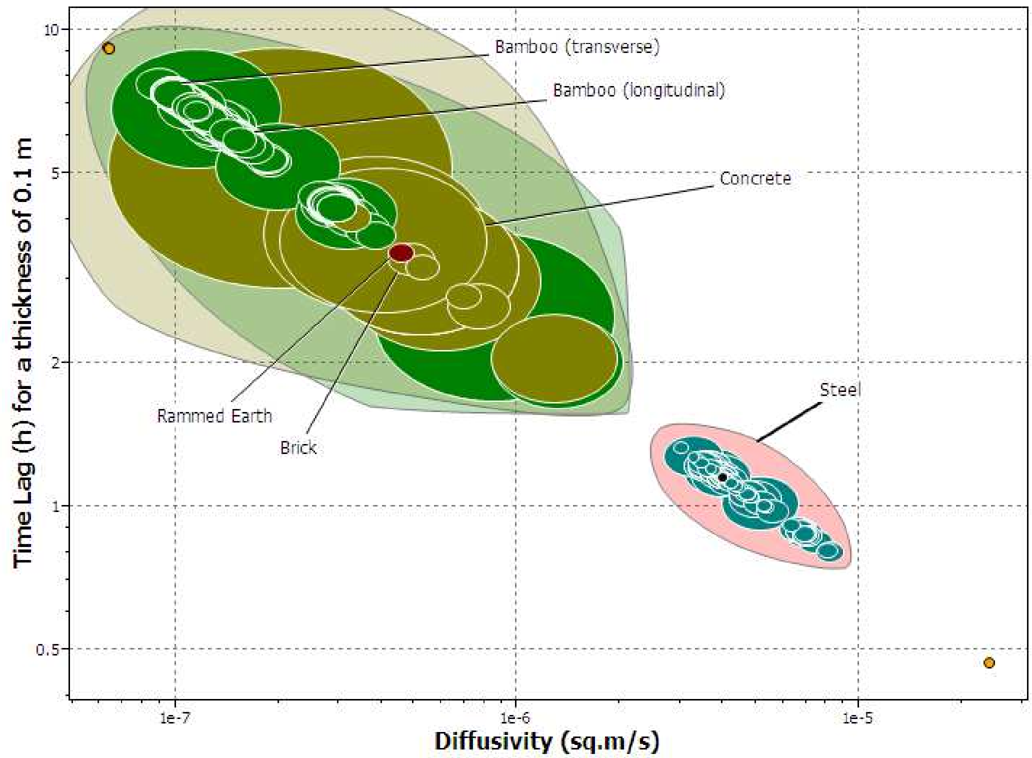


Figure 58 Comparison of Thermal Lag for a material thickness of 0.1 m [Source: CES EduPack 2013]

9.2 Determination of Optimum Thickness

Bamboo has comparatively low thermal effusivity as well as thermal diffusivity. The heat penetration through bamboo is only about 0.05 – 0.06 m. These values imply that it will behave as a good thermal insulator. The time lag for the heat to travel through 0.1 m thickness of each material is calculated and again it can be observed that bamboo has the highest time lag among all the materials considered. This time lag (7 – 8 hours) is ideal for buildings in the hot-humid climate which will predominantly be occupied during the day. (Heat released after 7-8 hours will increase the indoor temperature higher than the outdoor temperature).

In theory, this indicates that in the case of other materials, a thicker element will be required to store the same quantity of heat as stored by a 0.06m thick bamboo element. However this might be entirely applicable only when heat transfer is through the same direction throughout the construction. In reality however heat flow might not always be unidirectional, especially in free running buildings, a higher indoor air temperature can influence the temperature of the internal layers of the wall.

In an attempt to identify the optimum thickness for a bamboo construction the indoor surface temperatures for different thicknesses as well as that of a 0.2 m brick construction (current situation) are compared for a random day having an intermediate climate (September 26th).

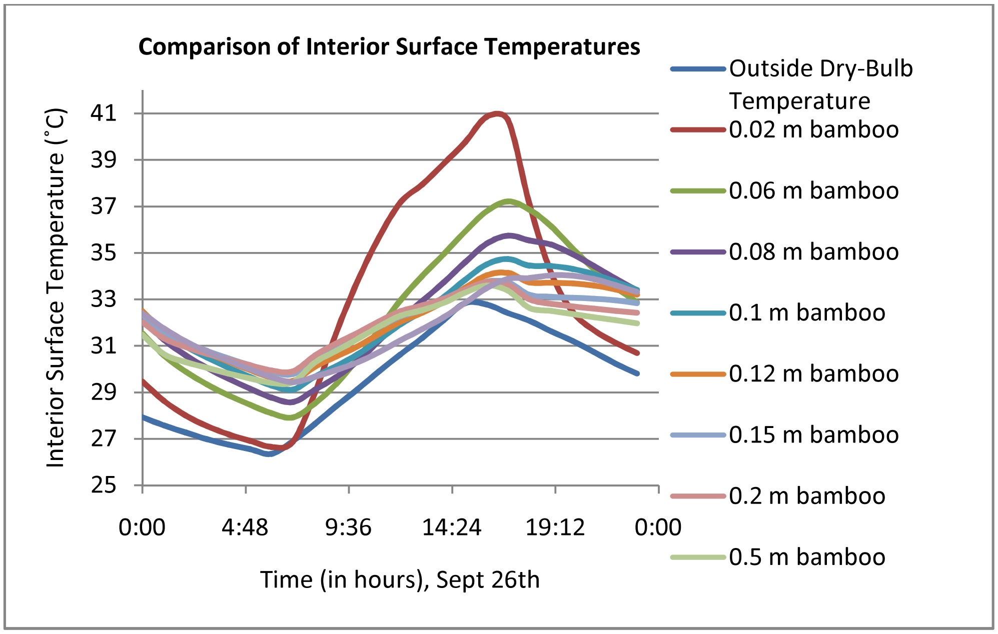


Figure 59Comparison of Interior Surface Temperatures for various thicknesses

For all cases, the outdoor dry bulb temperature is higher than the interior surface temperatures throughout the day for all cases. In the case of bamboo, it can be observed that during the day, the indoor surface temperature falls with increase in thickness of the wall. The decrement rate however decreases with the increase. This is obvious looking at the temperatures of a 0.2m and a 0.5m massive wall. This is because the thermal lag is directly proportional to the thickness of the construction. That is, if a 1m thick bamboo wall can store heat for 7 – 8 hours, a 0.5 m thick wall will be able to do so only for 3.5 – 4 hours. There is negligible change in values beyond a thickness of 0.12 m, barring a few hours in the late evenings. Therefore it can be assumed that beyond a thickness of 0.12m there is hardly any improvement in surface temperatures. This thickness can be increased up to 0.2 m, but the effect of the increment will be negligible.

Comparing the performance of a 0.2m brick wall and a 0.12 m bamboo wall, it can be noticed that the former has slightly lower temperatures until the late afternoon, after which the latter performs better.

9.3 Effect of Insulation

A thick (heavy) construction has the disadvantage of increasing the material costs as well as the dead weight of the construction. Introduction of an insulation layer (on the exterior) can be beneficial in lowering the surface temperature and at the same time to maintain a light weight structure. A thin panel of bamboo (0.01 m thick) can be additionally used to cover the insulation. The outermost layer of bamboo need not be very thick as it is only acting as a weather proof layer. That is, an insulation layer is considered to be sandwiched between two layers of bamboo. The insulation layer offers resistance to heat flow whereas the innermost layer of bamboo acts as a thermal mass.

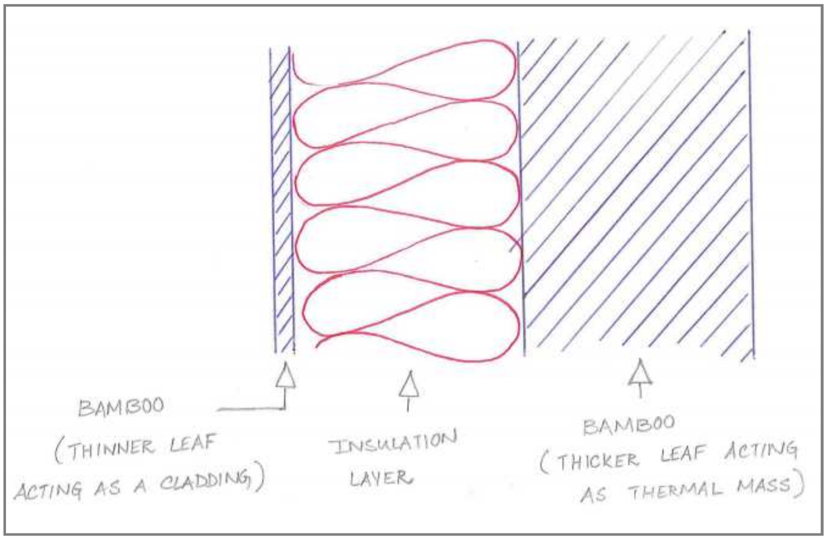


Figure 60 Cross section of the built-up with insulation

In order to study the effect of the insulation, an insulation material having a thermal conductivity of 0.05 W/mK is assumed. The following cases are compared:

a) Uninsulated 0.12 m thick bamboo construction
b) Uninsulated 0.2 m thick bamboo construction
c) Uninsulated 0.5 m thick bamboo construction
d) Uninsulated 0.2m thick brick construction
e) 0.01m thick bamboo + 0.1 m thick insulation + 0.12m thick bamboo construction (with denser layer on the inside)
f) 0.01m thick bamboo + 0.2 m thick insulation + 0.1m thick bamboo construction (with denser layer on the inside)

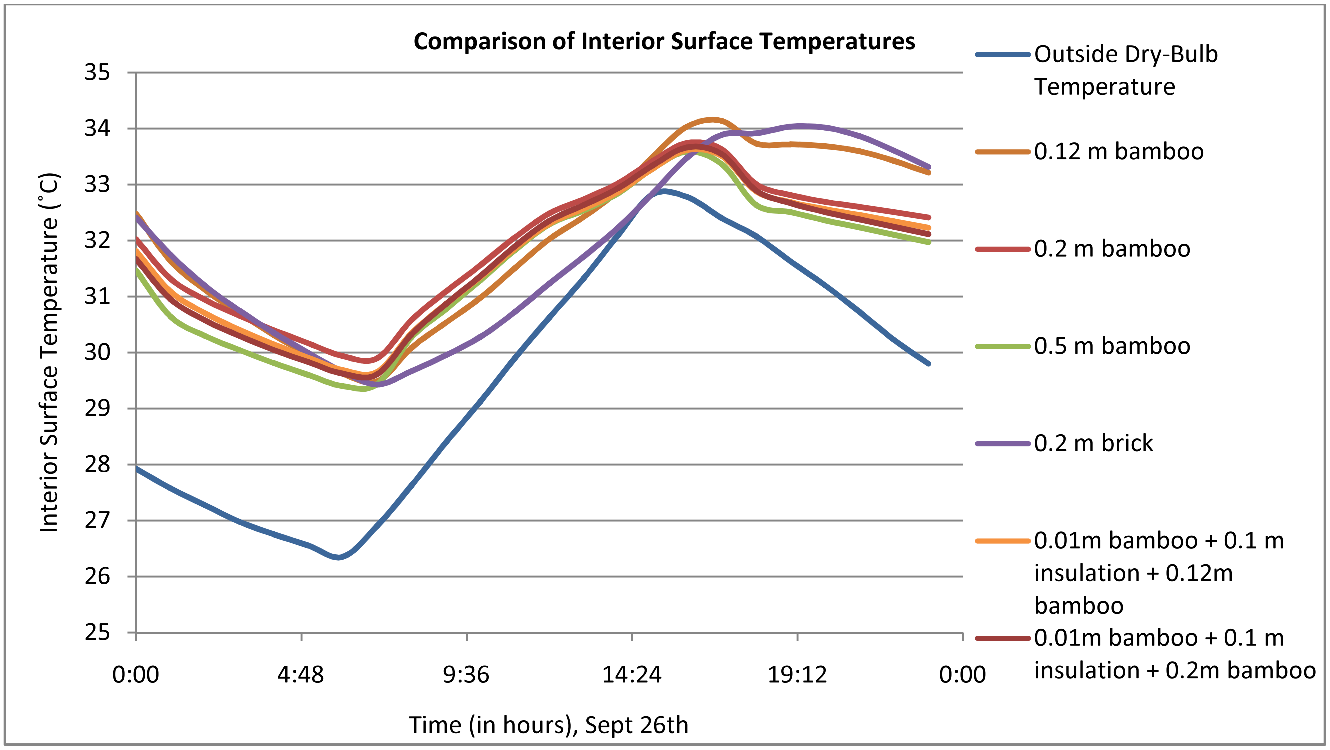


Figure 61 Comparison of Interior Surface Temperatures for constructions with and without insulation

Figure 61 compares the internal surface temperatures for the new set of cases. An additional layer of insulation to a 0.12 m thick bamboo construction results in a performance slightly better than an uninsulated 0.2m thick bamboo construction. Comparing the 0.12 m uninsulated construction with an insulated one, the latter appears to perform only slightly better (difference in temperature is ~ 1˚C). Assuming that the case is the same in the other 3 facades as well, the net reduction in operative temperature will be less than 0.5˚C. Further, increasing the insulation thickness to 0.2m also does not seem to have any effect. This behavior might be because the building is free running.

Comparing the indoor temperatures of a free running building with that of a completely closed building both having the same construction – 0.01m thick bamboo + 0.1 m thick insulation + 0.12m thick bamboo (with denser layer on the inside), shows the effect of insulation in both cases. From Figure 62 it is evident that insulation does not have much effect in a free running building.

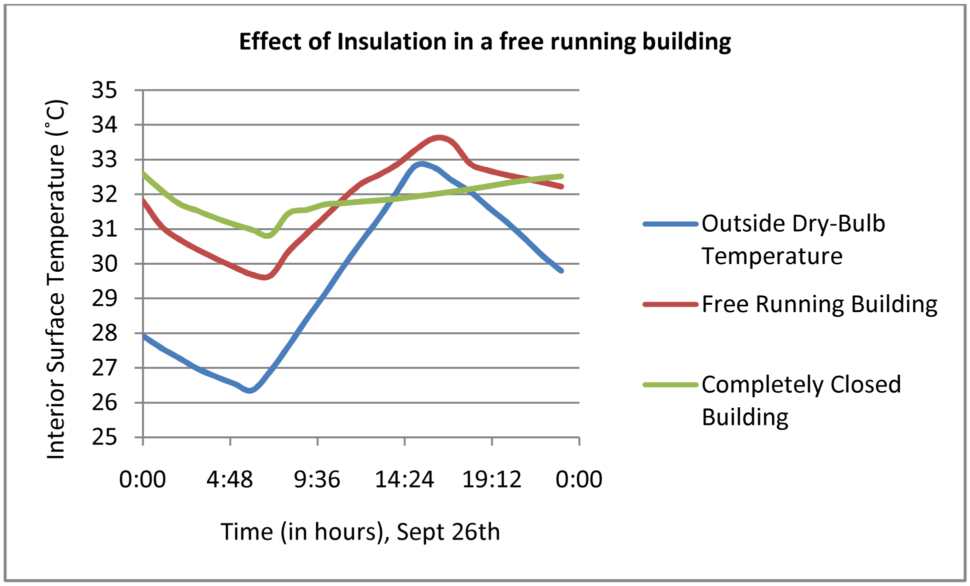


Figure 62 Effect of Insulation in a free running building

Figure 63 compares the variation of the exterior and interior surface temperatures with the outside dry bulb temperature.

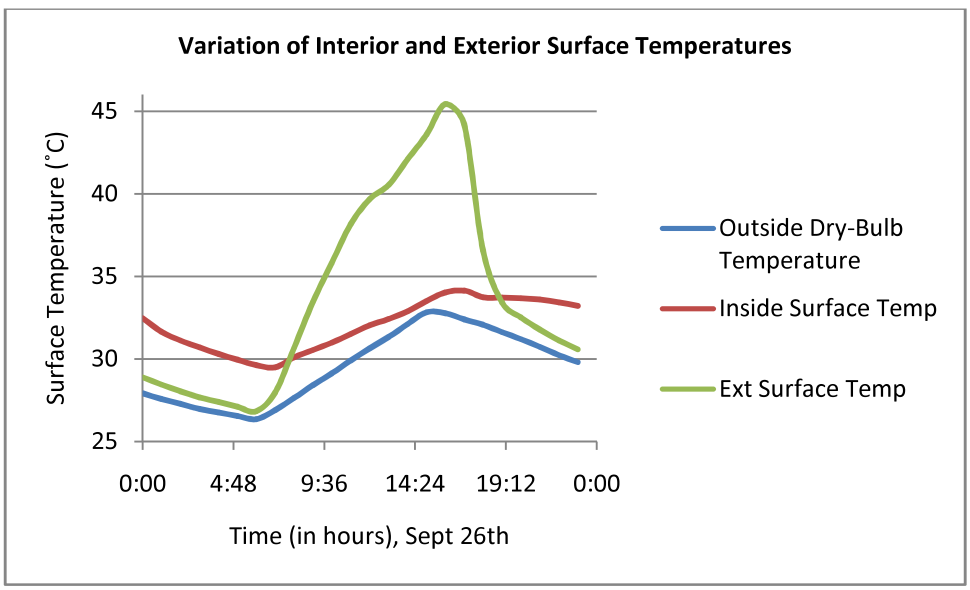


Figure 63 Variation of Interior and Exterior surface Temperatures during the course of a day

The exterior surface temperatures are more close to the outdoor temperature in the night and early morning hours whereas the interior surface temperatures are much higher. By interchanging the position of these two surfaces with respect to the boundaries that they are exposed to (inside/ outside environment), according to the trend in their surface temperatures, a constantly low interior surface temperature can be maintained. This will lead to lower mean radiant temperatures which will eventually result in lower operative temperatures.

9.4 Rotation of the elements

The previous chapters indicate the need for elements which are capable of movement: This is with respect to two different aspects:

1. **Ventilation point of view**:

- Position windward and leeward openings according to the direction of the wind.
- Control openings by opening or closing them in order to maintain an inlet/ outlet area ratio that maximizes air flow.

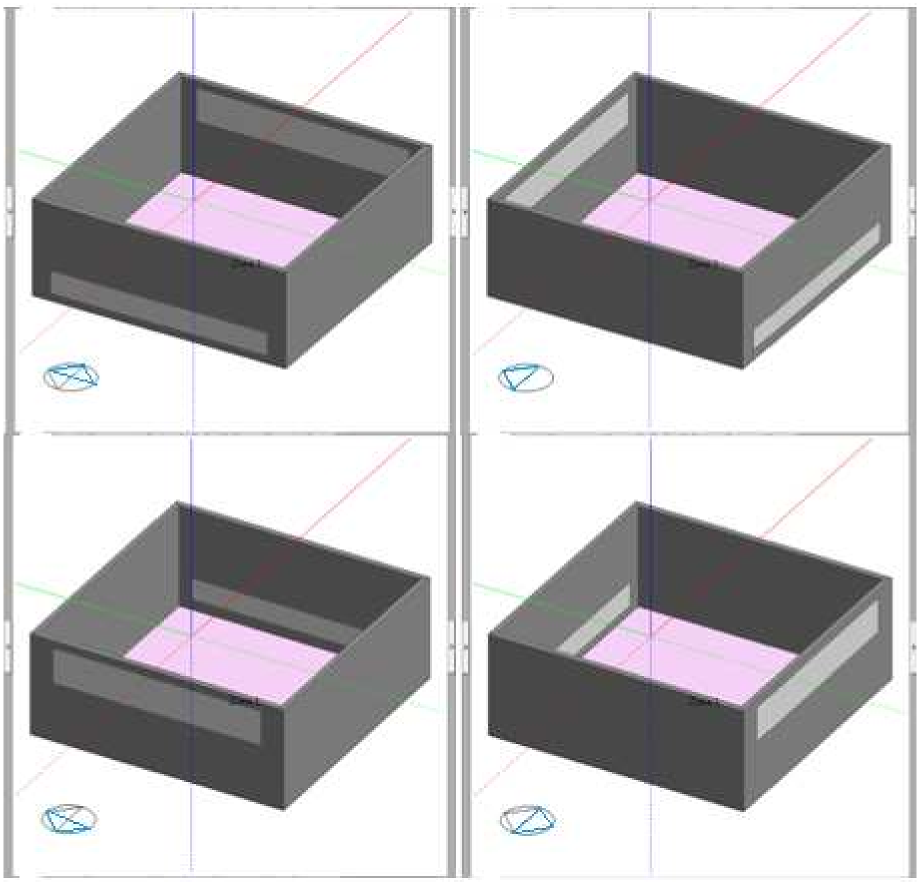


Figure 64 Location and sizes of windward and leeward openings according to different directions of the wind.

- Orient elements associated with the opening placed in such a way that it minimizes the obstruction to the flow and also maximizes the indoor air velocity.

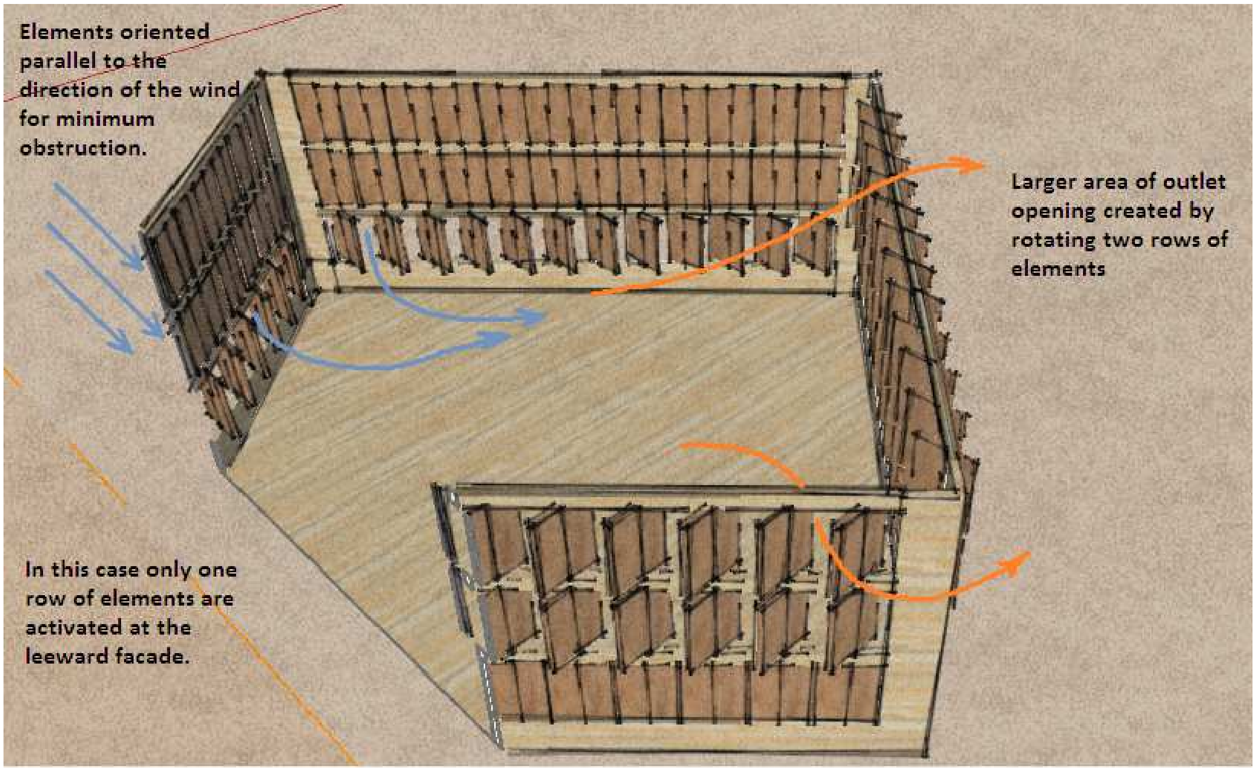


Figure 65 Shading Devices oriented in such a way that they cause minimum obstruction to the incoming wind.

2. **Thermal Mass point of view**: Interchanging the surfaces facing the interior in order to minimize the mean radiant temperatures of the surfaces.

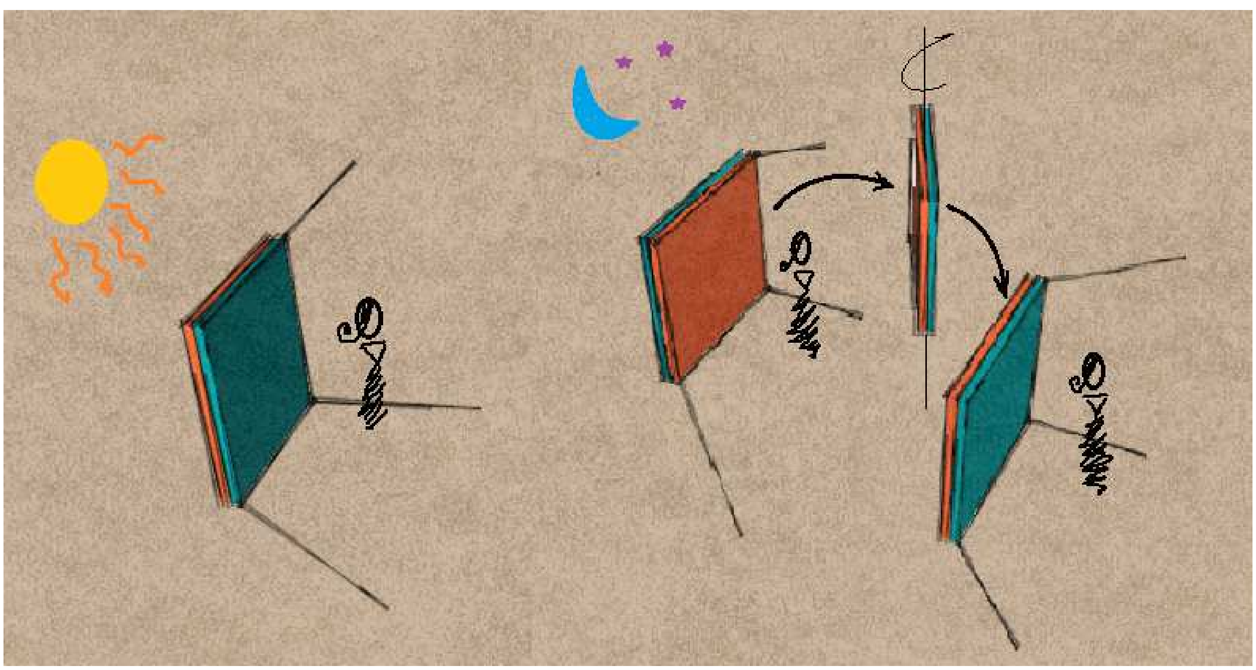


Figure 66 Variation in Surface Temperatures during the day (Transient Heat Transfer)

Both demand some sort of movement of the wall. If the wall as such can be considered to be made of a series of elements (bamboo slabs) which are capable of rotation about their axis, it can be dynamically controlled with respect to the needs of ventilation as well as thermal mass.

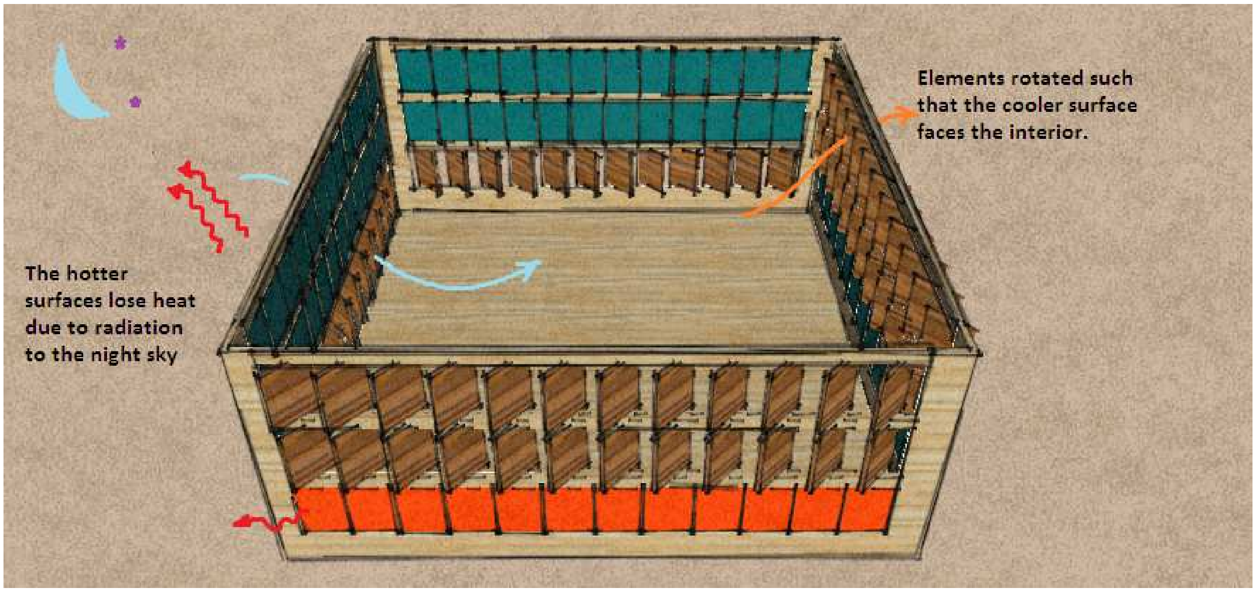


Figure 67 Combined Design Concept

9.5 Effect of Rotation on Heat losses through the construction

To roughly quantify the effect of rotation on the heat gain/ losses from the room, transient heat transfer calculations with and without rotation were done using a spreadsheet. The calculation methodology is explained in Appendix C.

The results from the calculation are represented graphically for the summer and intermediate situations. Rotation of elements is not considered for the winter situation as the increase in operative temperature during due to thermal mass is only advantageous during winter.

Intermediate Situation

The variation of temperature at different positions in the element over time is shown graphically in Figure 68. ‘0’ and ‘0.12’ represent the two outer surfaces of the element. From the image, the shift in temperature during the day is quite obvious.

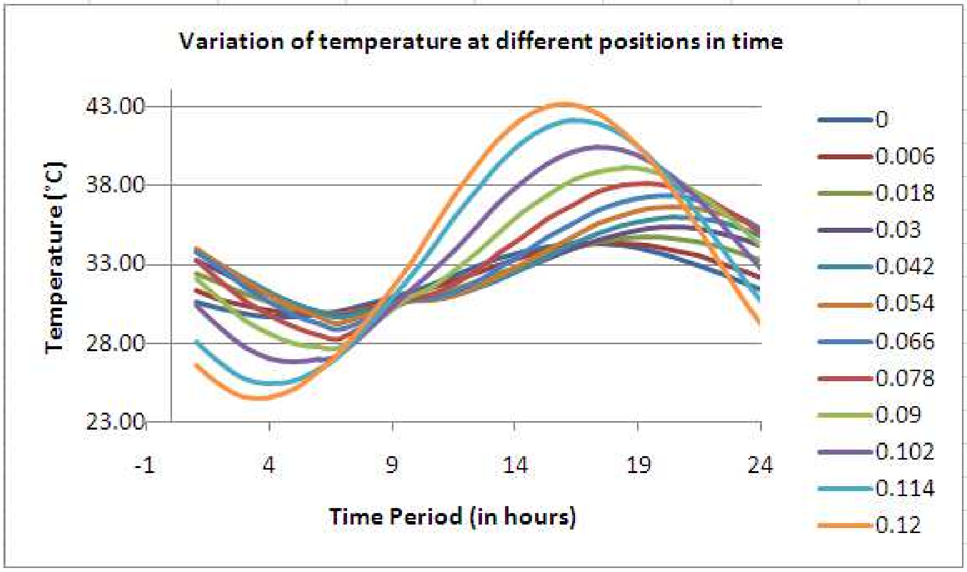


Figure 68 Temperature at different layers within the material, Intermediate situation- Chennai

The change in heat loss through a construction with and without rotation is represented in Figure 69. For the intermediate situation the MRT is higher than the indoor air temperature for most part of the day resulting in heat gains throughout the day. The difference is much higher during the nights, resulting in higher heat gains in a normal situation without rotation. With rotation, the relatively cooler side of the element is facing the room and hence creating a cooling effect in the form of heat losses through the construction.

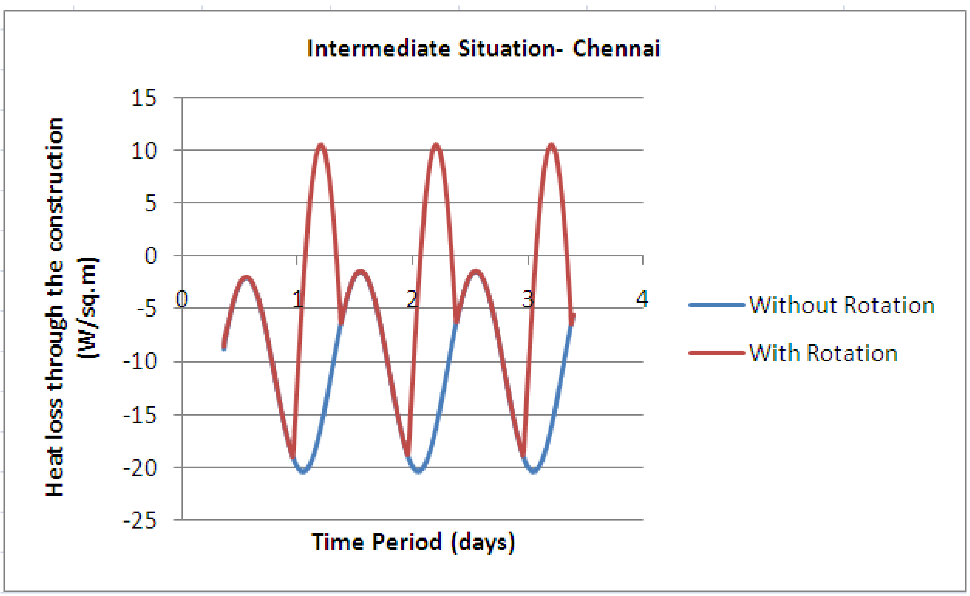


Figure 69 Heat losses through the construction- Intermediate Situation, Chennai

	Heat Loss ($W/m^2/day$)	Heat Gain ($W/m^2/day$)	Net Heat Loss ($W/m^2/day$)
Without Rotation	0.00	-10.93	-10.94
With Rotation	1.86	-5.37	-3.60
Net Improvement			7.34

Table 9 Comparison of Heat Loss through the construction- with and without rotation: Summer Situation

Rotation of the elements can lower the MRT by up to 3˚C during the nights. It has to be noted that the roof and the floors also have high thermal mass, thereby contributing to an increase in the MRT. When only the façade elements are considered (i.e., when the surface temperatures of the roof and the floor are neglected), the reduction in MRT can be up to 5˚C (Figures 70,71). Also, the indoor air temperature is quite high as compared to the outdoor air temperature, resulting in a higher net operative temperature. With proper ventilation (high air exchange rates), the indoor air temperature will follow the outdoor air temperature. In this case the operative temperature can be expected to be even lower. The decrease in the operative temerature for the current situation is about 2˚C. (The increase in day time indoor operative temperature in the latter case is due to neglecting the thermal capacity of the roof and the floor. This is only a hypothetical situation.)

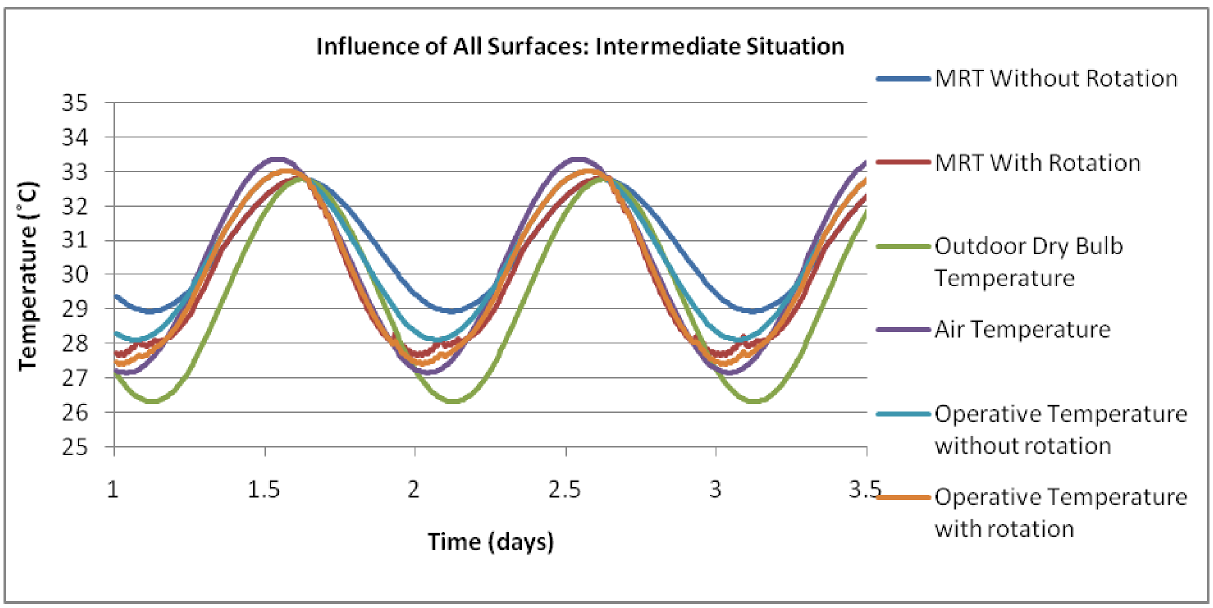


Figure 70: Effect of Rotation: Comparison of various temperatures- Intermediate Situation: Chennai

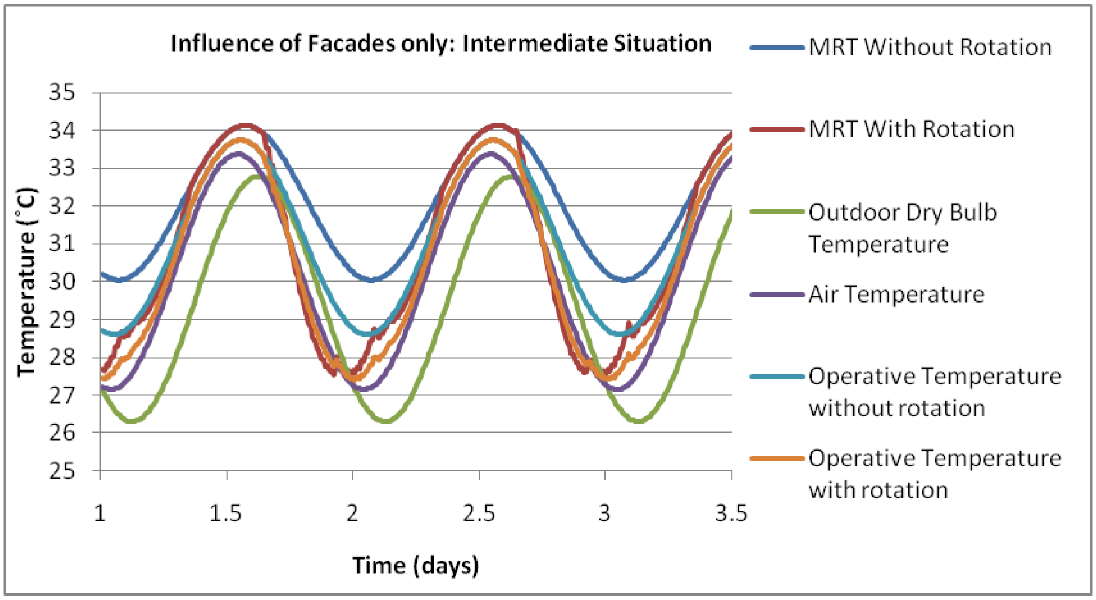


Figure 71: Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Intermediate Situation: Chennai

Summer Situation:

In the summer situation, day time indoor air temperatures are much higher than the temperatures at the inner layers of the element, leading to heat losses through the construction. In the original situation without rotation, this behavior is reversed as the inner layers get hotter during the course of the day, leading to excess heat gains. The variation in temperature at different positions within the member and the effect of rotation are represented by Figures 72, 73.

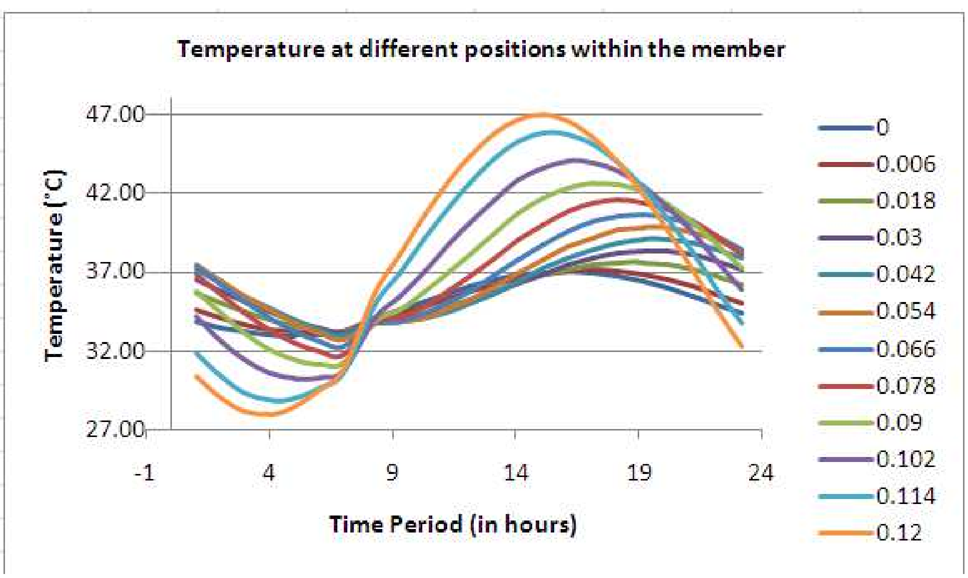


Figure 72 Temperature at different layers within the material, Summer situation- Chennai

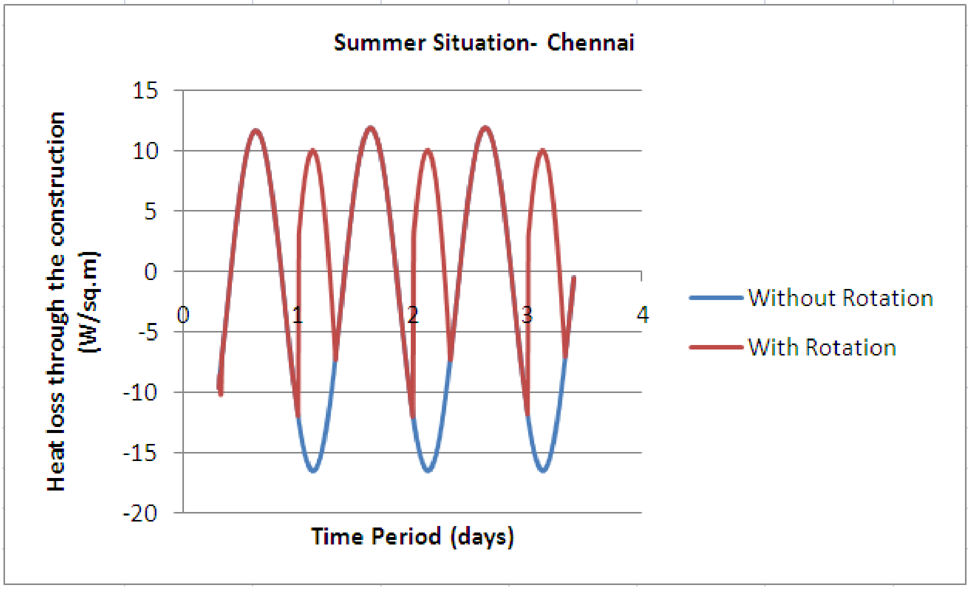


Figure 73 Heat loss through the construction- Intermediate Situation, Chennai

	Heat Loss ($W/m^2/day$)	Heat Gain ($W/m^2/day$)	Net Heat Loss ($W/m^2/day$)
Without Rotation	3.43	-5.70	-2.27
With Rotation	5.33	-1.40	3.93
Net Improvement			6.20

Table 10 Comparison of Heat Loss through the construction- with and without rotation: Intermediate Situation

Similar to the case of an intermediate situation, a reduction in the MRT can be observed in the summer situation as well. Since the indoor air temperature closely follows the outdoor temperature, the net operative temperature in the night is similar to the outdoor temperature- which is also the ideal requirement for thermal comfort for a hot humid climate.

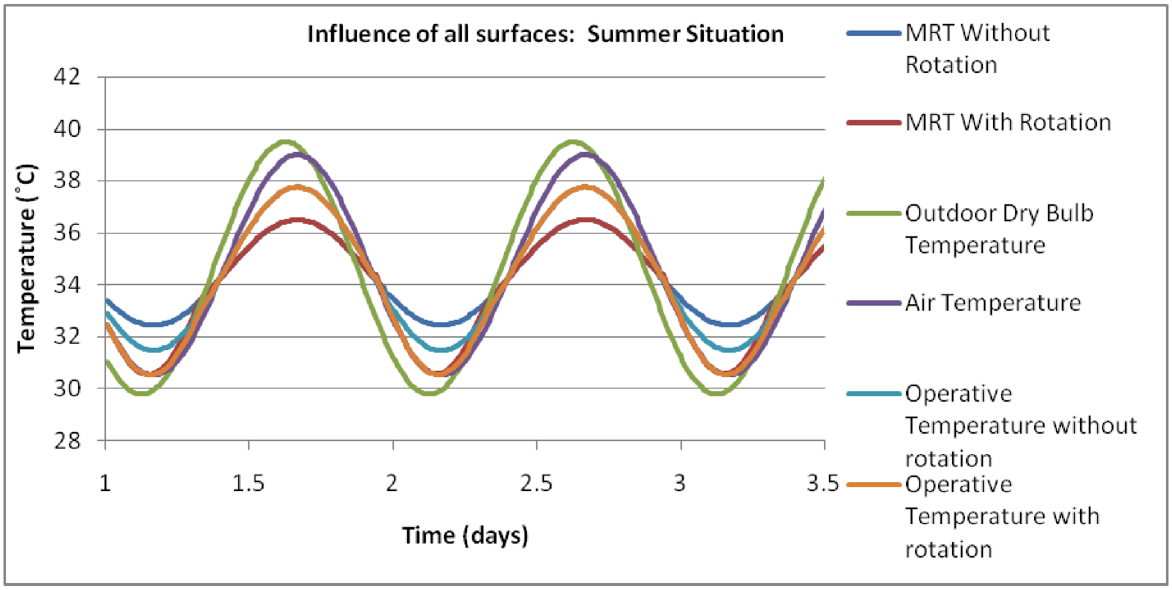


Figure 74 Effect of Rotation: Comparison of various temperatures- Summer Situation: Chennai

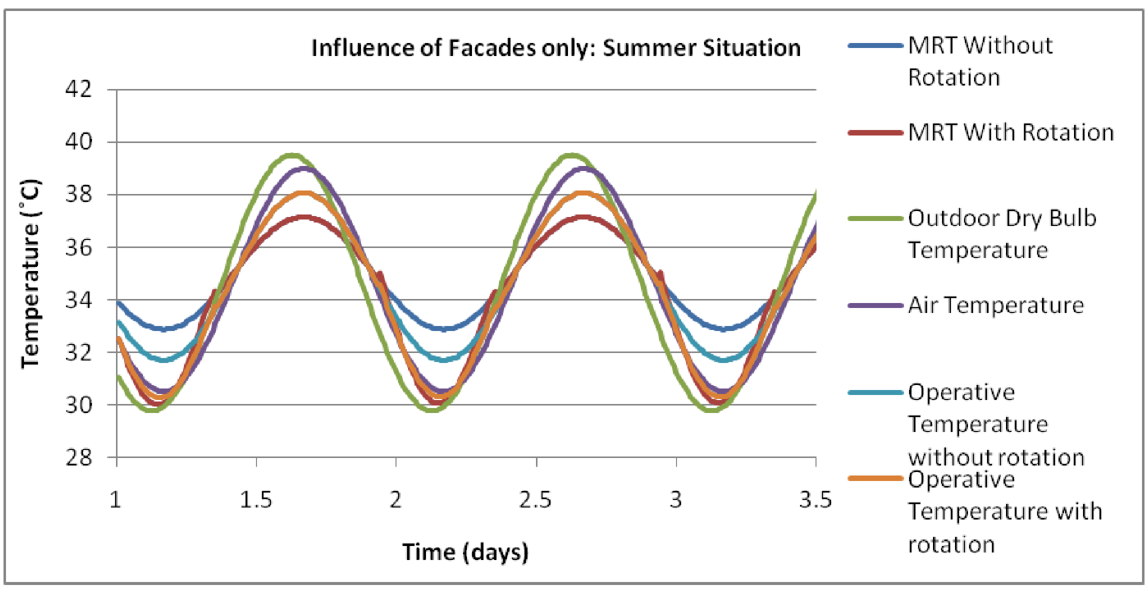


Figure 75 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Intermediate Situation: Chennai

9.6 Remarks:

The accuracy of these results needs to be verified as these calculations are based on several assumptions.

Firstly, results from the Energy Plus simulations of DesignBuilder were used as the base data for the calculations. A free running building, with positions of openings according to the predominant wind direction for the particular day was considered. According to the proposed design for ventilation, the positions of the openings as well as the elements controlling the openings vary from time to time. When an element in the windward façade is activated, positions of both its surfaces are altered (both of them partly exposed to the outside and partly exposed to the inside) – which will lead in surface temperatures different from what has been calculated. The schedule for the elements from the ventilation perspective can be different from that from a thermal mass perspective. It was not possible to include this sort of dual mechanism in the model, hence its effect is not known yet. Further, the initial proposal considers that the elements themselves will also act as shading devices for the respective openings. However, in the base building that was considered shading elements for the individual openings were not included. In order to not neglect the effect of shading entirely, horizontal shading at the roof level was provided for all four facades. However, appropriately shading the façade can result in a different set of results. A tool which can incorporate the dynamic nature of the various elements and perform reasonable building physics calculations is therefore required in order to test the real effect of this design proposal.

Secondly, the minimum time step for the results generated by DesignBuilder is half-hourly. For proper transient thermal analysis, the time steps have to be much smaller. For this reason, the results from design builder were tweaked to generate (cosine) curves with a smaller time step. The amplitude for these curves is slightly different from that in reality (explained in the appendix). This leads to small differences in the calculated and actual temperatures

Secondly, when the elements are rotated, the boundary conditions of the surfaces are interchanged as well. These new surface temperatures will no longer be the same as that estimated by DesignBuilder for a static condition. Previously the exterior surface (now facing the interior) could lose heat by radiation towards the night sky which lead to lower surface temperatures- in this case the heat losses are over estimated. At the same time, when the hotter interior surface is made to face outwards, it will lose a higher fraction of heat due to radiation towards the cooler night sky. The resulting surface temperatures may be much lower than that used in the calculations- in this case the heat losses when the element comes back to its original position the following morning are underestimated.

In order to account for the possible variations in the surface temperatures and to be slightly conservative, heat losses were calculated with respect to layers just below the surfaces (in this case, at a distance of 0.006m), the temperatures in these layers are slightly higher or lower than those at the surfaces.

Chapter 10: Applicability of the Design in Other Scenarios

10.1 Other Regions in the Hot-Humid Climate Zone

In Chapter 3, apart from the climate of Chennai, the characteristics of the climate of Mumbai and Kolkata were also discussed briefly and significant differences were identified. The applicability of the current design in these two cities, also in the hot-humid climate is discussed briefly.

The same building (similar construction and openings), was used for the study. The orientation of the building was based on the predominant wind direction.

10.1.1 Mumbai

Since each of the facades have very different rotating schedules it can be observed that except for a brief period during the day, the MRT and hence the operative temperature can be much lower than that without rotation. During the hours that the indoor and outdoor air temperatures are more or less the same the operative temperature is also close to the outdoor temperature. Unlike the situation in Chennai, the MRT in Mumbai during the summer months are slightly higher than the outdoor temperatures even during the day. This difference grows considerably larger during the nights.

The outdoor average high temperatures in Mumbai during the summer, as well as the intermediate periods are quite close. However, the MRT during the summer is much higher than that during the intermediate period- leading to a considerably high indoor operative temperature. The small difference in the diurnal temperatures during the summer also makes the effect of rotation negligible. On the other hand, the effect of rotation is evident during the intermediate period which has reasonably higher diurnal variation.

Intermediate Situation

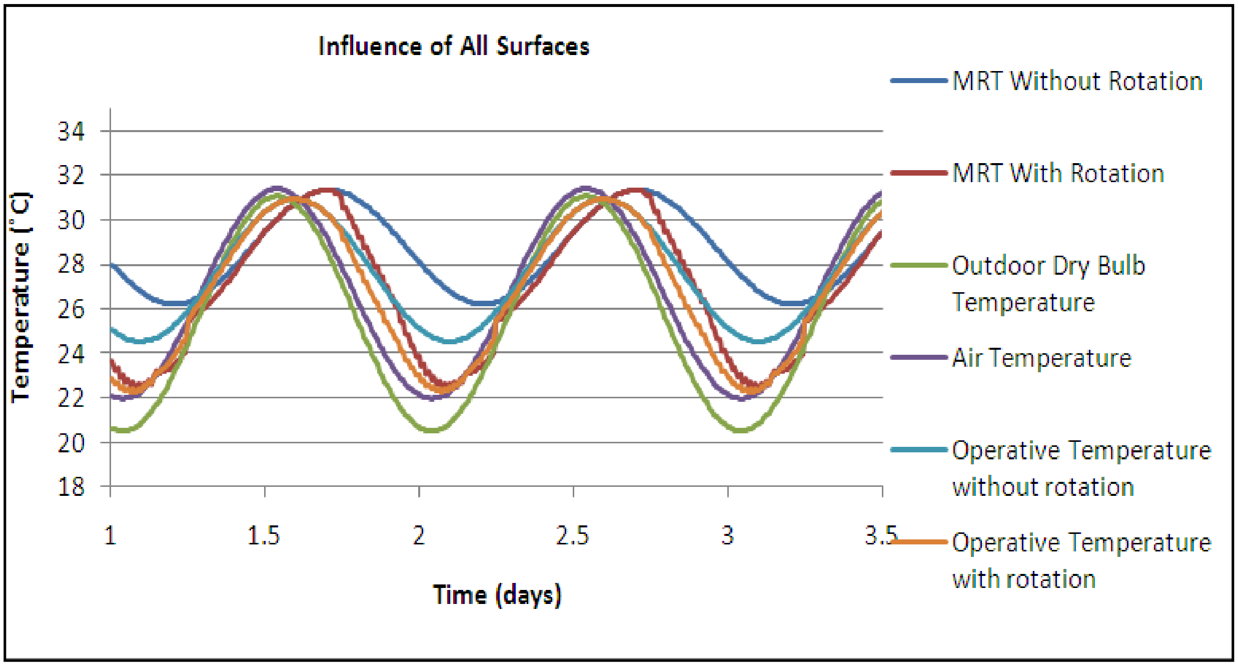


Figure 76 Effect of Rotation: Comparison of various temperatures- Intermediate Situation: Mumbai

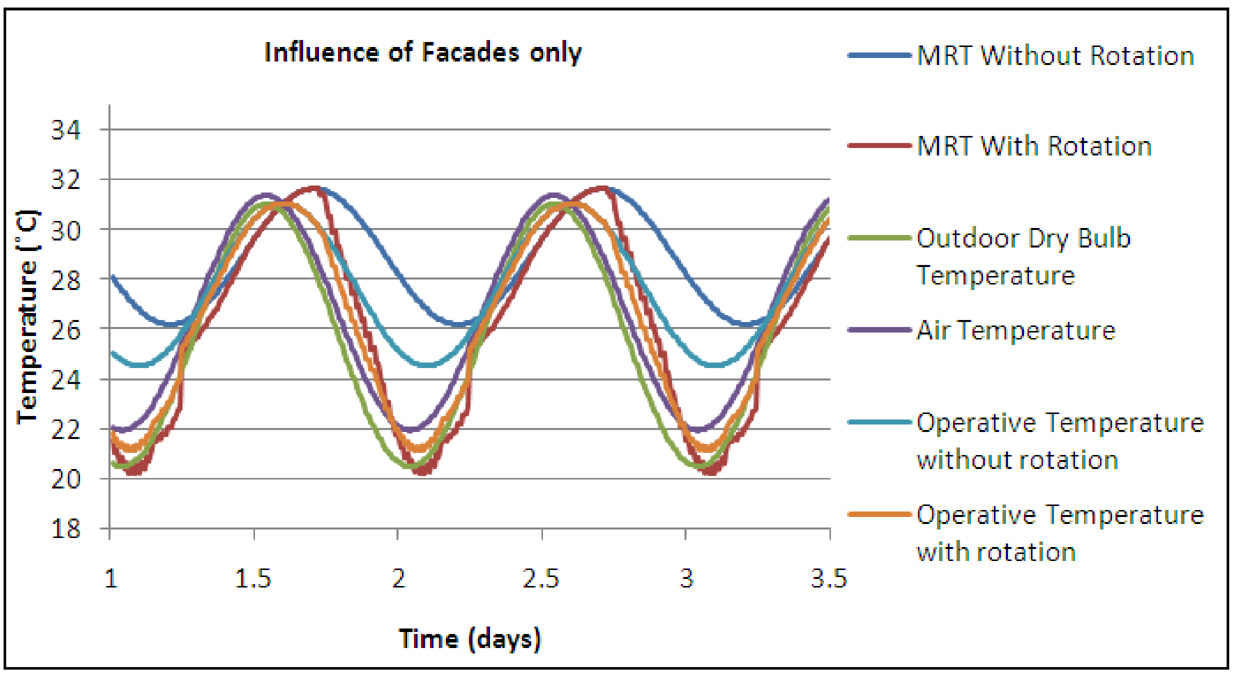


Figure 77 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Intermediate Situation: Mumbai

Summer Situation

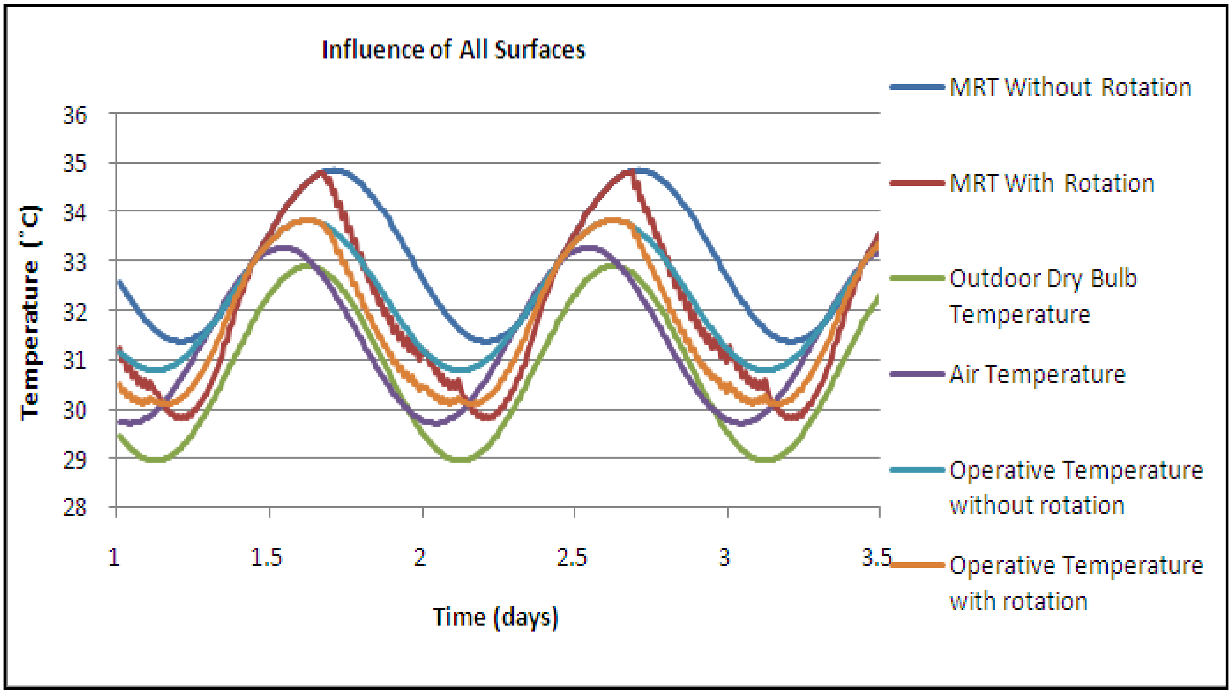


Figure 78 Effect of Rotation: Comparison of various temperatures- Summer Situation: Mumbai

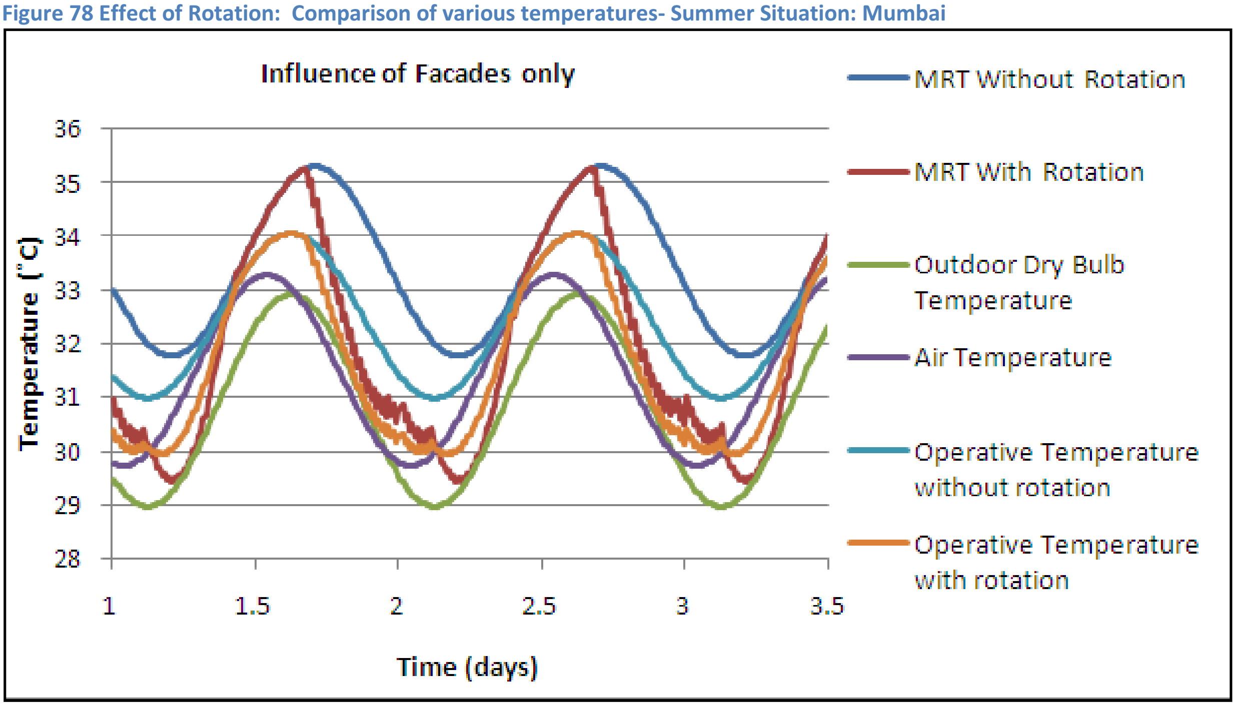


Figure 79 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Summer Situation: Mumbai

10.1.2 Kolkata

The behavior of diurnal variation in temperature of Kolkata is the exact opposite of that of Mumbai. That is the diurnal variations are high during the summer and low during the intermediate period. This results in a better effect of rotation during the summer months as compared to the intermediate period.

Intermediate Situation

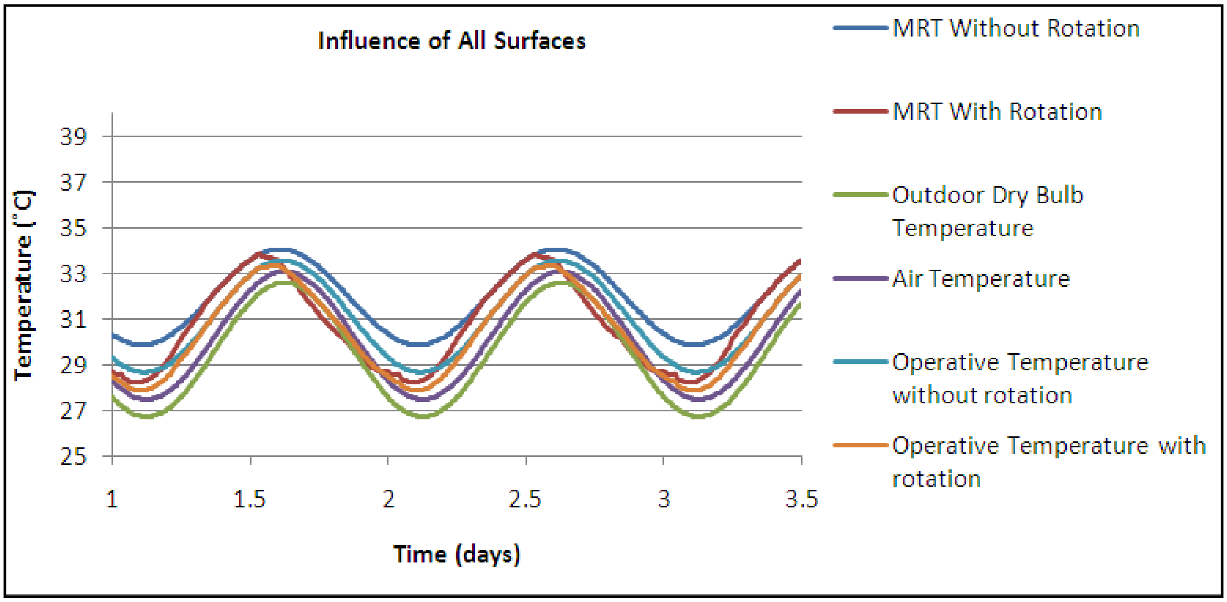


Figure 80 Effect of Rotation: Comparison of various temperatures- Intermediate Situation: Kolkata

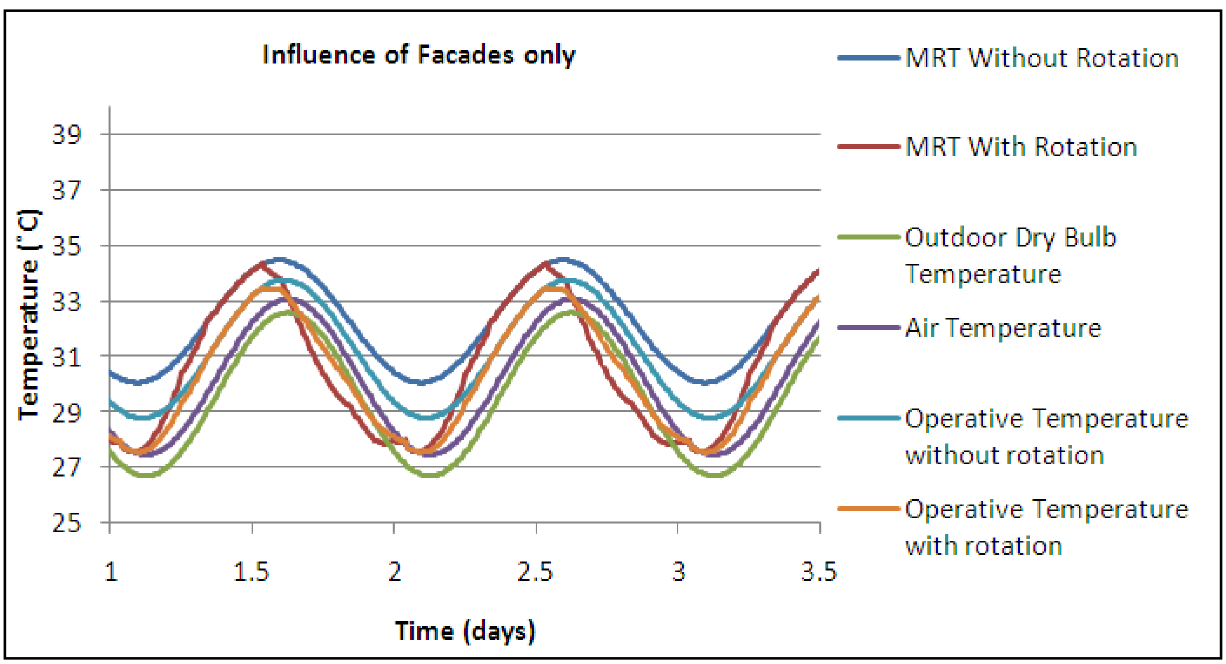


Figure 81 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Intermediate Situation: Kolkata

Summer Situation

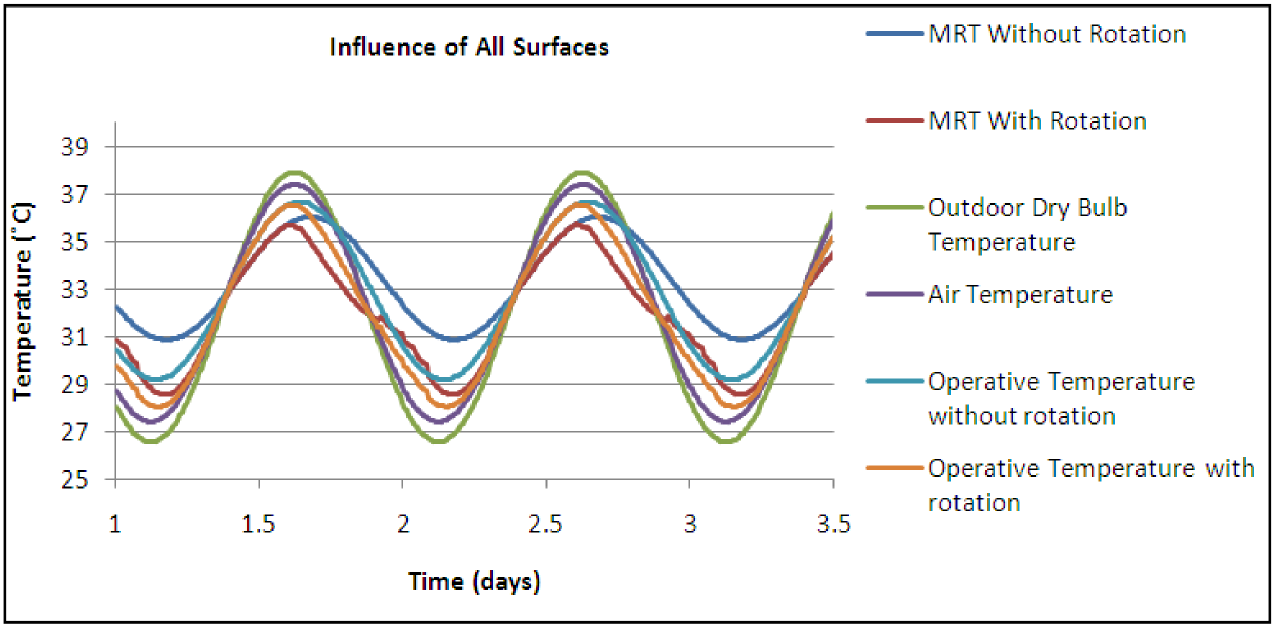


Figure 82 Effect of Rotation: Comparison of various temperatures- Summer Situation: Kolkata

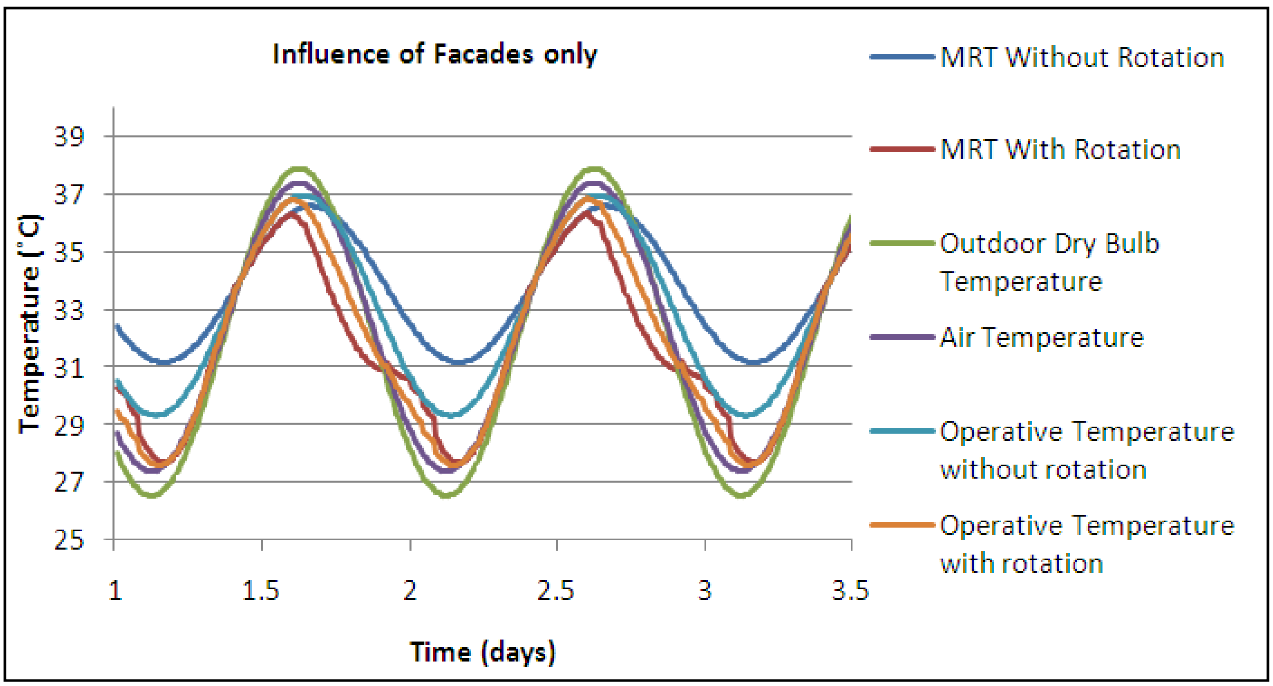


Figure 83 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Summer Situation: Kolkata

Although this is a very rough study, it can be concluded that the same concept can be extended to Mumbai and Kolkata as well. In both cities a substantial drop of temperature can be noticed starting from the late afternoon hours. The system can particularly be useful in the case of Mumbai where the average high temperatures are much lower than that of Chennai/ Kolkata.

With regards to ventilation potential, air speeds in Kolkata are quite low, therefore it might be difficult to achieve good indoor air velocities. Mumbai on the other hand has quite high outdoor wind speeds with wind directions not as erratic as Chennai. However, one main factor which might make the applicability of this design difficult is the severity of the rains. The louvers should be able to sufficiently block the rain as well as provide reasonable ventilation in order to reach thermal comfort.

The thickness of the element was not changed in this case, however it can be optimized according to the needs of the specific city.

10.2 Applicability of the Design in Other Climate Zones

The study is further extended to determine the suitability of the design in other climate zones. Although in depth climate study is required in order to propose any suggestions, that was not done in this case due to the time constraints. Area of openings, nor the built-up of the wall element is changed. That is the performance of the same building is merely studied for a different climate.

10.2.1 Bengaluru

Bengaluru has a moderate climate with outdoor temperatures and relative humidity both under fairly comfortable lmits. The summer is way milder than the other three cities discussed earlier. An overview of its climate is as given in Table 11.

Climate data for Bangalore													[hide]
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	32.1 (89.8)	34.5 (94.1)	37.0 (98.6)	38.9 (102)	37.8 (100)	36.4 (97.5)	28.1 (82.6)	27.4 (81.3)	28.2 (82.8)	28.0 (82.4)	27.0 (80.6)	26.2 (79.2)	38.9 (102)
Average high °C (°F)	27.6 (81.7)	30.2 (86.4)	32.9 (91.2)	34.1 (93.4)	33.3 (91.9)	29.4 (84.9)	28.1 (82.6)	27.5 (81.5)	28.3 (82.9)	28.0 (82.4)	27.0 (80.6)	26.2 (79.2)	29.38 (84.89)
Daily mean °C (°F)	21.3 (70.3)	23.6 (74.5)	26.1 (79)	28.0 (82.4)	27.4 (81.3)	24.6 (76.3)	23.9 (75)	23.5 (74.3)	23.9 (75)	23.7 (74.7)	22.2 (72)	21.1 (70)	24.11 (75.4)
Average low °C (°F)	15.3 (59.5)	17.2 (63)	19.6 (67.3)	21.8 (71.2)	21.5 (70.7)	20.0 (68)	19.8 (67.6)	19.6 (67.3)	19.7 (67.5)	19.4 (66.9)	17.7 (63.9)	16.0 (60.8)	18.97 (66.14)
Record low °C (°F)	10.6 (51.1)	11.4 (52.5)	13.9 (57)	16.8 (62.2)	17.2 (63)	17.4 (63.3)	17.0 (62.6)	17.5 (63.5)	16.8 (62.2)	13.0 (55.4)	11.3 (52.3)	10.6 (51.1)	10.6 (51.1)
Rainfall mm (inches)	1.8 (0.071)	7.9 (0.311)	7.0 (0.276)	40.0 (1.575)	110.2 (4.339)	89.1 (3.508)	108.9 (4.287)	142.5 (5.61)	241.0 (9.488)	154.5 (6.083)	54.1 (2.13)	17.5 (0.689)	974.5 (38.367)
Avg. rainy days	0.2	0.5	0.8	3.0	6.9	6.0	7.4	10.0	10.3	7.9	3.9	1.6	58.5
% humidity	60	52	45	51	60	72	76	79	76	73	70	68	65.2
Mean monthly sunshine hours	263.5	248.6	272.8	258.0	241.8	138.0	111.6	114.7	144.0	173.6	189.0	211.8	2,367.4

Table11 Climate Data for Bengaluru (Various sources, extracted from Wikipedia)

Intermediate Situation

Although rotation of the elements few hours during the day can lower the indoor operative temperature even closer to comfort situation, in the nights it can result in additional cooling which might not be preferred.

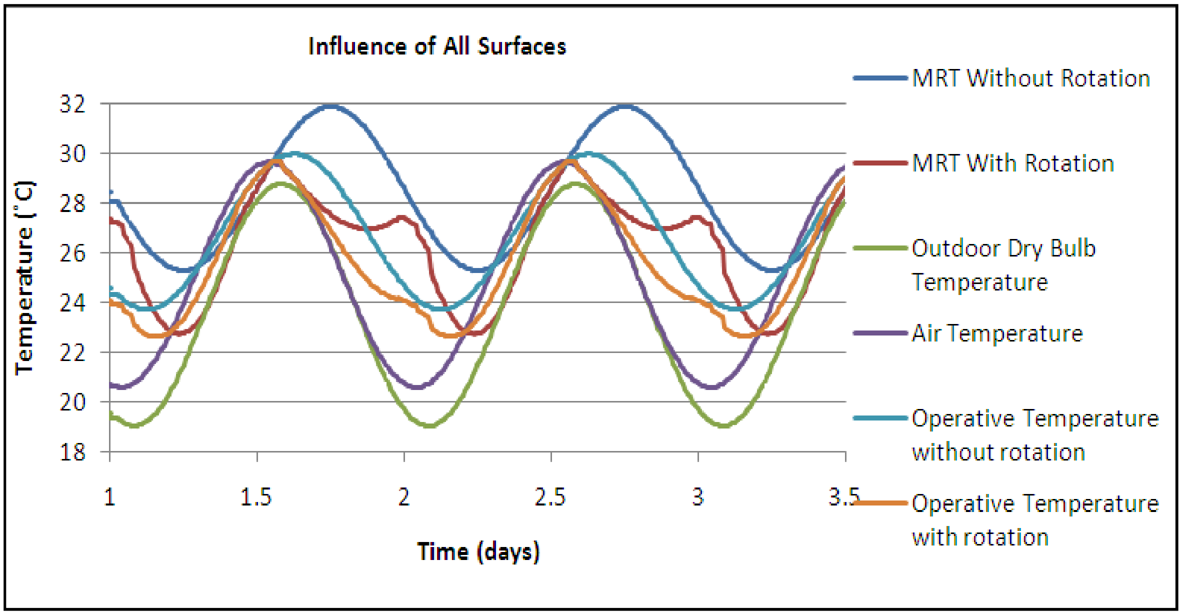


Figure 84 Effect of Rotation: Comparison of various temperatures- Intermediate Situation: Bengaluru

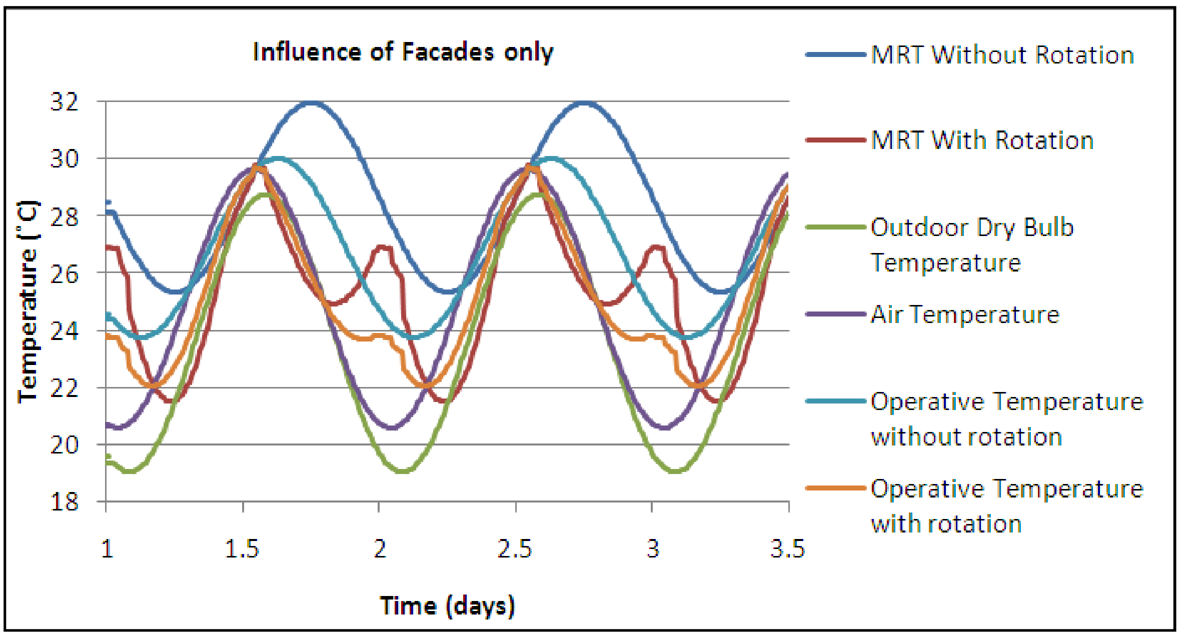


Figure 85 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Intermediate Situation: Bengaluru

Summer Situation

Rotation of elements in the summer situation can help lower the indoor temperatures in the night by up to 2˚C. With reduction in air temperature this can further be lowered, however, the wind speeds in Bengaluru is quite low, especially during the nights.

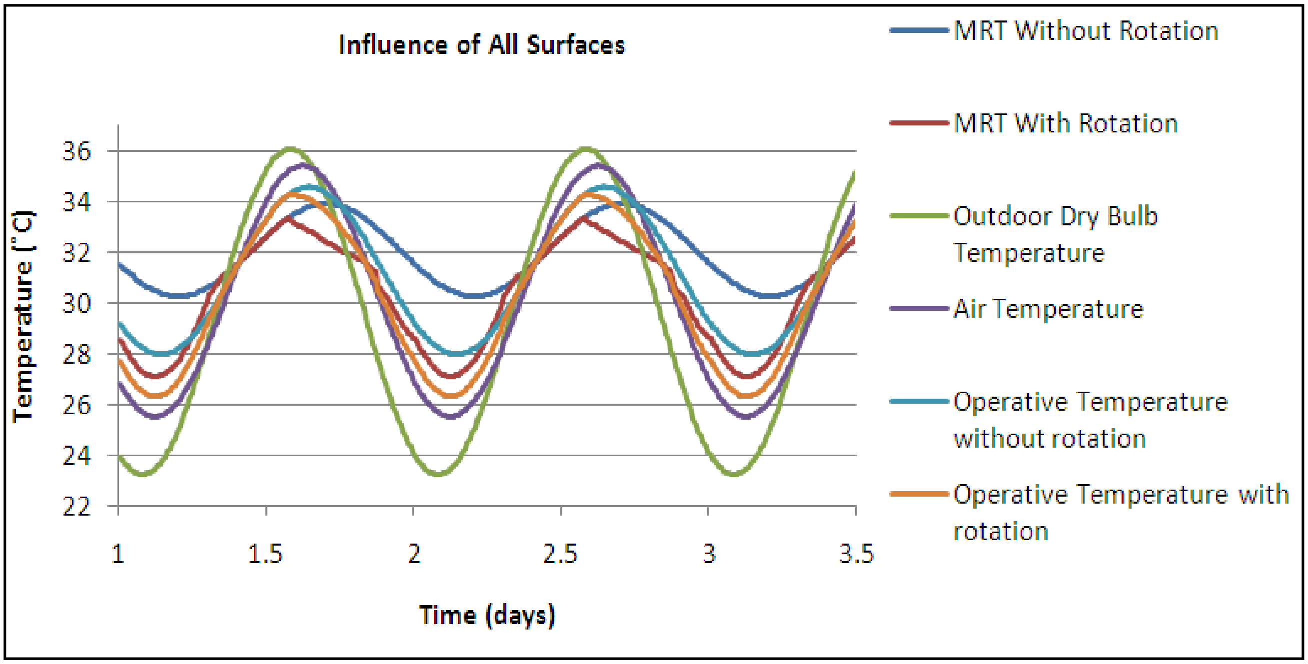


Figure 86 Effect of Rotation: Comparison of various temperatures- Summer Situation: Bengaluru

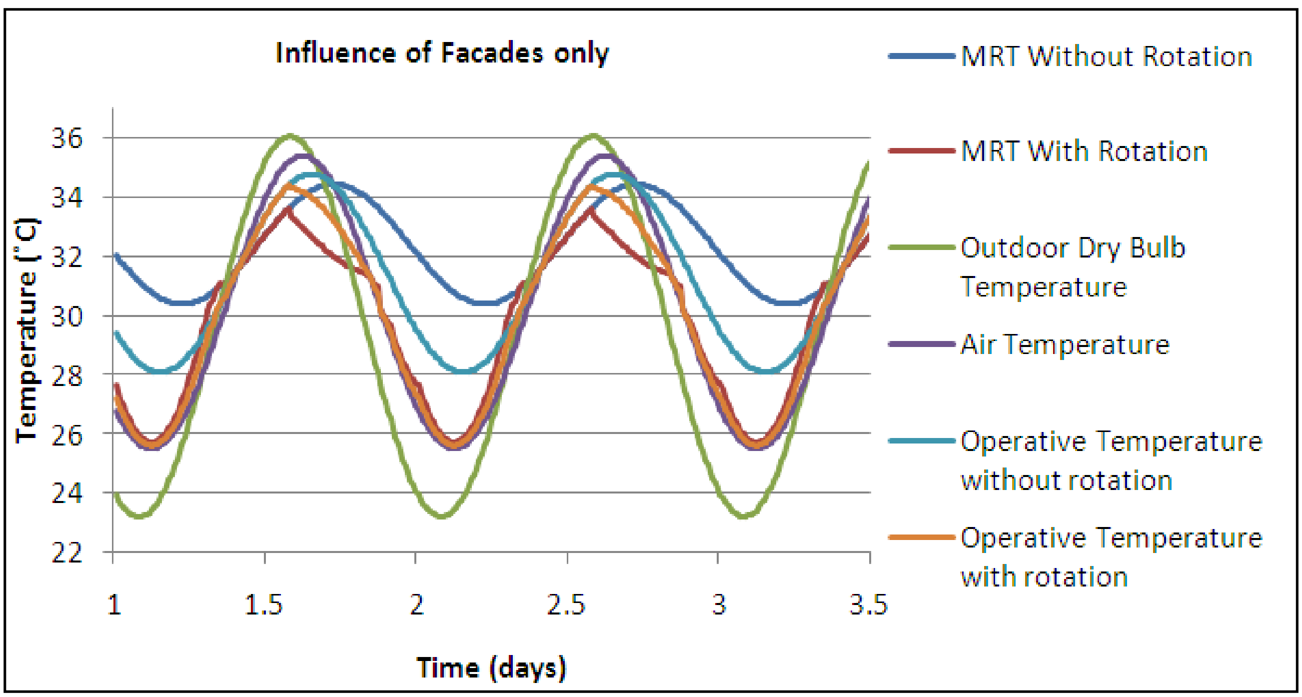


Figure 87 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Summer Situation: Bengaluru

10.2.2 Delhi

Delhi has a composite climate with considerable variations in diurnal temperatures. Summer and winter seasons are both quite extreme.

Climate data for Delhi [hide]													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average high °C (°F)	21.1 (70)	24.2 (75.6)	30.0 (86)	36.2 (97.2)	39.6 (103.3)	39.3 (102.7)	35.1 (95.2)	33.3 (91.9)	33.9 (93)	32.9 (91.2)	28.3 (82.9)	23.0 (73.4)	31.4 (88.5)
Average low °C (°F)	7.3 (45.1)	10.1 (50.2)	15.4 (59.7)	21.5 (70.7)	25.9 (78.6)	28.3 (82.9)	26.6 (79.9)	25.9 (78.6)	24.4 (75.9)	19.5 (67.1)	12.8 (55)	8.2 (46.8)	18.8 (65.8)
Rainfall mm (inches)	20.3 (0.799)	15.0 (0.591)	15.8 (0.622)	6.7 (0.264)	17.5 (0.689)	54.9 (2.161)	231.5 (9.114)	258.7 (10.185)	127.8 (5.031)	36.3 (1.429)	5.0 (0.197)	7.8 (0.307)	797.3 (31.389)
Avg. rainy days	1.7	1.3	1.2	0.9	1.4	3.6	10.0	11.3	5.4	1.6	0.1	0.6	39.1
Mean monthly sunshine hours	213.9	217.5	238.7	261.0	263.5	198.0	167.4	176.7	219.0	269.7	246.0	217.0	2,688.4

Table 12 Climate Data for Delhi (Various sources, extracted from Wikipedia)

Intermediate Situation

Day time temperatures during the intermediate situation are slightly higher than the outdoor temperatures. With rotation, the indoor temperature during the day is found to dip by 2.5˚C, resulting in a temperature slightly lower than the outdoor temperature. The reduction in the temperatures during the night is slightly better- about 1˚C. With proper ventilation this can be lowered further.

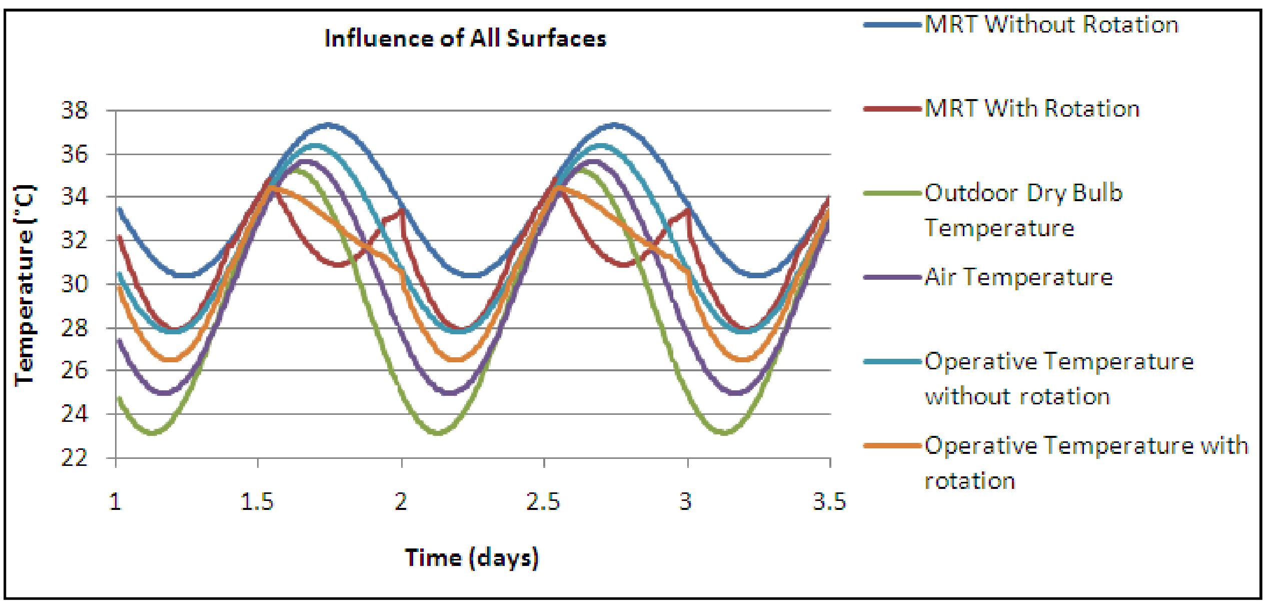


Figure 88 Effect of Rotation: Comparison of various temperatures- Intermediate Situation: Delhi

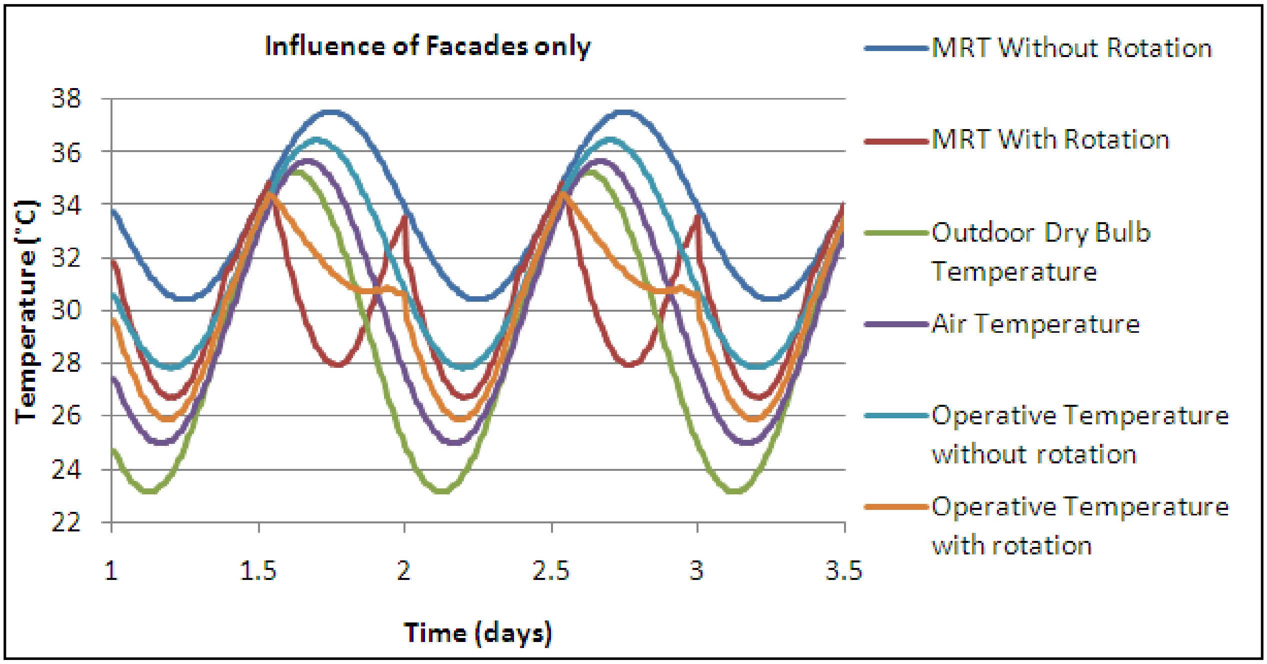


Figure 89 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Intermediate Situation: Delhi

Summer Situation:

Rotation of elements in the summer has the potential to lower the indoor operative temperature by up to 2˚C even during the day. Although natural ventilation is used in this scenario, generally it is not preferred during the day time as the air is extremely hot and dry. It can also be seen from the graph that the operative temperature is partly influenced by the high air temperature. Keeping the air exchange rate to a minimum can have a better effect. In the night, the reduction in operative temperature is only about 0.5˚C.

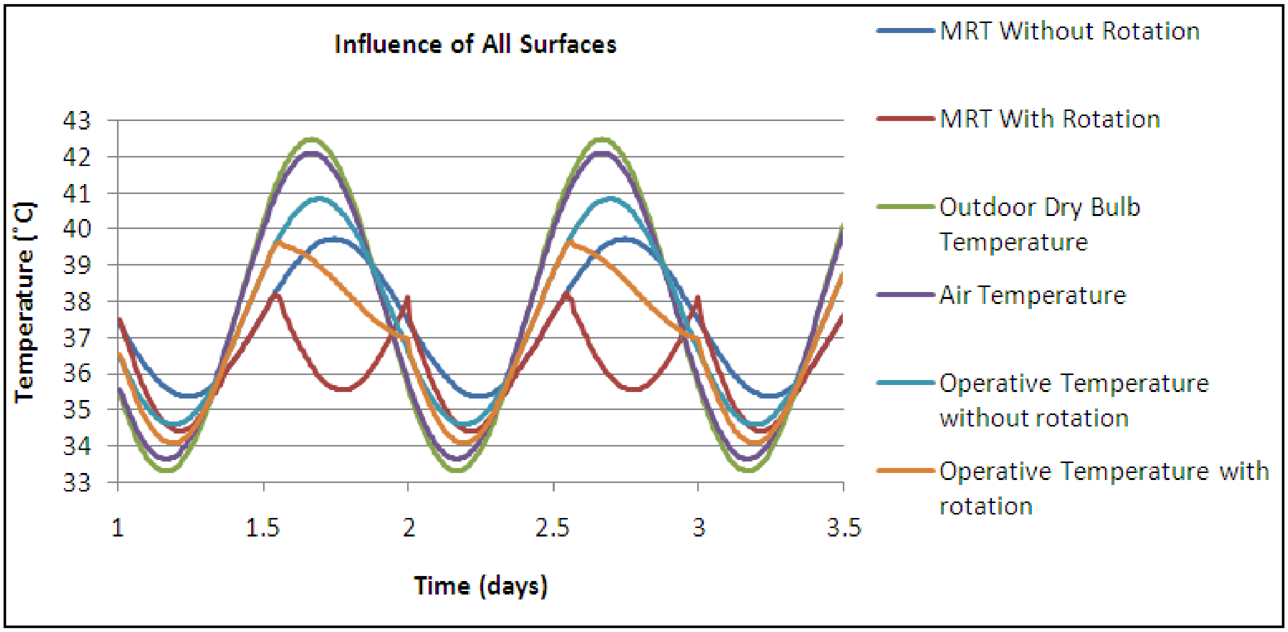


Figure 90 Effect of Rotation: Comparison of various temperatures- Summer Situation: Delhi

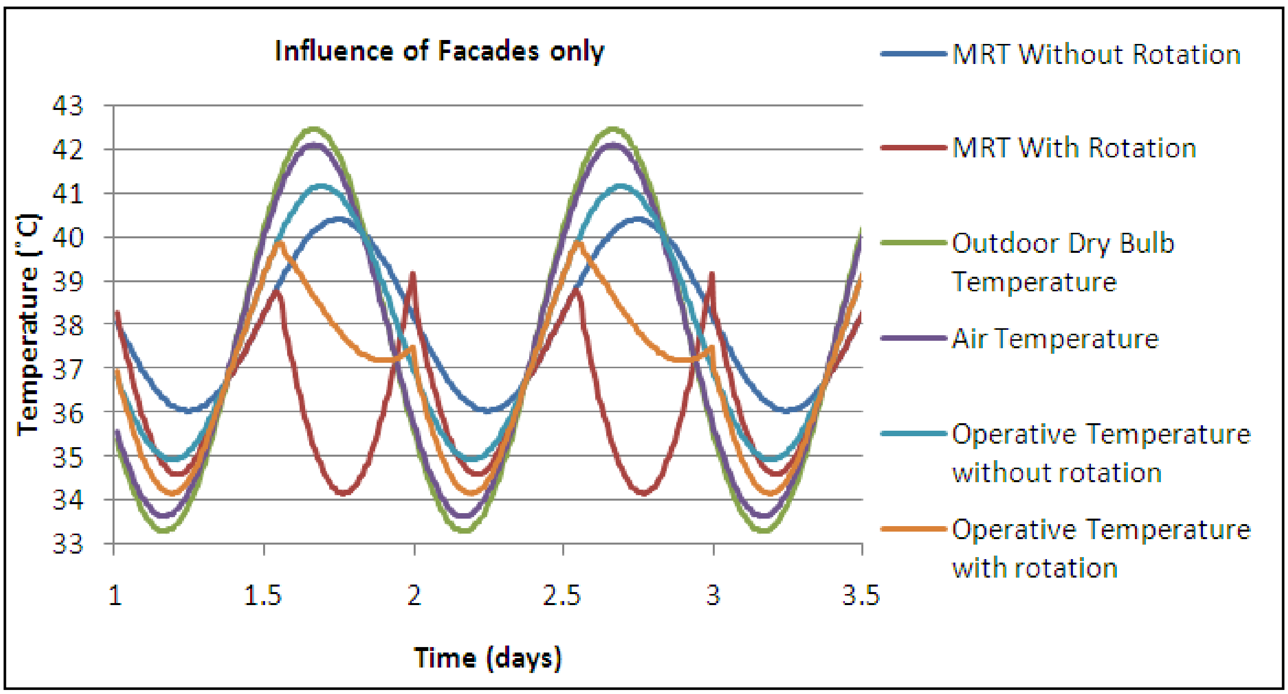


Figure 91 Effect of Rotation: Comparison of various temperatures neglecting the effect of the storage capacity of roof and the floor- Summer Situation: Delhi

Chapter 11: Design

11.1 Material

Chapter 2 and Appendix A provides information on the commercially available bamboo based products. The various demands to be met by a façade were discussed in Chapter 5 and among the different requirements, thermal performance was chosen as the key criteria for this particular study. The last section of Chapter 9 discussed a proposal to meet the same. The results from this forms the basis for choosing a suitable product from the inventory provided in Chapter 2.

From the thermal mass point of view a thickness of 0.12m was identified as the optimum thickness of the element. Going back to the inventory it can be seen that not many of the products come in this thickness range. Looking at the product catalogue of various suppliers suggested that such thickness is possible with bamboo laminates (Strand Woven Bamboo), which is also one of the few products which is suitable for outdoor application.

11.2 Durability

Bamboo laminates have reasonable resistance to moisture and provides good protection against fire. SWB produced by manufacturers such as Lamboo (US based) and MOSO Bamboo (based in the Netherlands) are accredited with the highest fire resistance class. MOSO Bamboo is now in the process of developing façade cladding material. Information from the product catalogue reads: "MOSO Bamboo X-treme cladding is a solid, high density exterior bamboo board, made from compressed bamboo fibers. A special, patented heat treatment process provides Bamboo X-treme the highest durability class possible in the appropriate EU norms, increases the stability and density, and consequently the hardness. Furthermore, contrary to other wood products this product reaches fire safety class B-s1 d0 (EN 13501-1) without impregnation with expensive and eco-damaging fire retardants." The product's technical specifications are as follows:

• Dimensional stability: length: + 0.1 %; width: + 0.9% (24 hours in water 20°C)

• Resistance to Indentation: Brinell Hardness: ≥ 9.5 kg/mm^2 (EN 1534)

• Reaction to fire: Class B-s1 d0 (EN 13501-1)

• Biological durability:

Class 1 (EN 350 / ENV 807)

Class 1 (EN 350 / EN 113)

• Effectiveness against Blue Stain: Class 0 (EN 152)

• Use Class: Class 4 (EN 335).

Such high standards indicate that bamboo based products for extreme situations- in this case, for a façade, are commercially available. However, there is not much information about the availability of such a product in India.

11.3 Positioning

The elements should ideally be located in a series of rows and columns, each row of elements having its own control system. By doing so, elements can be 'opened' (not in the plane of the façade) or 'closed' (along the plane of the façade) as per the direction of the wind. The inlet to outlet opening ratio can typically be controlled by the number of rows (of elements) that are opened. A low inlet to outlet opening ratio is said to increase air flow as well as velocity within the room.

11.4 Sizing the elements

The elements, when kept in an open position, not only aid in ventilation but can also act as solar shading devices. Horizontal shading devices are said to be effective for the North and the South façade, whereas vertical shading devices are more efficient for the West and East façade. The elements therefore need to be horizontal (short and wide) or vertical (long and narrow) depending on the orientation of their corresponding facades. They can be imagined as pivoted windows (except made of bamboo) whose axis is along the horizontal or vertical.

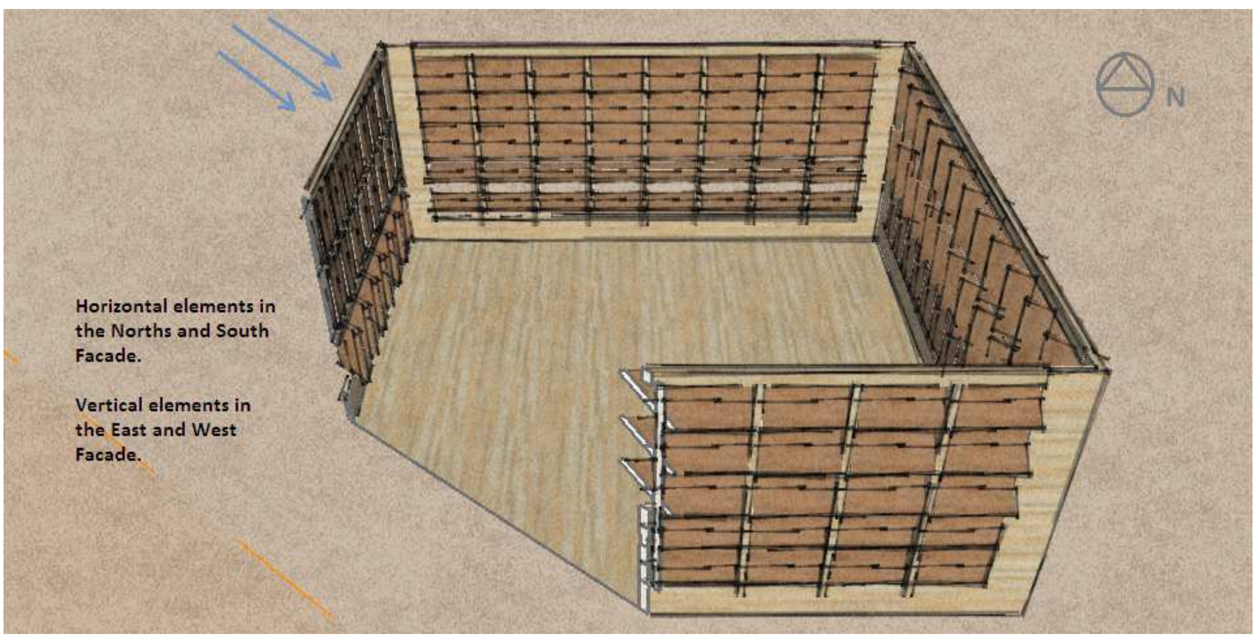


Figure 92

The widths of the elements are dependent on the requirements for effective ventilation as well as their ability to act as solar shading devices. Another decisive criteria is the relative movement of each of the elements. Often there might be situations when not all the elements in a particular row are expected to be open. During such times an element should be able to move independent of the elements adjacent to it. This is not possible when two elements overlap each other (Figures 93- 95).

11.5 Possible Cross-sections of the elements

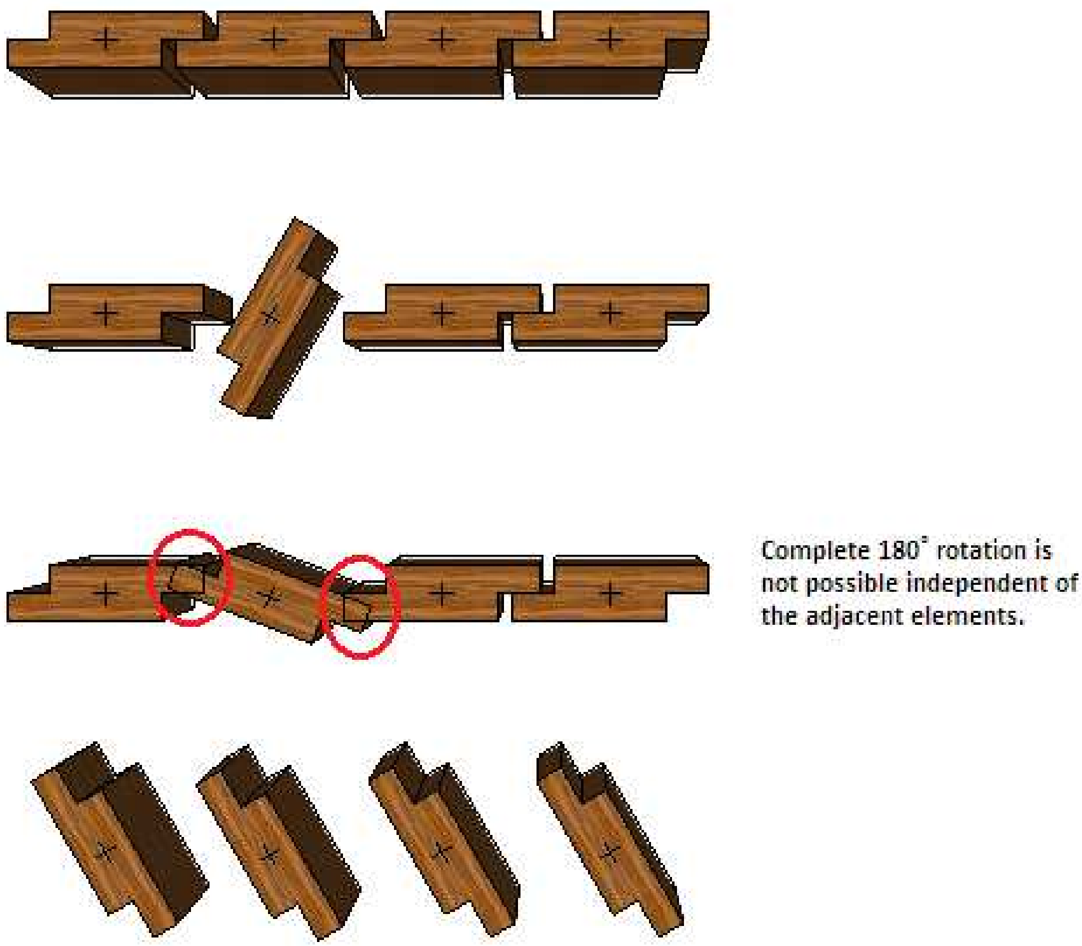


Figure 93

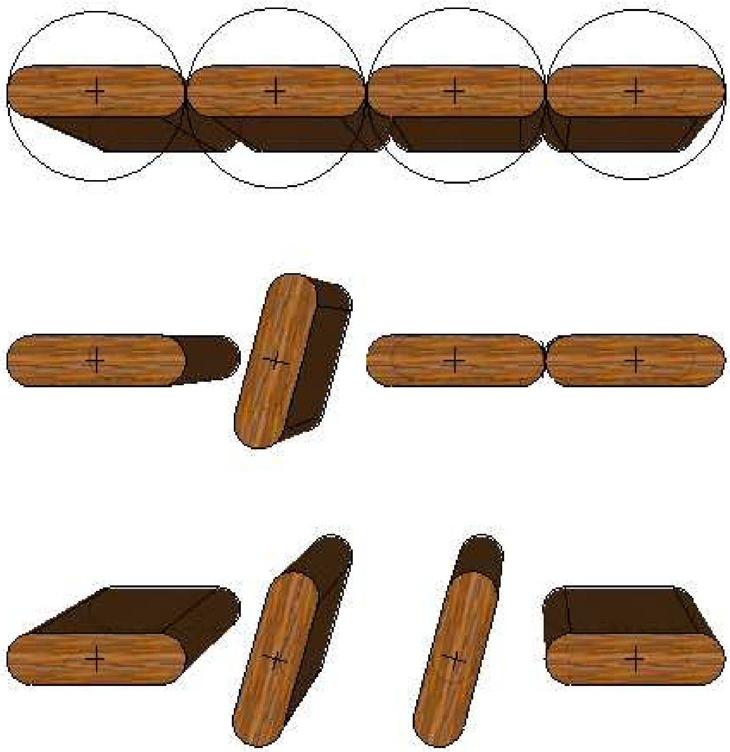


Figure 94

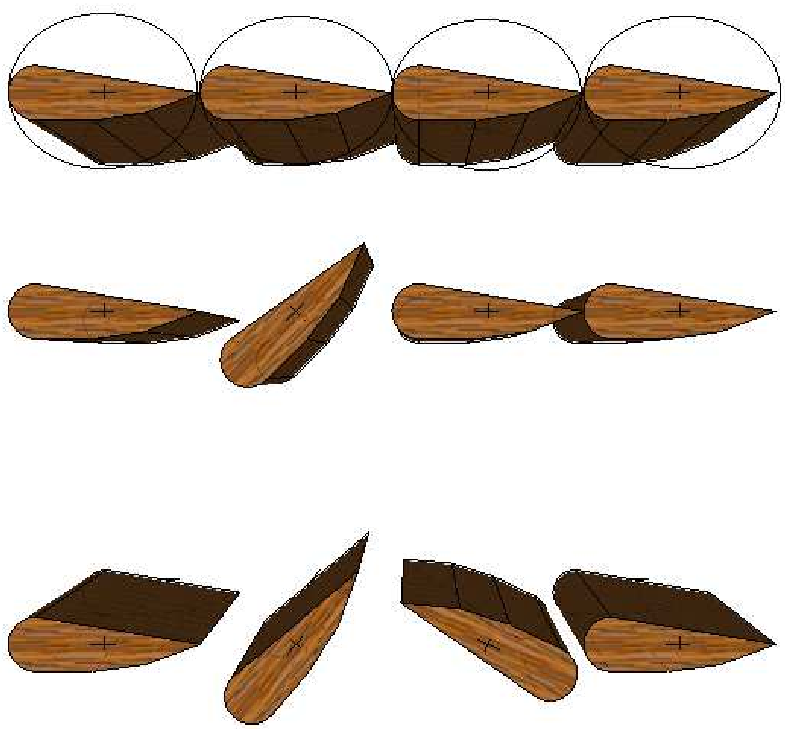


Figure 95

Further, the axis of rotation should be at the centre of the horizontal plane in the case of a vertical element and at the centre of the vertical plane in the case of a horizontal element (Figure 96).

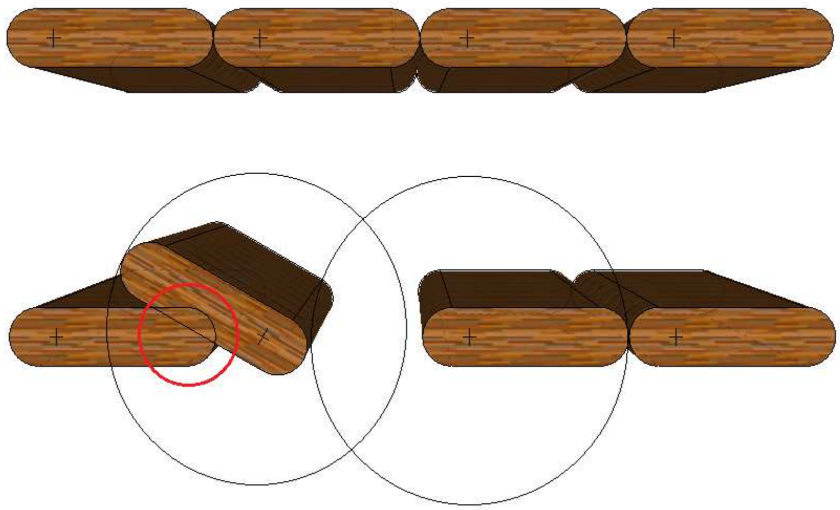


Figure 96

According to the requirement of the National Building Code of India (2005), the depth of projections outside of a façade should not exceed 0.75m. From the ventilation point of view, a projection greater than 0.36 m is required for horizontal louvers to move out the internal heat effectively. Further, even though a depth higher than 0.36 m has been proven to be effective, increasing the depth depends on the space demands. Similar requirement for a vertical louver is not known. However, assuming that a vertical louver also has to have a certain minimum depth projecting inwards to be effective, the minimum width of the elements can be calculated as twice the depth of projection inwards. Considerations should also be given based on the function of the building- a larger depth may invite burglars, cause accidents due to fall, etc.

An alternative to have an increased width for shading/ efficient ventilation purposes, but still maintaining a smaller width is to design the elements in such a way that a part of it can be extended. Essentially each of the elements can be of two individual slabs- both lying one over the other. When the element is in a closed position, the two slabs together act as a thermal mass. However, when the element is used for ventilation/ for shading purposes, the depth of the element can be extended based on the need. (Figure 97) (The thermal behavior of such an element has to be studied, as it is no longer a homogenous material.)

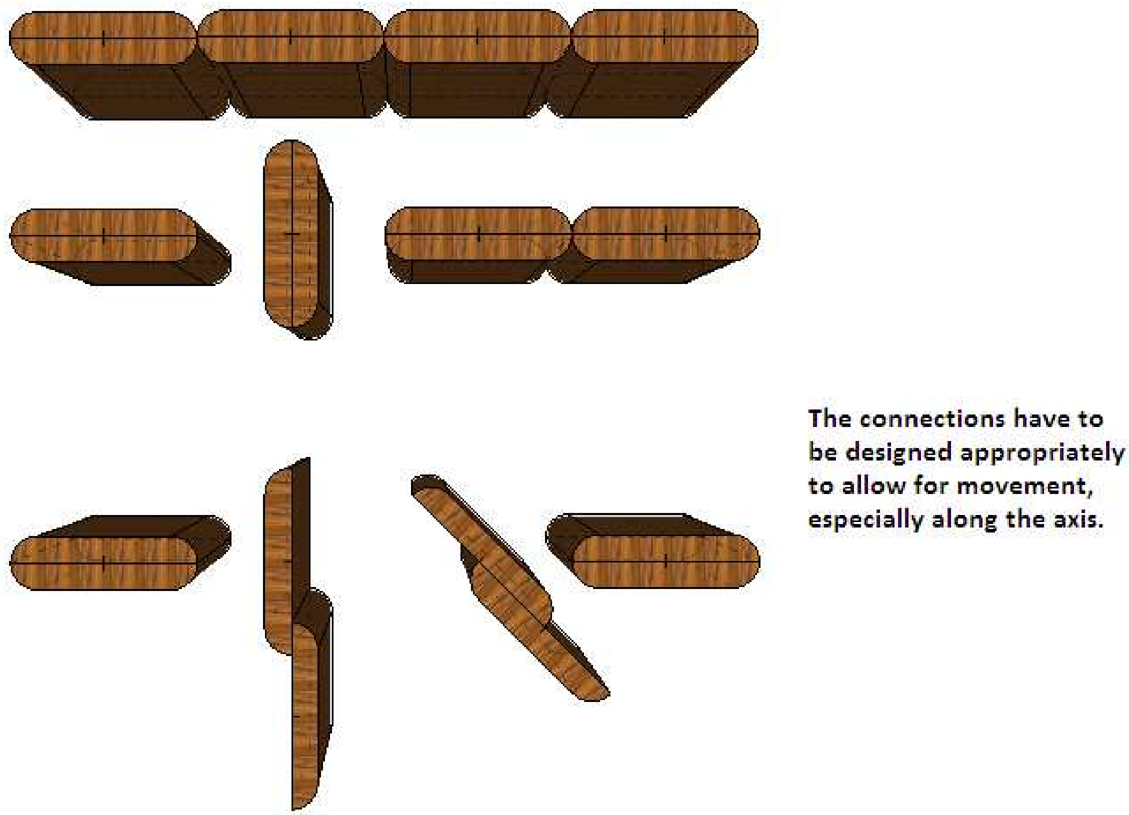


Figure 97

11.6 Mechanism

Manually opening/ closing windows has been proven to provide occupant satisfaction. Yet if the knowledge about when and how the openings should be positioned is not known, the system might not work the way it is intended to work and result in discomfort. With respect to the rotation of the slabs from the thermal mass point of view, the concept is quite simple and not as daunting as the elements have to be rotated only twice a day-(elements in each of the façade may however have different schedules based on their orientation). It can be based more on the intuition of the user but provision of additional instructions on the number of hours the elements have to be rotated during the different seasons can be helpful. With respect to ventilation it is a little more complicated as the system is now based on the wind directions, which is quite erratic, especially in a city like Chennai. A simple toolkit with instructions about the basic principles behind the operation along with local hourly wind directions (updated on a regular basis) can prove to be useful for the occupants.

An even simpler option can be locally locating a simple weather sensor or a wind-rose device. In this case either manually regulate the openings or use a mechanical system to do the same. Again, in order to keep the operational costs to a minimum, mechanical control systems which are not powered by electricity is preferred.

The theory behind the working of mechanical toys which are based on several motion based mechanisms and perform a range of movements can be extended for this purpose. The principle behind the working of wind-up toys in particular seems suitable. These toys are powered by a metal spring that is tightened by turning it. Additionally gear wheels and pulleys are employed to transfer the power and control the toy's motion. The idea is to connect the façade elements in each row in parallel using a similar spring which is in turn controlled by the user according to the information gathered from the wind-rose. This is only a suggestion and its feasibility should be studied.

Figure 98 Transfer of Principle of a Mechanical Toy to the Façade System

11.7 Performance of the designed Façade System

The current design was based on several assumptions and the scope itself was restricted so as to suit the time constraints. Comparing the designed façade system with the requirements that must be met by a façade as discussed in Chapter 5 can help identify the drawbacks of the current design.

Shelter	
Climate: Sun, wind, rain	The system of louvers should be able to block the effects of the sun, wind and the rain effectively.
Fire Safety	Market study shows that there are bamboo based products engineered to perform very well in the case of a fire. However, there is not enough information about the availability of such products in the Indian market.
Safety against Burglary	As such large depths of the louvers are suitable for a good ventilation design. The depth of the louver and its position directly determines the effective size of the openings. The current design will invariably result in large openings which are not safe against burglars. However, if the function of the building is not of much importance to the thieves, the building can still be considered burglar proof.
Accessibility of Insects/ pests	Openings in the current design do not provide the opportunity to be shielded by nets and other such components which are commonly used to prevent insects from entering the indoor space. Provision of nets was not considered in this design as it blocks a considerable amount of air from entering the building. Therefore this is a drawback.
Structural Factors	
Loads - Dead load, Wind Load, Impact Load	Structural calculations were not performed in the current study. However, by roughly comparing the properties of bamboo and brick (commonly used construction material in the region), we can assume that the current façade will be much lighter than the existing solution. The load paths of this dynamic system will be different from the conventional system and it has to be worked out.
Repair and Maintenance	Repair and maintenance is slightly more complex in the current design as a large number of inter connected elements are involved.
Microclimate and Physical Comfort	
Internal temperature	This was the main part of the current study. The design proves that thermal comfort for a large part of the year can be achieved by improved air movement within the building. Further, rotation of the elements leads to night time temperatures closer than the outdoor temperature making thermal comfort at night hours as well achievable.
Humidity	High rate of natural ventilation will lead to a situation where the indoor humidity levels follow the outdoor condition. Relative Humidity was not considered in the current study as literature study shows that high humidity, especially in hot-humid climate will not affect thermal comfort as the users will be accustomed to it. Bamboo being a hygroscopic material will have some amount of moisture regulating properties. This should be studied in more detail.
Ventilation (Air change per hour)	The current design manages to achieve a ventilation rate that is more than required by the standards, hence this criteria has been addressed adequately.
Air Quality	Continuous air flow within the room should help achieve a reasonably good quality of air. However, this was neither assessed in this study nor was any special measures taken to improve the quality of the incoming air.
Daylight and visual comfort	This was not studied in the current design. However, presence of large number

	of openings should be able to provide adequate daylight and at the same time control glare.
Acoustics- External noise + Internal transmission	The study did not focus on the acoustic properties as well. But because the façade is generally open to the exterior, poor acoustic performance can be expected.
Ease of User Control	As such the design does not provide for easy user control. However provision of a manual with simple instructions for operation can make control slightly easier.
Aesthetics, Cultural Aspects/ Tradition	
Compatibility with other building materials	Although this was not studied in the current design, it is assumed that an engineered product will be reasonably compatible with other building materials.
Acceptance among people using the building	These are subjective and more analysis is required to analyse the extent to which the design is accepted.
Impact on the urban fabric-acceptance among neighbours.	
Maintenance Costs	A highly durable material combined with a design that reasonably improves the thermal performance should be able to minimize the operational and maintenance costs. However, proper calculations are required to determine the actual cost performance.

Table 13 Performance of the Current Design

The current design was based on a simple open plan building with all four facades exposed to the outside. But, in reality this will seldom be the case. In case of rooms with one or more facades that are not exposed, another suitable ventilation strategy should be chosen. In the case of rotation of elements for thermal mass, the effect will be even lesser as the 'cooling effect ' from one or more of the 4 facades is lost. With respect to maximizing indoor air velocity, this will particularly be a problem in places like Chennai which do not have a single major predominant wind direction.

Chapter 12: Applicability of Cradle2Cradle Principle

12.1 Introduction to Cradle2Cradle (C2C)

As interpreted by Geldermans (2009) in his Master thesis report, “alongside other differences – C2C puts the emphasis on effectiveness instead of efficiency, as its proponents do not believe in slowing down in the wrong direction, but rather turning and accelerating into the right one.”The term, originally coined by the think-tanks behind the concept, Michael Braungart and William McDonough, refers to a design process based on a holistic economic, industrial and social framework that emphasizes on creating systems that are not just efficient but essentially waste free. Their principle is aimed at seeking a sustainable solution to the vicious cycle associated with the need for increased production due to the demands of the growing population on the one hand and increasing wastes associated with increasing production on the other. Their solution distinguishes itself from the popular 3Rs concept, by laying emphasis on the extent of recycling (upcycling instead of downcycling) in order to not just minimize the wastes but to eliminate the concept of wastes in its entirety.

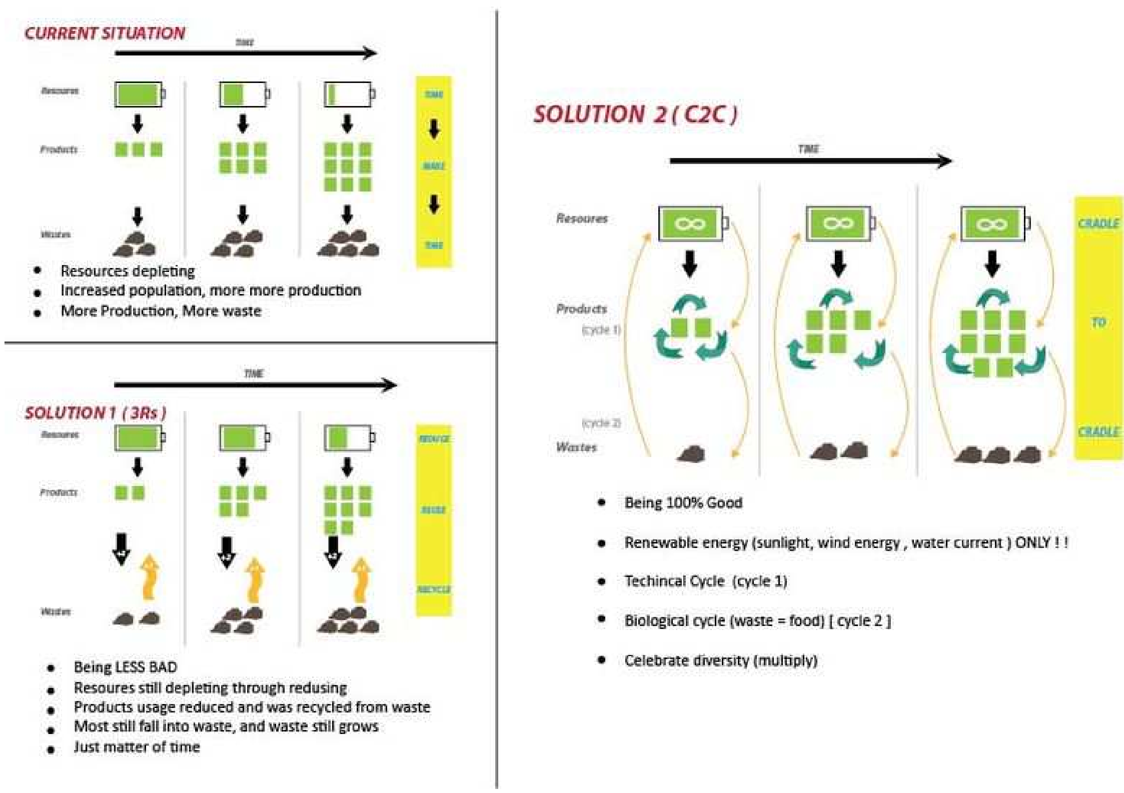


Figure 99 The current economic system, the current solution (the 3Rs), and the C2C framework as an alternative solution. [Source: Zhiying.lim; From: Wikipedia]

McDonough and Braungart define the following 5 criteria as the basis to meet the Cradle to Cradle certification:

Material Health - Products are made with materials that are safe and healthy for humans and the environment.
Material Reutilization - Products are designed so all ingredients can be reused safely by nature or industry.
Renewable Energy and Carbon Management - Products are assembled and manufactured with renewable, non polluting energy.
Water Stewardship - Products are made in ways that protect and enrich water supplies.
Social Fairness - Products are made in ways that advance social and environmental justice.

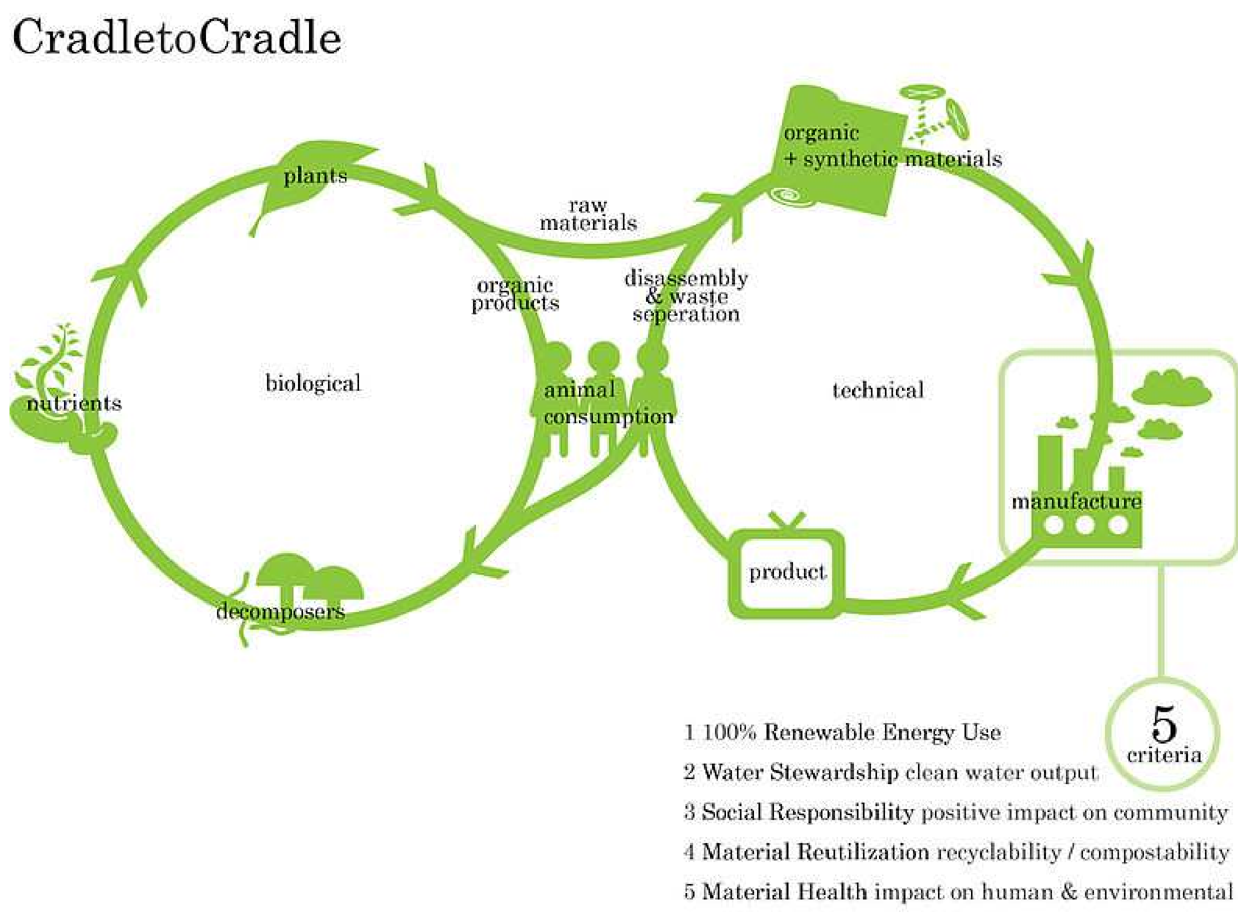


Figure 100 Biological and Technical Nutrients in the Cradle to Cradle Design Framework. [Source: Zhiying.lim; From: Wikipedia]

12.2 C2C in the context of engineered bamboo based products

The underlying principles of C2C are assessed in the context of engineered bamboo based products. It has to be noted that this is only a brief analysis based on the various literature encountered in the last 8 months. An extensive study specific on this topic is highly recommended.

12.2.1 Material Health

Identifying the chemical composition of the various constituents that make up the product is critical to assess the material health. Bamboo as such is an organic material which can be decomposed safely after its use. However, engineered bamboo products make use of various types of resins and or chemicals at different stages of preservation and development in order to make the product meet the desired structural as well as durability needs. Therefore significant attention has to be paid with respect to the additives that are used.

Currently a wide range of additives as well as treatment methods are in use. Some of them, such as CCA have already been identified as toxic and its use has been banned in several countries. On the other hand there have been some significant developments in identifying environmentally friendly preservatives- such as the one prepared from camphor leaf extract (Xu et al., 2013).

The development of appropriate bio-resins is always a subject of interest, however so far there is no clear evidence of usage of a 'healthy' additive which does not compromise on the properties of the end product. Apart from commercial manufacturers, there are a large number of traditional groups in different parts of the world that work with bamboo. Some amount of research has already been carried out to record the effectiveness of their practices however there is scope for more. Attention to traditional practices especially might help identify less harmful substitutes.

The timber sector which is very similar to that of bamboo in terms of the material and the needs, is more advanced than that of bamboo. Research on the development of eco-friendly additives/ treatment processes has been going on for several years now and some successful solutions have also been identified. Examples include PLATO (Providing Lasting Advanced Timber Option- which does not contain any chemicals, nor produce any toxic wastes and has been identified as 100% recyclable), Accoya (the free hydroxyl groups within the wood are changed into acetyl groups which subsequently reduces the ability of the wood's cell wall to absorb water- also does not produce any toxic wastes and is 100% recyclable) and TimberCIL (uses sodium silicate for the treatment and is C2C certified) (Geldermans, 2009). Knowledge transfer from these solutions can lead to arriving at sustainable solutions for bamboo as well.

The source of the raw materials is also a crucial factor which determines the material health. Forest source for bamboo is important in the context of exploitation and mismanagement of forest resources. Currently in India bamboo grows in registered forests as well as uncertified local plantations. As discussed earlier, the practice regarding the cultivation and trade of bamboo in India is quite vague – making it difficult to monitor the material health based on its source.

12.2.2 Material reutilization

At the fundamental level, materials according to the C2C concept are defined as an intended part of a biological or technical metabolism- that is they are either food to the biological cycle or to the technical cycle.

The possibility of recovery and safe reutilization of the different materials depends on how well the different ingredients that make the product are gelled together and the scope for separation of the same at the end of its life. For bamboo based products two different types of treatment methods can be identified: traditional and chemical. Traditional methods consist of curing, smoking, soaking and seasoning, and lime-washing. The latter, on the other hand involves impregnation of chemicals which have to go deep into the fibers in order to be effective but making material separation difficult. Janssen (1987) in his book 'Designing and Building with Bamboo', mentions about a boron-based fertilizer used in Costa Rica- disodium octoborate tetrahydrate, which after its use in the preservation process gets mixed with the starch and sugar contained in the bamboo. The bamboo after its intended period of usage can be later applied as a fertilizer. In this case, the additive is part of the biological cycle. Identifying other such possible additives which aid in the preservation process during the usage period but gets completely consumed at the end of the product's life shall make the process of material can prove to be useful.

12.2.3 Renewable Energy and Carbon Management

C2C certification requires that the energy associated with the product/material/service be derived from renewable energy sources. The use of fossil fuels and nuclear sources are not accepted. Bamboo being an organic material is known to trap large quantities of carbon- therefore as far as carbon management is considered it will perform fairly well. The potential of generating biomass energy using bamboo has also been identified and gaining popularity. As far as the façade element is considered, energy is required at different stages, especially for the various treatment methods and the transformation process of developing a finished engineered product from its natural culm form. By using the bamboo that has been cultivated locally, energy consumed for transportation can be largely reduced. Further, in a country like India where human labour is more popular (and appropriate) over mechanically powered systems, the energy consumed can be even more less. The façade element itself has been designed keeping in mind the need for the reduction of operational costs of a building- if its performance meets the intended design, it can aid in reducing the dependence on energy to a considerable extent. As far as the functioning of the element is considered, some form of energy is required to support its dynamic behavior and renewable energy should be considered for the same.

12.2.4 Water Stewardship

Large quantities of water are required for the growth as well as the treatment process (especially the traditional methods). Efficient flow management between different processes at the various stages can prevent wastage of water. During its growth stage, bamboo plantations help prevent the run off of rain water and soil erosion. There is not much information available about the efficient use of water in bamboo plantations or processing plants, however this is something which, looking from an overall picture does not seem impossible. Dell uses bamboo packaging for its computers. A brief description from their webpage reads: “Sustainability is built into all processes associated with the production of the bamboo. For example, after it is harvested, it is mechanically pulped at a nearby facility. During this process, 70 percent of the water is reclaimed and used in the process (the other 30 percent is lost to vaporization). Nothing is poured out and no toxic chemicals are used. If it's sunny, the pulp is dried by the sun, reducing electricity use.”

Knowledge transfer between companies which already implement such ‘sustainable’ principles and also other similar sectors especially those related to wood can help provide suitable solutions. Some rural communities use moving water as a mode of transport of the raw culms (the culms float in the water and are carried to the required destination). So far no threat has been identified with respect to this activity, however, this could also be because of inadequate study of the same.

12.2.5 Social responsibility

Social responsibility deals with adopting a fair approach “which ensures that progress is made towards sustaining business operations that protect the value chain and contribute to all stakeholder interests including employees, customers, community members, and the environment.”

Social responsibility should be observed at all stages of the life of the product. With respect to this several problems associated with various stakeholders can be identified at different stages. At the retrieval stage of raw materials, problems are mainly associated with various policies framed by the government. In India, there are several factors which lead to a situation of unfairness, particularly for the community members. Over the last few decades, the Government of India has made long-term agreements with industrialists for supplying forest products (including Non Timber Forest Products (NTFP) such as bamboo) at very nominal prices (Saxena, 1999). Gadgil (1989) writes about bamboo being sold to industrialists for less than one to two thousandth of the market price which was not only lead to industrial over-exploitation but also threatened the livelihood of the communities which were solely dependent on bamboo. There are also critical remarks on the crude methods adopted by industries to extract raw bamboo which endanger future regeneration (Furer-Haimendorf, 1985). In spite of rules which prevent the use of better quality culms by the pulp industries, these are easily breached.

The tribal groups are the ones which are directly affected by these activities. Various policies such as land ownership being a criteria for entitlement to get bamboo, that too after a lot of verification from various officials create a situation where the landless cannot even buy bamboo for a price. This forces the landless artisans to resort to illegal harvesting. The sensitivity of the issue further leads to social tensions between the government and the communities involved. Reforms in policies are required which ensure that industries in no way hinder the development of the communities dependent on the forests. Further there must be adequate control to prevent over exploitation of resources by the industries. With respect to this, the requirement that the raw material should come from sustainably maintained forests is of utmost importance.

According to Lobovikov et al. (2007), the overexploitation of bamboo resources is more of a universal problem. He suggests growing them in plantations can be a better means to dealing with this: "In the last two or three decades, population growth and new bamboo processing opportunities have led to the overexploitation of bamboo resources, their stricter regulation and even harvesting bans in some countries. These factors have contributed to the development of bamboo plantations. Oprins *et al.* (2004) present an outline of traditional propagation techniques and the most recent micropropagation technology, which has emerged as a result of the growing interest in planted bamboo and its productivity. Several studies and pilot projects were developed, addressing seed and clump propagation and rhizome and culm cuttings. The traditional methods have relatively low cost and do not require skilled labour, but they are not always applicable to large-scale areas. While micro-propagation is currently used primarily in ornamental horticulture, it can also be applied in large-scale initiatives. Studies are currently underway to transfer this technology to tropical bamboo countries."
Currently, in India 74% of the total stock is naturally regenerated whereas 26% is planted. The National Bamboo Mission has also recognized the need for plantations and is now in the process of identifying the potential areas for raising bamboo plantations in Government forest lands. Need for plantations, especially to meet the demands of tribal artisans have also been recognized now and plans are underway to develop the same.

Manufacturing bamboo based products requires considerable amount of manual labour at various stages. For a country like India which has large unemployment rates, promoting bamboo based products can, if the business is profitable, provide jobs to a large number of population. According to IPIRTI, bamboo mat board (BMB) production has revived mat weaving in the tribal areas of India, and is now generating more than 2.5 million days of work annually. They have identified that in India alone, the industry has the potential to generate up to 16.7 million days of work each year.

The focus should continue to be on the rural folk who are not only the economically backward sections, but also because they already possess the know-how of working with bamboo or similar materials. Activities such as weaving of mats have been found to promote a sense of togetherness and community development. However, fair labour practices should be established as the rural population, especially women, are often victims of cheap labour.

Safe working conditions should be ensured in production stage as well as when the product is in use. The use of additives (especially the ones that are found to be toxic) is of concern again.

Animal Species associated with Bamboo:

The best-known animals dependent on bamboo are the giant panda and red panda (Lobovikov et al. 2007). Their diet almost exclusively consists of bamboo shoots and leaves. Red pandas are found in the bamboo forests of North-Eastern India and are marked as endangered species. However, there is not much information on the impact of the various activities in bamboo forests on these species. Bamboo flowering and seeding are known to cause an explosion of the rodent population, resulting in famine in various parts of the world. Local populations in North-East India suffer particularly from the rat outbreaks triggered by bamboo flowering. The erratic flowering pattern of bamboo makes it difficult to study the dynamics of the rat population fluctuations (Lobovikov et al. 2007). Again, not much information on this subject could be gathered due to time constraints. However, it has to be recognized that the impact on the environment and ecology is of utmost importance, especially in the context of a C2C certification.

12.3 Conclusion

To sum, the first two principles relating to the material seem to have the maximum bottlenecks for meeting C2C standards. Having said that, it does not seem impossible, especially because similar problems have been addressed to some extent in the case of timber, which has quite comparable traits. The last three principles are more related to the decision making process at different levels, at different stages and with respect to different stakeholders. These are dependent on the mindset of the people- who need to make conscious design choices. It is the coming together of all the principles that will eventually result in a positive outcome.

By recognizing the obstacles for meeting C2C principles with respect to bamboo based products, we can identify the stages in the cycle where problems will be encountered. It can be seen in the diagram that raw materials are a core part of the cycle. Even though bamboo in itself is an organic material, if it cannot be separated from the other additives that are added during the manufacturing of the product, the cycle can no longer continue. Therefore choice of an appropriate additive that is biodegradable is necessary.

Chapter 13: Conclusion and Recommendations

The starting point of this work was to address the increasing trends in the energy consumption by the building industry. With regards to this, the embodied costs and more importantly the operational costs were identified as the key contributors. This lead to an hypothesis that a combination of an alternative building material and a smart façade design, can address the energy consumption to an adequate extent. Bamboo, owing to its large availability in India, was chosen as the material for this study.

The focus of this study was not on directly calculating the costs or the energy demands, however, it was an attempt at using an alternative material in a system where passive design concepts prevail over conventional indoor climate regulation systems. Therefore, it not only has the potential to lower the embodied energy, but also provides the opportunity to improve the thermal comfort which will consequently lower the operational costs.

The following Research Questions were set in order to answer a part of the bigger question:

- Does the designed façade system contribute to the performance of the indoor climate positively? (With emphasis on the thermal comfort).

- Will the end product meet the standards to be certified as a Cradle2Cradle product?

13.1 Answer to Question 1

The focus of the first question is on arriving at a technical design solution for a façade design, aimed at providing optimum comfort without the use of artificial (HVAC) systems. The research was based on a set of boundary conditions with respect to the climate, location and functional requirements- also arrived based on the applicability of the material and the functional demands. The proposed design has been for an open plan room located in an urban region in the city of Chennai which is located in a hot-humid climate zone.

The design solution proved that by an appropriate natural ventilation system and control over the effects of the thermal mass, adequate thermal comfort can be achieved for a large part of the year. A good natural ventilation system was found to lead to increased air circulation as well as indoor air speeds (higher than 0.65 m/s during the peak summer afternoon hours) both of which are necessary to attain optimum thermal comfort. However, comfort from natural ventilation is possible only when the outdoor wind velocity is reasonably high. Thermal comfort during the night hours, when wind speeds are relatively low can be achieved by lowering the mean radiant temperature (MRT) which in turn leads to a reduction in operative temperature. This was proven to be possible by a 180˚ rotation of the façade elements. By doing so, the originally hotter interior surface can be replaced by the cooler outdoor surface causing a net reduction in MRT. In the case of Chennai, the night time MRT during summer, as a result of rotation was found to reduce by 3˚C causing a 1.5˚C reduction in operative temperature. During the intermediate months a 2˚C reduction in operative temperature was observed. Further reduction is possible when the effect of the thermal mass of the roof and the floor are taken care of by other means and/or by lowering the indoor air temperature by means of an exhaust fan or similar devices.

The applicability of the system has been checked further for two other locations- Mumbai and Kolkata, both of them technically belonging to the same climate belt, but with some significant differences. Results indicate that the design is applicable to these two locations as well, particularly to Mumbai, which has good wind speeds and a comparatively less challenging climate. The same concept has been further extended to two other different climate zones- moderate and composite. Even though a thorough investigation can prove otherwise, a preliminary study indicates that the façade design has scope for extension for other climate zones as well. It especially looks promising for a moderate climate zone with reasonably good wind speeds.

13.1.1 Recommendations

Various combinations of calculation methodologies have been used to arrive at the results owing to the dynamic nature of the design concept. During the course of which several assumptions have been made. In order to arrive at a more accurate assessment of the proposed design, use of an advanced tool that can perform building physics calculations for a dynamic design is recommended. Alternately, developing a scale model and testing at the field or a climate chamber can also give better insights.

This design was based on several boundary conditions- an urban location being one of the most important one. Ventilation will definitely be more easily achievable in a suburban or rural area. The prospects of this design in such situations should therefore be considered.

13.2 Answer to Question 2

The second question concentrates on the sustainability aspect of the design, with more emphasis on the choice of materials for the design- in this case, engineered bamboo. This part has been addressed briefly. However, based on an overall outlook, it can be concluded that the product as such cannot be labeled Cradle2Cradle with 100% certainty yet as there are still aspects that need to be addressed to meet the criteria. Apart from the problems at the different organizational levels, the main problems which hinder the flow of the C2C cycle lies with the possible need for use of additives to improve the durability of the material. Durability of the material is highly important, especially if it has to be used for a façade system not only because it affects the life of the element itself, but also due to the impact it has on its occupants.

13.2.1 Recommendations

Recognizing the various constraints and working towards eliminating them can pave way towards a fully C2C solution. Knowledge transfer between similar successful fields can particularly help in achieving better standards. Development of better policies at the governmental level must be a top priority in order to ensure fair treatment of all stakeholders involved as well as to ensure correct harvesting practices.

13.3 Items for Further Research

- The current design was for a single zone square building whose all four sides are exposed to the outside. Although this is seldom the case in reality, this assumption was made in order to avoid a too complex situation for the preliminary design concept. The study of the influence of this design for more conventional floor plans/ layout is recommended in order to see how effective it is for such scenarios.

- Air quality is of high importance in the case of naturally ventilated buildings. Further study in order to combine a suitable air purification system with the proposed façade design is recommended, especially if the design location is in an urban area which has higher pollution levels.

- Acoustics is another issue which was not addressed in the current design. A building with large openings, located in an urban area will perform poorly in terms of acoustic demands. Although it is not possible to completely dampen the noise levels, the inherent property of bamboo in combination with a noise dampening system should be studied in order to arrive at a reasonably acceptable acoustic performance.

- The thickness of the façade elements in this design was chosen solely based on the thermal performance. Use of Phase Change Materials (PCM) which are capable of storing much larger quantities of latent heat, in combination with bamboo, can not only aid in better cooling effect but also reduce the thickness of the elements, leading to a much lighter construction. It is recommended to study the contribution of such materials and the possible usage of the same.

- In the current design, the material chosen (Strand woven Bamboo- SWB) is mainly popular in the European market. The durability of the material as discussed in the report was also based on the Dutch climate which is very different from that in India. Although SWB is available in India, there is not much information regarding its performance in exterior environments. Combined market as well as material performance study with this respect is required in order to develop suitable products to meet the demands of different Indian climates.

- Bamboo being a hygroscopic material will be able to regulate the moisture levels to some extent depending on its pore structure. Engineered bamboo products are reasonable dense, hence the effect of moisture may not be that prominent. Absorbed moisture on the surface, if any, can help in evaporative (adiabatic) cooling especially during the day when the relative humidity is low and the wind speeds are high. At the same time, presence of moisture will also cause an increase in thermal conductivity, causing higher rates of heat transfer. The software used for this project, DesignBuilder does not take into account the moisture buffering performance of materials. Therefore, detailed study of the effect of moisture in the external air on the material performance can prove to be quite useful to arrive at a more realistic assessment.

- Lastly, the nature of the design requires a lot of involvement from the occupants. It is anticipated that some amount of time will be required to get accustomed to using such a system. It will be interesting to study the extent to which the occupants succeed in controlling the performance of the façade system in order to improve their comfort levels.

Bibliography

Bansal, A. K. and Prasad, T. R. N., 2004. ‘Manufacturing laminates from sympodial bamboos: an Indian experience’, INBAR J. Bamboo and Rattan, Vol. 3, No. 1, pp. 13–22.

Bansal, N.K., Hauser, G. and Minke, G., 1994. ‘Passive Building Design: A Handbook of Natural Climatic Control’,Elsevier Science B.V., Amsterdam.

Chiang, C.M., Chen, N.T., Chou, P.C., Li, Y.Y., and Lien, I.C., 2005. ‘A Study on the Influence of Horizontal Louvers on Natural Ventilation in a Dweling Unit’, In Proceedings: Indoor Air, Edinburg, UK, pp.3142–3147.

Chand, I., Krishak, N. L. V., 1971. ‘Laboratory Studies of the Effect of Louvers on Room Air Motion’, Building Science, Vol. 6, Issue 4, pp.247–252.

deDear, R.J. and Brager, G.S., 2002. ‘Thermal Comfort in naturally ventilated buildings: Revisions to ASHRAE standard 55’, Energy and Buildings Vol. 34 (6), pp. 549–561.

Deuble, M.P. and deDear, R.J., 2012. ‘Mixed-mode buildings: a double standard inoccupants' comfort expectations.’ Building and Environment, Vol. 54, pp. 53–60.

Fanger, P. O., 1972. ‘Thermal comfort Analysis and applications in environmental engineering’, McGraw-Hill, New York.

Fong, K. F., Chow, T. T. and Givoni, B., 2008. ’Optimal Air Temperature and Air Speed for Built Environment in Hong Kong from Thermal Comfort and Energy Saving Perspectives’, World Sustainable Building Conference, Australia

Furer-Haimendorf, C.von, 1982. ‘Tribes of India: The Struggle for Survival.’, Oxford University Press, New Delhi.

Ganapathy, P.M., Zhu Huan-Ming, Zoolagud, S.S., Turcke, D. and Espiloy, Z.B., 1999. ‘Bamboo Panel Boards a State-of-the-Art Review’, In: INBAR, No. 12, New Delhi.

Gadgil, M., 1989. ‘Deforestation: Problems and Prospects’, Lokayan, Vol. 7(4).

Geldermans, R. J., 2009. ‘Cradle-to-Cradibility: Two Material Cycles and the Challenges of Closed Loops in Construction.’, Graduation Report TU Delft.

Givoni, B., 1968. 'Ventilation problems in hot countries', Research report to the Ford Foundation, Building research Station, Technion, Haifa, Israel

Givoni, B. and Goldman, R. F., 1971. 'Predicting metabolic energy cost', Journal of Applied Physiology, Vol. 30, No. 3, pp. 429–433

Givoni, B., 1974. 'Buildings for hot climates', Building Research and Practice, 2(6), pp.336–343.

Givoni, B., 1991. 'Performance and applicability of passive and low-energy cooling systems', Energy and Buildings, Vol. 17, pp.177-199.

Givoni, B., 1994. 'Building Design Principles for Hot Humid Regions', Renewable Energy, Vol. 5, pp. 908–916.

Givoni, B., Khedari, J., Wong, N. H., Feriadi, H., and Noguchi, M., 2006. 'Thermal sensation responses in hot, humid climates: effects of humidity', Building Research & Information, Vol. 34:5, pp. 496-506

Givoni, B., 2010. 'Thermal Comfort Issues and Implications in High-Density Cities', In: Designing High Density Cities for Social and Environmental Sustainability, Earthscan, London, pp. 97-104, 2010.

Global Footprint Network, September 2013. Retrieved from http://www.footprintnetwork.org/en/index.php/gfn/page/world_footprint/

Hazra, A., 2007. 'Industrialisation of Bamboo Sector in India', For: Confederation of Indian Industry.

Hien, W. N. and Istiadji, A. D., 2003, 'Effect of External Shading Devices on Daylighting and Natural Ventilation', Proceedings: Eighth International IBPSA Conference, Eindhoven, pp. 475-482.

Hughes, B. R. and Ghani, S. A. A. A., 2010. 'A numerical investigation into the effect of Windvent louvre external angle on passive stack ventilation performance', Building and Environment, Vol. 45, pp.1025–1036.

Humphreys, M.A., 1981. 'The dependence of comfortable temperatures upon indoor and outdoor climates.' In: Cena, K., Clark., J.A. (Eds.), Bioengineering, Thermal Physiology and Comfort, Elsevier, Amsterdam, pp.229–250.

Janssen, J.J.A., 1987. 'Designing and Building with Bamboo' , In: INBAR Technical Report No. 20.

Khedari, J., Yamtraipat, N. and Hirunlabh, J., 2001. 'A new concept for setting thermal comfort standards In Moving Thermal Comfort Standards into the 21st Century', Windsor, UK, pp. 472–478.

Khedari, J., Yamtraipat, N., Pratintong, N., and Hirunlabh, J., 2003, 'Thailand ventilation comfort chart', Energy and Buildings, Vol. 32, No. 3, pp. 245–250.

Kiran, M. C., Nandanwar, A., Naidu, M. V. and Varada Rajulu, K., 2012. 'Effect of Density on Thermal Conductivity of Bamboo Mat Board', International Journal of Agriculture and Forestry, Vol. 2(5), pp. 257-261.

Knaack, U., Klein, T., Bilow, M. and Auer, T., 2007. 'Principles of Construction', Birkhäuser Architecture, Berlin.

Larasati, D. 1999. 'Uncovering the green gold of Indonesia', Working Paper No. 31, INBAR, Beijing, China.

Lobovikov, M., Paudel, S., Piazza, M., Ren, H. and Wu, J., 2007, 'World bamboo resources: A thematic study prepared in the framework of the Global Forest Resources Assessment 2005', Food and Agricultural Organization of the United Nations, Rome.

Lugt, P. van der, Dobbelsteen, A. van den & Abrahams, R., 2003. 'Bamboo as a building material alternative for Western Europe? A study of the environmental performance, costs and bottlenecks of the use of bamboo (products) in Western Europe.' In: Journal of Bamboo and Rattan, 2(3), pp.205–223.

Lugt, P.van der, 2005. 'The bamboo sector in Colombia and Ecuador: a state of the art analysis of opportunities and constraints.', In: Journal of Bamboo and Rattan, 4(4), pp.421–440.

Lugt, P. van der, Dobbelsteen, A. van den & Janssen, J.J.A., 2006. 'An environmental, economic and practical assessment of bamboo as a building material for supporting structures.' In: Construction and Building Materials, 20(9), pp.648–656.

Lugt, P. van der, 2008. 'Design Interventions for Stimulating Bamboo Commercialization- Dutch Design meets Bamboo as a Replicable Model', Design for Sustainability (DfS) Program publication No. 18, VSSD.

Lugt, P. van der, Vogtländer, J.G., Brezet, J.C. 2009 (draft version). Bamboo, a Sustainable Solution for Western Europe - Design Cases, LCAs and Land Use . INBAR Technical Report 30. INBAR, Beijing, China.

Mathur, G. C., 1981. 'State of art report on use of bamboo in low cost housing', NBO and UN Regional Housing Centre, ESCAP, New Delhi, India.

Mishra, H. N., 1990. 'Know-how of bamboo house construction' In: Ramanuja Rao, I.V.; Gnanaharan, R., Sastry, C. B., ed., Bamboos: current research. Proceedings of the International Bamboo Workshop, Cochin, India, 14-18 November 1988. Kerala Forest Research Institute, Kerala, India; International Development Research Centre, Ottawa, Canada. pp. 242-249.

McDonough, W. and Braungart, M., 2002. 'Cradle to Cradle: Remaking the Way We Make Things', North Point Press, New York.

Nicol, F., 2004. 'Adaptive thermal comfort standards in the hot–humid tropics', Energy and Buildings, 36(7), pp.628–637.

Nicol, F. & Humphreys, M., 2010. 'Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251.' Building and Environment, Vol. 45(1), pp.11–17.

Priyadarsini, R., Cheong, K. W. and Wong, N. H., 2004. 'Enhancement of natural ventilation in high-rise residential buildings using stack system', Energy and Buildings, Vol.36, pp. 61–71.

Prianto, E., Depecker, P., 2003, 'Optimization of architectural design elements in tropical humid region with thermal comfort approach', Energy and Buildings 35, pp.273–280.

Ranjan, M.P., Iyer, N. and Pandya, G., 1986. 'Bamboo and Cane crafts of Northeast India' , National Institute of Design, The Development Commissioner of handicrafts, New Delhi.

Rees, W. E., 1998, 'The Built Environment and the Ecosphere: A Global Perspective', for presentation to Green Building Challenge, Vancouver.

Reubens, R., 2010. 'Bamboo in Sustainable Contemporary Design', In: INBAR Working Paper no. 60, Beijing

Saxena, N. C., 1999, 'Policy and Legal Reforms for the poor', Planning Commission, Government of India, http://planningcommission.nic.in/reports/articles/ncsxna/index.php?repts=ft.htm#top, Published online: June 1999.

Schneider, S. H., Root, T.L. and Mastrandrea, M.D., 2011. 'Encyclopedia of Climate and Weather', Volume 1', Oxford University Press

Su, X., Zhang, X. and Gao, J., 2009. 'Evaluation method of natural ventilation system based on thermal comfort in China', Energy and Buildings, Vol. 41, pp. 67–70.

Toe, D.H.C., Kubota, T., 2013, 'Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE', Frontiers of Architectural Research.

Vyawahare, M., 2009. 'Bamboo: Poor Man's Gold- A case for developing the bamboo sector in India', working paper, Centre for Civil Society, New Delhi.

Wong, N.H. and Tanamas, J., 2002, 'The effect of wind on thermal comfort in naturally ventilated environment in the tropics, in Karyono', In: Proceedings of International Symposium on Building Research and the Sustainability of the Built Environment in the Tropics, Jakarta, Indonesia, pp. 192–206.

Whole Building Design Guide, April 2013, Retrieved from

http://www.wbdg.org/resources/greenhousegasemissions.php?r=sustainable

Xu, G., Wang, L., Liu, J. and Hu, S., 2013. ‘Decay resistance and thermal stability of bamboo preservatives prepared using camphor leaf extract’, International Biodeterioration & Biodegradation, Vol. 78, pp. 103- 107.

Yuan, L. J., 1987. ‘The Malay House: Rediscovering Malaysia’s Indigenous Shelter System.’ Kuala Lumpur: Institut Masyarakat.

Zheng, W., Yiping, R. E. N. and Wenjing, G. U. O. 2003. ‘A study comparing the performance of bamboo mat corrugated board with other corrugated boards.’ In: INBAR, Working Paper No. 45, pp.1–5.

Appendix A

Manufacturing Procedure of BMB

According to TECA (Technologies and practices for small agricultural products) (2012), the manufacturing process of BMB broadly involves the following steps:

1) Material preparation: splitting bamboo, knot removal, sliver making - From split bamboo epidermal layer is removed and slivers of thickness ranging from 0.6mm to 1.0 mm are made. Higher thickness of slivers results in increased resin requirement.
2) Weaving of mats: The two most common weaving patterns are the herring bone pattern (45 degrees) and the rectangular pattern (90 degrees).
4) Resin application.
5) Stabilization and drying of resin coated mats: Resin coated mats are dried to a moisture content of around 8 to 12% either in drying chambers or industrial dryers.
6) Assembly and hot pressing: Resin coated and conditioned mats are assembled between two aluminium caul plates whose surfaces are coated with releasing agent. The number of mats assembled depends upon the required thickness of the board. Hot pressing melts the resin in the mats and bonds them together tightly. The mats shall be hot pressed at not less than 140˚C at a specific pressure of 1.5 to 2 N/mm^2. Hot pressing time depends on the thickness of the board (about 6 minutes for 3 mats with additional 1 minute for every additional mat layer). For thickness greater than 6mm, bamboo mats are interleaved with wood veneers to make bamboo mat veneer composites.
7) Trimming.

Performance of Bamboo mat corrugated board (BMCB)

Properties	
MOR (Modulus of Rupture)	40-45 N/mm^2
Internal bond strength(dry/wet*)	1.3 - 1.4 N/mm^2 (* sample subjected to 3hrs boiling is dried to 12% moisture content and tested)
Load bearing capacity	5.4 N/mm of width (span length - 1000mm) (Graph showing comparative performance of BMCS and Asbestos Cement Corrugated Sheet (ACCS) is enclosed).
Water resistance test	Withstands 72 hours of boiling test prescribed for BWP grade Plywood in IS:808
Permeability	No percolation of water observed after storing water for over 24 hours. However, considering the biological nature of the material, a protective water-proof / UV coating is recommended on the side exposed to sun/rain.
Fire resistance	Conforms to flammability test as per IS:5509 Indian Standard Specification for Fire Retardant plywood.
Thermal conductivity	BMCS has low thermal conductivity compared to other roofing materials. Tests are in progress.
Application	Roofing, walling, structural

Table A. 1 Product Profile developed by IPIRTI and BMTPC [Source: Website IPIRTI- http://www.bamboocomposites.com]

In a study by Zheng et al., (2003), comparison of properties of Bamboo mat corrugated board with iron sheet board, plastic composite board and asbestos board gave the following results:

- Compared with the other three materials BMCB has the best thermal insulating property.
- Moderate noise transmission performance. Plastic and asbestos boards perform better.
- Combustion performance of BMCB was found to be better than plastic board- lower heat release and smaller combustion heat. (Iron and asbestos boards were not considered).
- Bamboo board has the lowest density and highest water absorption ratio compared to the other alternatives i.e. absorbs water/ moisture easily.

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
Basic Form					
Culm	Sustainable building material	The inside of the bamboo culm is susceptible to moulds; Design constraints due to variation in cross-section, thickness, etc; Splits easily; Weak in tension	Constuction, scaffolding, Water transport	Traditional: heating over open fire after applying oil on the surface; Lime dipping; Chemical Methods: treatment with boron,	Yes
Strips	More susceptible to decay due to moiture/ fire/ fungal or insect attack.		Baskets, storage structures		Yes
Woven Mats	No restriction to species; culms with narrow diameter and wall thickness are also possible raw materials; potential for employment opportunities for rural folk.	Labour intensive	Walls/ doors, baskets		Yes

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
Bamboo Mat Boards (BMB)	Versatile panel material (upto 6mm thick); water proof; Good internal bond strengths, high plane rigidity and high racking strength; Good resistance to fire; Scratch and stain resistance; Durability can be improved by incorporating a preservative in the glue; Environmentally friendly* ;	Emission of formaldehyde; Because it is usually made of green bamboo, the product shrinks unevenly when drying, resulting in irregular dimensions. Adequate drying the strips or laminating them are solutions.Another weakness is colour differences in each product caused by the use of strips from different parts of the culm.	Non-load bearing construction- Panelling, ceilings, prefab shelters, making of corrugated board, packing cases and storage containers, door panels, furniture, etc	Quality of culms is not very important (culms which can't be used for plybamboo are usually used). Phenol Formaldehyde resin (large quantities)- can be replaced by a biodegradable resin such as Poly Lactic Acid (PLA) resin made from plant sources, lignin from pulp mill effluent	Yes
Bamboo Mat Veneer Composites (BMVC)	Superior physical and mechanical properties compared to BMB; Thickness range 4- 25 mm;			Phenol Formaldehyde resin, lignin from pulp mill effluent; Veneer	Yes
Bamboo Mat Corrugated Board	Better load bearing property comparable to other roofing material; Waterproof (over 24 hours) - a protective water-proof/ UV coating is recommended; Good resistance to fire, decay, termites/ insect attacks; Low thermal conductivity	The adhesive resin used makes it less environmentally friendly.	Roofing, walling, structural		Yes

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
Bamboo Curtain Board	several species of bamboo are suitable for this, and the process of making curtains is simpler and less time-consuming than weaving mats. Simple processing technology and high quality of the product; Good heat resistant compared to other formwork materials		Formwork	Resin impregnated Kraft paper. (PF resin/ modified melamine resin)	
Bamboo Laminates / Strand woven bamboo (Plybamboo)	Moisture resistance; Durability; good mechanical and physical strength; wide range of thickness possibilities.	Quality of culms is important (high quality culms are preferred). High requirements posed to the input strips.	Flooring tiles, laminate boards, doors/ window frames, furniture; concrete formwork, floors in vehicles/ ships	Melamine fortified UF Resin (Formaldehyde emission as per International norms); Water based acrylic pre-coating to prevent moisture related problems; UV cured melamine acrylate system, water based PU resin for finishing of floors	Yes

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
Bamboo Particle Board	Environmentally friendly resins*, durable, good mechanical strength and modulus of elasticity; low expansion rate when absorbing water, can be strengthened by adding several surfaces (coating, resin impregnated Kraft paper, wood veneer, bamboo mat, etc., Requirements for raw materials are few- residues from manufacturing of other bamboo based products are often used. High utilization rate of raw materials		Used for concrete formwork, Ceiling, various kinds of light partitions, door shutters, panelling, small window and door frames, etc, Wall insulation, furniture and packing	Adhesive containing wax emulsion	Yes
Bamboo mat overlaid rice husk board				PF resin in which phenol is partially replaced by Cardanol (CPF); rice husk formed into mat	
Bamboo fibre Moulding Technology	panels are made from strips and residues from other bamboo panel mills are the raw material. Various shapes and patterns are possible.		Stair handrails, cross bandings, small window and door frames, doors, decorative panels (if overlaid with thin strips)		

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
Bamboo-plastic composite	Formaldehyde-resin free; Waste plastic can be used, Possesses good water resistance, durability and dimensional stability properties compared to common bamboo particleboard.				
Cement-bonded particleboard/ Gypsum-bonded particleboard/ Bamboo particle plaster board.	No free formaldehyde emission, Good fire resistance		used in housing applications, such as insulation board, ceiling and partition; recommended as ideal material for architecture		

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
Bamboo Fibre Reinfoced Plastic	Good Mechanical and Thermal Properties; much lighter than GRP and stronger than other natural fiber (jute, coir, banana stem) reinforced plastic (FRP). Environmentally friendly; Recycled plastic is ideal to reduce production cost;		Flooring	The ratio of plastics should be over 30 % for higher water-resistance and dimensional stability. Polypropylene is recommended, the others must be co- blended and co-polymerized before using. The density of the substrate should be higher than 1 g/cm3 (1.0-1.10 g/cm3) to ensure the best mechanical properties.Emulsion type biodegradable resin	Yes
Strand Woven Bamboo (SWB)	Requires high quality processing, leaving no holes in the cross section. Suitable for outdoor application. (higher glue content, high compression level)	High weight, expensive	Outside decking	Quality of input strips is less important. (culms which can't be used for plybamboo are usually used). Phenol Formaldehyde Resin	Unknown

	Advantages	Weakness	Uses	Special Additives/ Treatment methods	Use in India
MOSO X-treme	Density-heat treated production resulting in high Durability; Dimensional stability of 24hours after submerging in water; Fire Safety class 1; Surface fungi resistance: Class 0; Requires regular cleaning and maintenance; Longer life		Outdoor decking		Unknown

Statistics- Distribution of Bamboo in India

The State of Forest Report (2011) gives statistical information on the distribution of bamboo in the various states of the country. Details about the quantity and quality of the individual species are not recorded.

Table 6.5.3: State-wise Distribution of Bamboo Area in Recorded Forests	(km^2)
State/UT	Bamboo bearing area
Andhra Pradesh	8,184
Arunachal Pradesh	16,083
Assam	7,238
Bihar	739
Chhattisgarh	11,368
Dadra & Nagar Haveli	55
Goa	308
Gujarat	4,091
Haryana	19
Himachal Pradesh	508
Jharkhand	3,603
Karnataka	8,186
Kerala	2,882
Madhya Pradesh	13,059
Maharashtra	11,465
Manipur	9,303
Meghalaya	4,793
Mizoram	9,245
Nagaland	4,902
Orissa	10,518
Punjab	75
Rajasthan	2,455
Sikkim	1,181
Tamil Nadu	3,265
Tripura	3,246
Uttar Pradesh	1,313
Uttarakhand	451
West Bengal	1,042
Total	**139,577**

Table A. 2 State wise distribution of Bamboo area

Table 6.5.4: State-wise Bamboo bearing area by Density in Recorded Forests (km^2)							
State/UT	**Pure bamboo**	**Dense bamboo**	**Scattered bamboo**	**Bamboo present but clumps completely hacked**	**Bamboo re-generation**	**No bamboo**	**RFA (km^2)**
Andhra Pradesh	26	1795	3963	309	2091	55630	63,814
Arunachal Pradesh	217	8681	6953	144	88	35457	51,540
Assam	105	4049	2878	166	40	19594	26,832
Bihar	1	239	393	75	31	5734	6,473
Chhattisgarh	54	3046	4577	1496	2195	48404	59,772
Dadra & Nagar Haveli	0	15	28	3	9	149	204
Goa	0	40	212	12	44	916	1,224
Gujarat	0	799	2408	367	517	14836	18,927
Haryana	0	3	9	7	0	1540	1,559
Himachal Pradesh	0	37	422	24	25	36525	37,033
Jharkhand	14	898	1571	509	611	20002	23,605
Karnataka	0	1925	4390	297	1574	30098	38,284
Kerala	0	461	2105	86	230	8383	11,265
Madhya Pradesh	76	2732	5264	2284	2703	81630	94,689
Maharashtra	56	2618	4604	1466	2719	50474	61,939
Manipur	192	5825	3101	124	61	8115	17,418
Meghalaya	63	2815	1830	68	17	4703	9,496
Mizoram	226	6116	2757	104	42	7472	16,717
Nagaland	101	3064	1644	65	28	4320	9,222
Orissa	35	2479	5230	1066	1708	47618	58,136
Punjab	0	5	39	31	0	3009	3,084
Rajasthan	0	516	1188	333	418	30185	32,639
Sikkim	0	481	684	8	8	4660	5,841
Tamil Nadu	5	650	1707	130	773	19612	22,877
Tripura	67	2039	1079	43	18	3048	6,294
Uttar Pradesh	2	311	647	189	164	15270	16,583
Uttarakhand	0	67	329	47	8	34200	34,651
West Bengal	0	362	582	58	40	10837	11,879
Total	**1240**	**52068**	**60596**	**9511**	**16162**	**602420**	**741,997**

Table A. 3 Bamboo bearing area by density in Recorded Forests

Table 6.5.5: State-wise Number of Estimated Culms by Soundness in Recorded Forests

(in million)

State/UT	Green Culms	Dry Culms	Decayed	Total
Andhra Pradesh	837	198	63	1098
Arunachal Pradesh	2666	234	80	2980
Assam	2046	201	94	2341
Bihar	270	38	19	327
Chhattisgarh	458	123	20	601
Goa	10	4	0	14
Gujarat	114	50	7	171
Himachal Pradesh	161	103	27	291
Jharkhand	181	49	8	238
Karnataka	310	97	10	417
Kerala	115	37	5	157
Madhya Pradesh	1229	819	222	2270
Maharashtra	536	191	21	748
Manipur	2035	192	70	2297
Meghalaya	1109	104	38	1251
Mizoram	1953	185	67	2205
Nagaland	1077	102	37	1216
Orissa	720	169	54	944
Punjab	3	2	0	5
Rajasthan	500	404	122	1026
Sikkim	206	17	5	228
Tamil Nadu	367	86	33	485
Tripura	735	70	25	830
Uttar Pradesh	122	87	26	235
Uttarakhand	143	92	24	259
West Bengal	568	59	33	660
Dadra & Nagar Haveli	3	0	0	3
Total	**18474**	**3713**	**1110**	**23297**
%	**79**	**16**	**5**	**100**

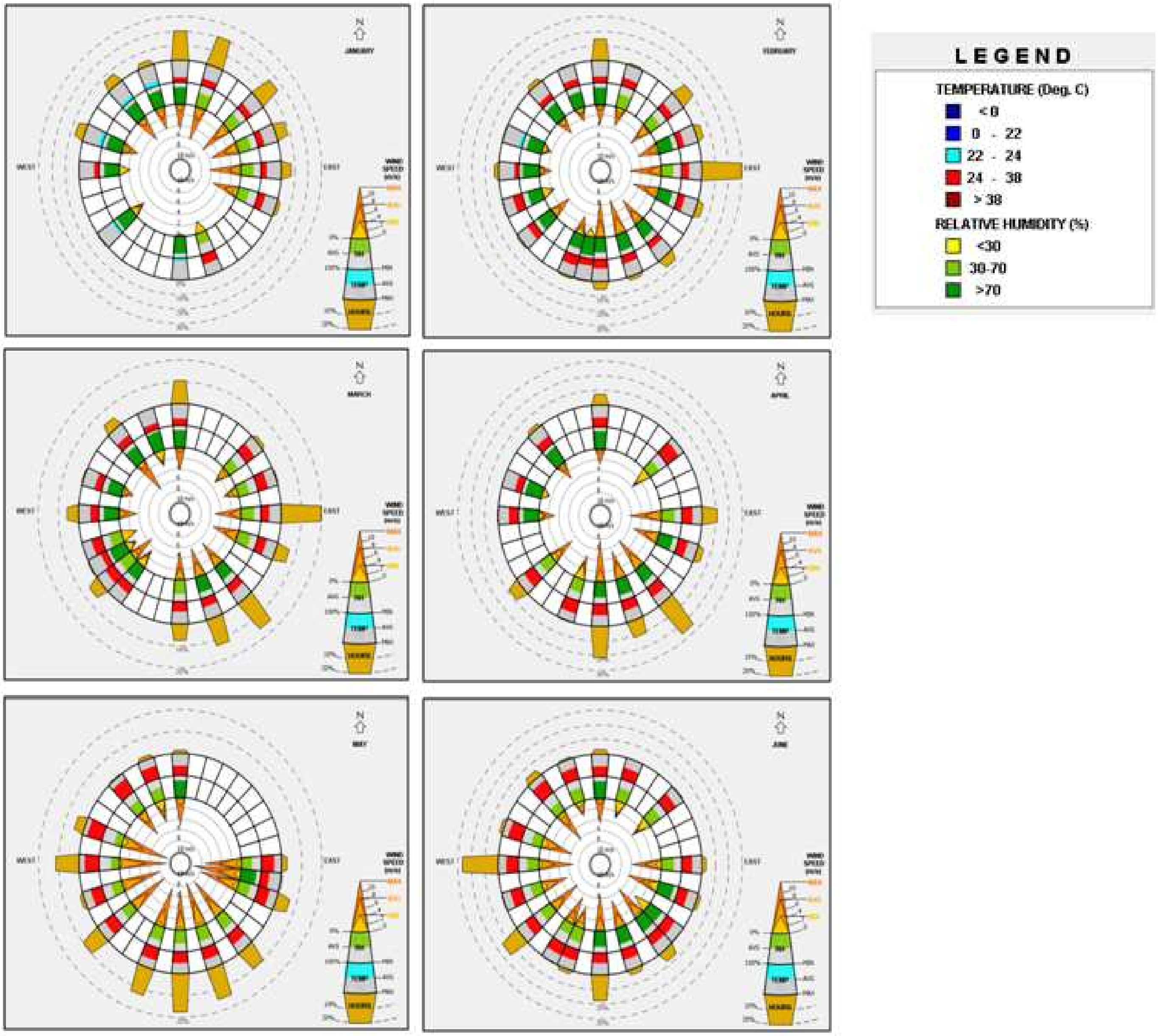
Table A. 4 State-wise Estimation of Soundness of the culms

Table 6.5.7: Physiographic Zone-wise* Bamboo Estimation in TOF (Rural)			
Physiographic Zone	**Geographical Area**	**Total Culms (million)**	**Equivalent Green Weight (million tonnes)**
Western Himalayas	329255	120	0.55
Eastern Himalayas	74618	83	0.32
North East	133990	289	1.72
Northern Plains	295780	57	0.24
Eastern Plains	223339	943	4.07
Western Plains	319098	8	0.03
Central Highlands	373675	124	0.53
North Deccan	355988	45	0.23
East Deccan	336289	212	0.97
South Deccan	292416	16	0.16
Western Ghats	72381	30	0.28
Eastern Ghats	191698	3	0.02
West Coast	121242	135	0.77
East Coast	167494	55	0.24
Total	**3287263**	**2127**	**10.20**

Note: **The state wise estimates of number of culms and their weight is not given as the sample size was not adequate to give estimates with an acceptable precision.*

Table A. 5 Physiographic zone wise estimation of Bamboo

Appendix B


WEST
EAST
LEGEND
TEMPERATURE (Deg. C)
<0
0 - 22
22 - 24
24 - 38
> 38
RELATIVE HUMIDITY (%)
<30
30-70
>70

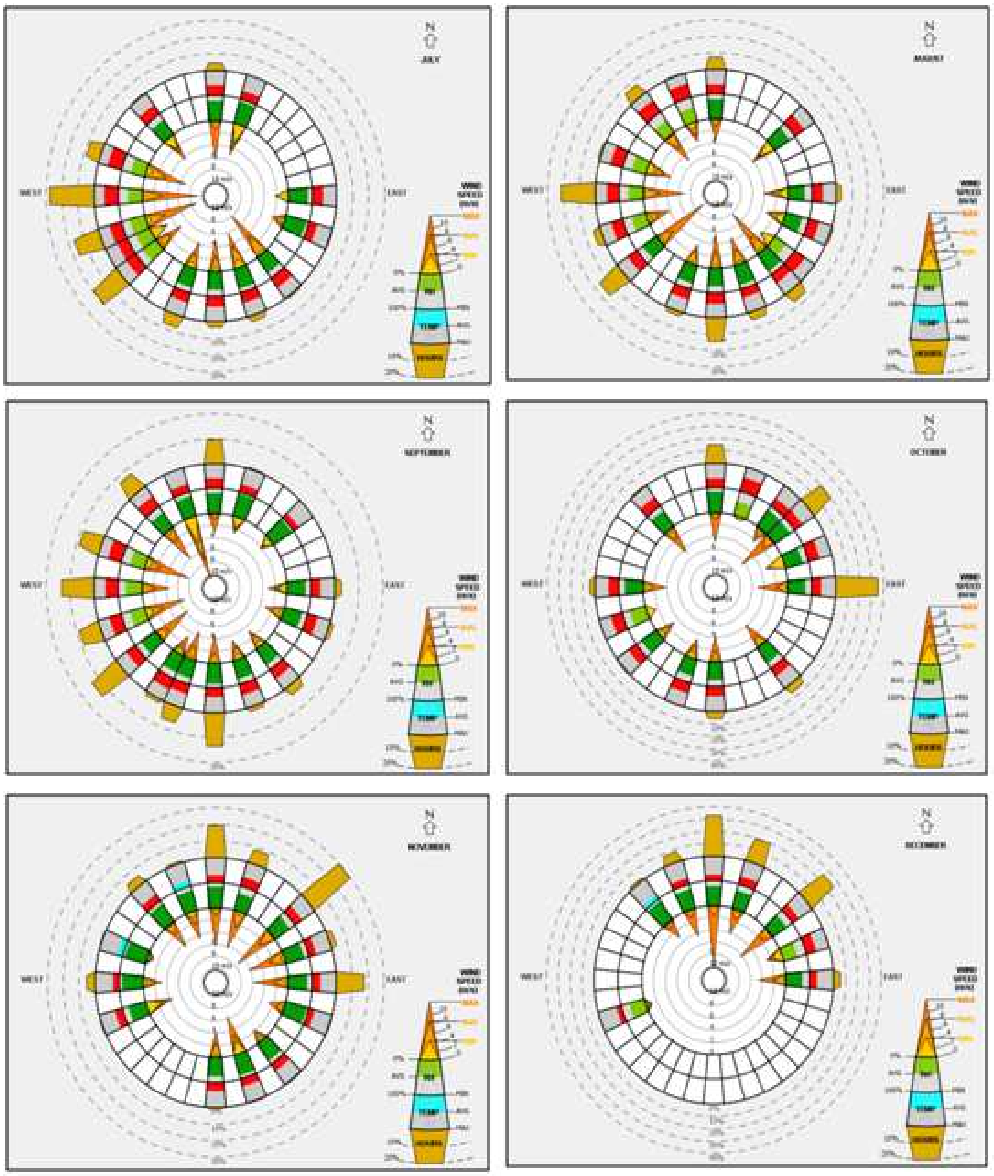


Figure B. 1 Windrose Diagram: Chennai. [Source: Climate Consultant]

B.2 Climate Data: Mumbai and Kolkata

B.2.1 Mumbai

Mumbai, formerly known as Bombay, is located on the Western coast of India at the mouth of the Ulhas River. It is the capital of the state of Maharashtra and the country's commercial as well as entertainment capital. With a total population of roughly 20.5 million people, it is the most populous metropolitan area in India and the 4th most populous city in the world.

Mumbai has an annual average temperature around 27.2˚C with an average maximum at 31.2˚C and average minimum as 23.7˚C. These values are much lower than the other two cities that are considered. Winter is from December to February during which the average night time temperatures are around 18˚C and day time temperatures quite high at around 32˚C. Summer starts from March and lasts till June after which the monsoon season commences. The diurnal variations are even more lower than normal during the monsoon period (only about 4 -5˚C). The day time temperatures are also slightly lower as compared to the other months (including winter). The average maximum temperatures in summer is around 33˚C, clearly indicating that there is hardly any seasonal variation in temperatures (Figure B.2).

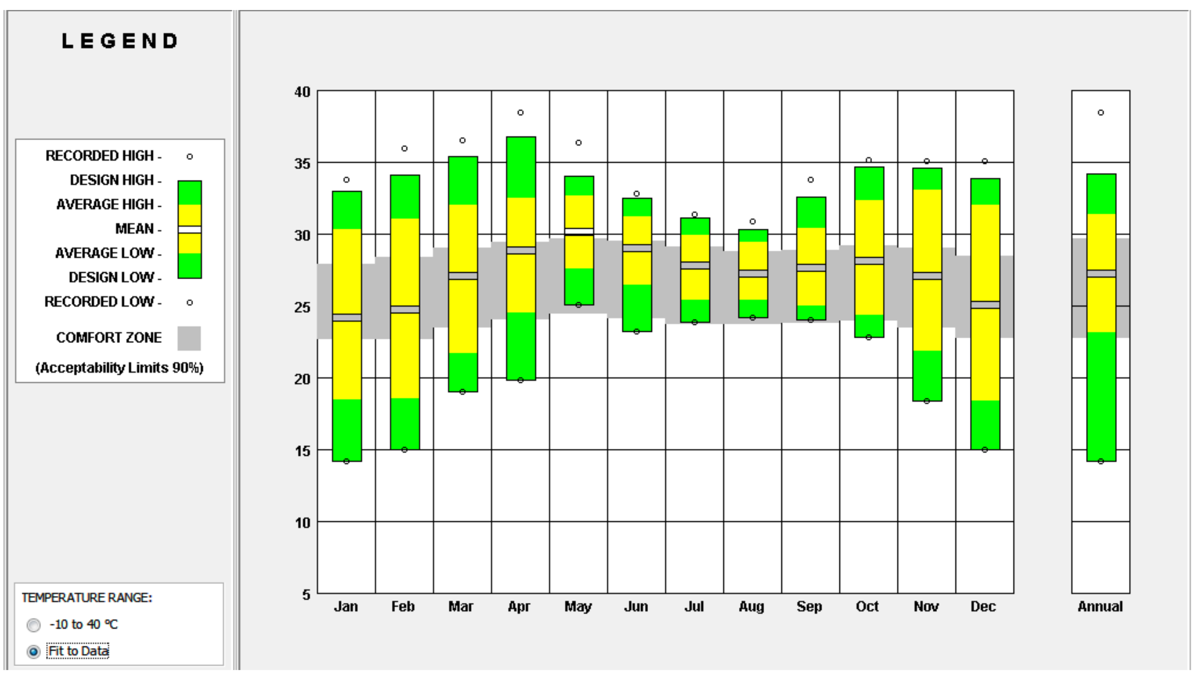


Figure B. 2 Annual Temperature Distribution of Mumbai [Source: Climate Consultant]

Mumbai is known for its monsoon season which lasts for roughly 5 months during which heavy rains lash the city. Pre-monsoon showers are received in May whereas October and November form the post-monsoon season. The remaining months are relatively dry. Occasionally, North-East monsoon showers occur in October and November. The average total annual rainfall ranges between 2,100 mm to 2,457 mm, much higher than that received in Chennai or Kolkata (Figure B.3).

25 years average (1982-2006)

Months	Av. Annual Rainfall (mm)	Rainy Days
Jan	1.0	0.0
Feb	0.5	0.1
Mar	0.7	0.1
Apr	0.4	0.0
May	29.6	1.0
Jun	475.1	13.5
Jul	815.9	22.8
Aug	579.3	21.7
Sep	328.4	13.8
Oct	93.7	3.4
Nov	8.2	0.4
Dec	1.9	0.3
Total	**2334.6**	**77.2**

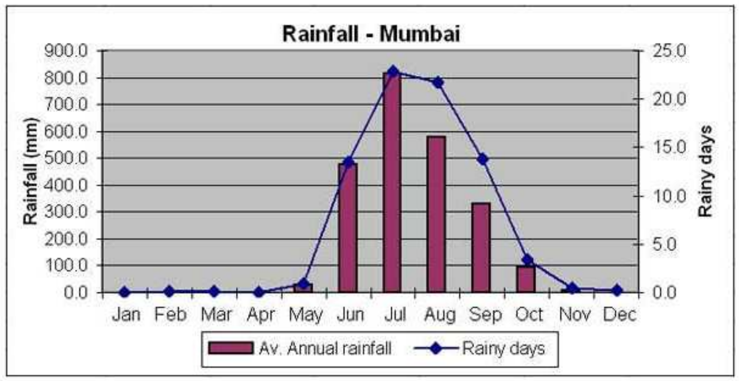


Figure B. 3 Annual Rainfall Distribution of Mumbai [Source: Climate Consultant]

The relative humidity is high for most part of the year. It is highest between the late evening hours until the early morning hours. It has to be noted that for 38% of the year the RH is higher than 80%. For a

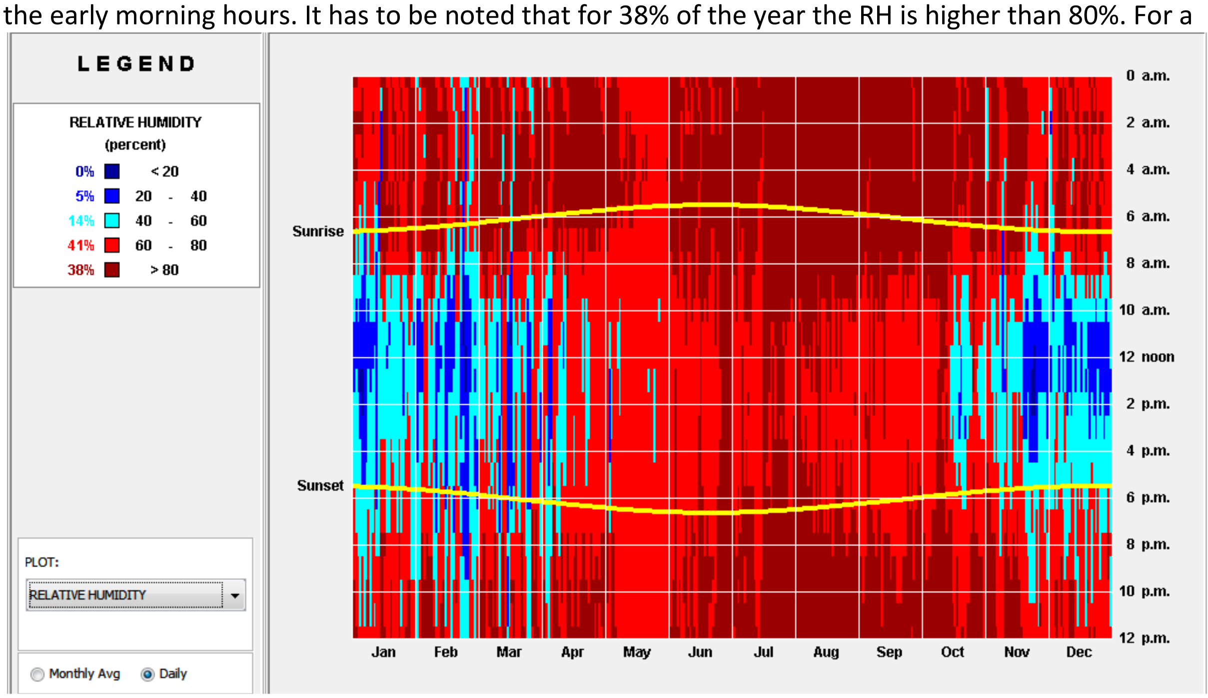


Figure B. 4 Annual Relative Humidity Distribution of Mumbai [Source: Climate Consultant] period of almost 5 months during the monsoon season the RH is higher than 60 % day and night and has a monthly average RH greater than 80%. Few afternoon hours during the winter have low RH of 20 – 40%, rarely also extending till the late evenings. During the rest of the year the RH is between 40- 60 % during the day (Figure B.4).

Wind directions are almost seasonal. The predominant wind direction during the monsoon ranges between South-West and North-West. This period also experiences high wind speeds varying between 3-9 m/s and has an average value of 2-3 m/s. Post monsoon, the wind direction is mostly North-East. During the winter winds are mostly from the North or the North-West. The wind speed generally subsides during the nights, with the monsoon season being an exception. About 38% of the year is calm with wind speeds less than 2% (Figure B.5).

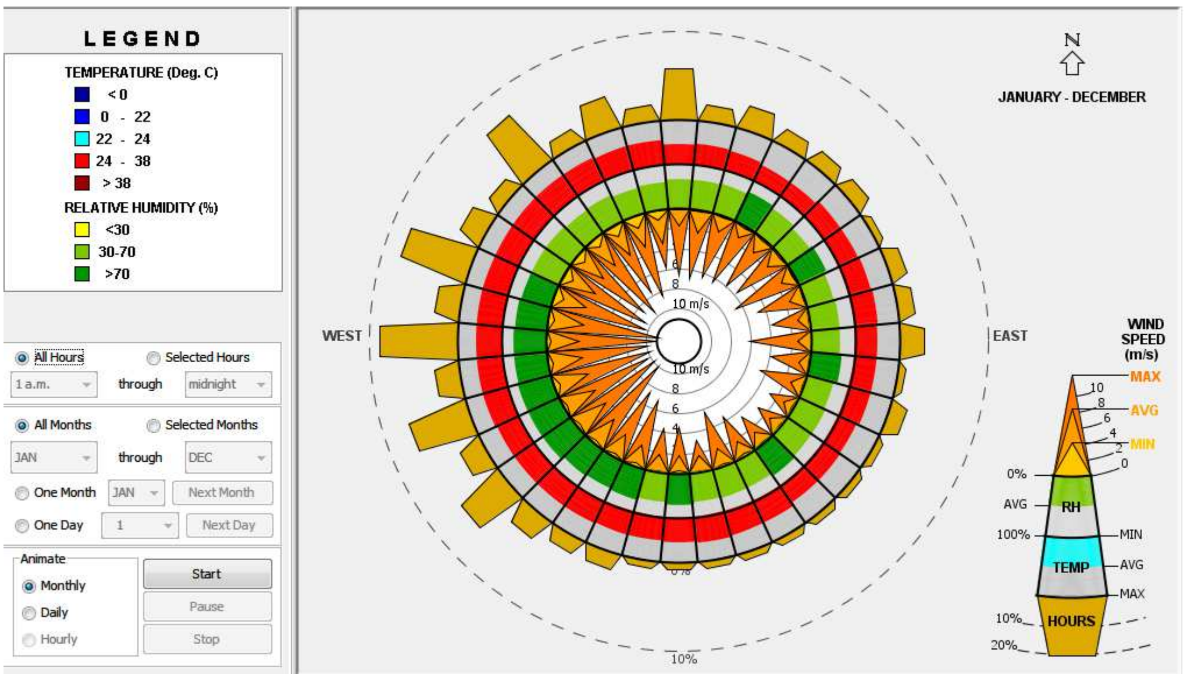


Figure B. 5 Annual Windrose Diagram of Mumbai [Source: Climate Consultant]

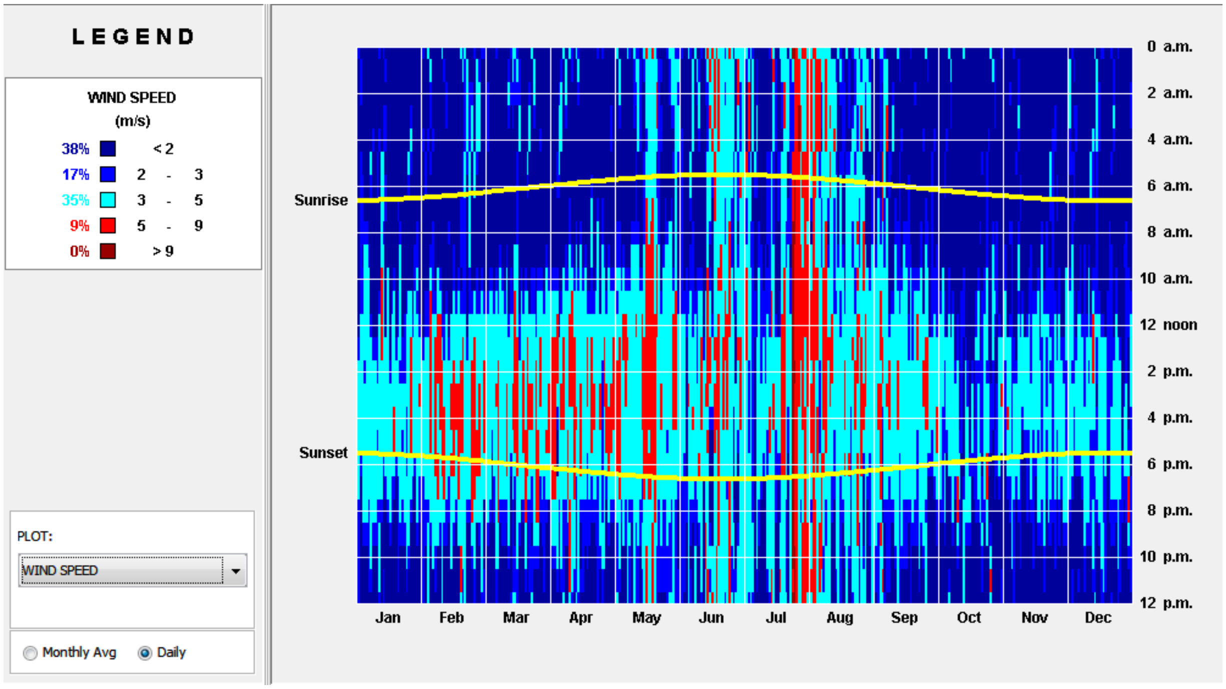


Figure B. 6 Annual Wind Speed Distribution of Mumbai [Source: Climate Consultant]

The psychometric chart for Mumbai indicates that adaptive comfort is possible for 49.6% of the year.

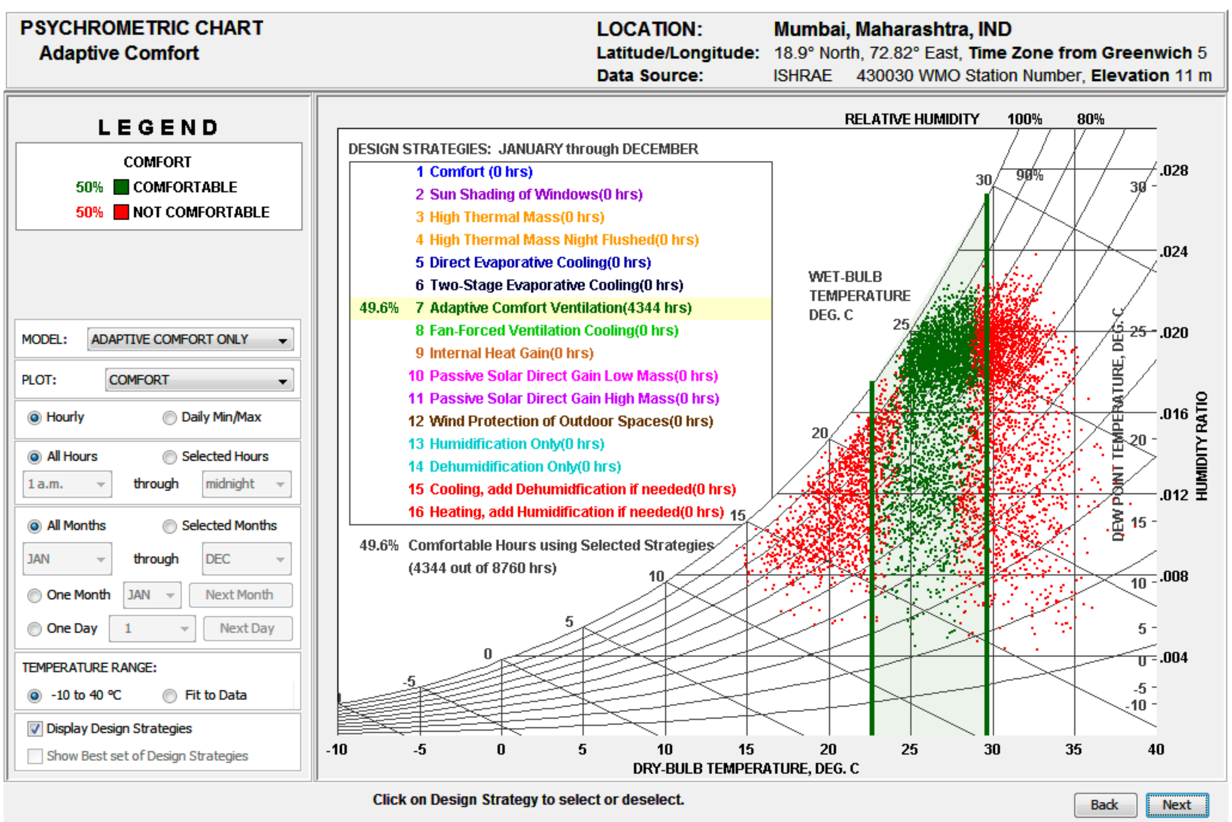


Figure B. 7 Psychometric Chart for Adaptive Comfort: Mumbai [Source: Climate Consultant]

B.2.2 Kolkata

Kolkata (colonial name: Calcutta) was the former national capital of India and the current state capital of the state of West Bengal. The city is known for its literary and artistic heritage and is often referred to as the "Cultural capital of India". Located on the East bank of the river of Hooghly and at the lower delta region of the Ganges, has long been a region of human settlement. Currently, the city and its suburbs are home to a total of 14.1 million people, making it the third most populous metropolitan city in India.

The annual mean temperature of Kolkata is 26.8 °C with monthly mean temperatures ranging between 19 – 30 °C. Summer starts in March and lasts till June. May and June are the hottest period during which the peak temperature during the day often exceeds 40 °C and the daily temperatures vary between 27-37°C. Winter is between December and January during which the temperature can dip up to 9-11°C occasionally. January is the coldest month and has temperatures fluctuating between 12–23 °C. The differences in the diurnal temperature becomes smaller during the monsoon season (Figure B.8).

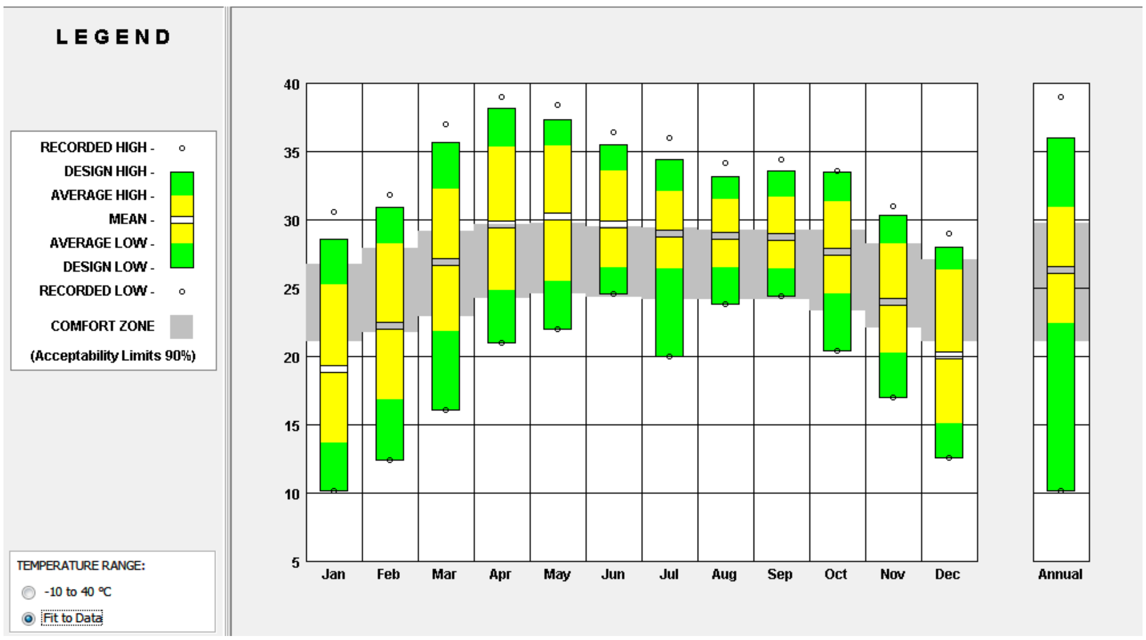


Figure B. 8 Annual Temperature Distribution of Kolkata [Source: Climate Consultant]

Heavy rains often followed by hailstorms or thunderstorms are usually observed between April and June. These are said to bring cooling relief from the prevailing humidity. However, the South-West monsoon rains between June and September are the ones responsible for the majority of the rainfall. The annual rainfall is approximately 1,500 mm with August being the month receiving the highest rainfall ~300 mm (Figure B.9).

25 years average (1964-2005)

Months	Av. Annual Rainfall (mm)	Rainy Days
Jan	12.1	1.0
Feb	24.5	1.8
Mar	44.8	2.4
Apr	55.7	3.7
May	153.6	6.8
Jun	311.9	12.8
Jul	332.5	17.2
Aug	349.5	17.0
Sep	287.3	13.3
Oct	147.0	6.3
Nov	36.9	1.2
Dec	9.4	0.5
Total	**1765.1**	**84.0**

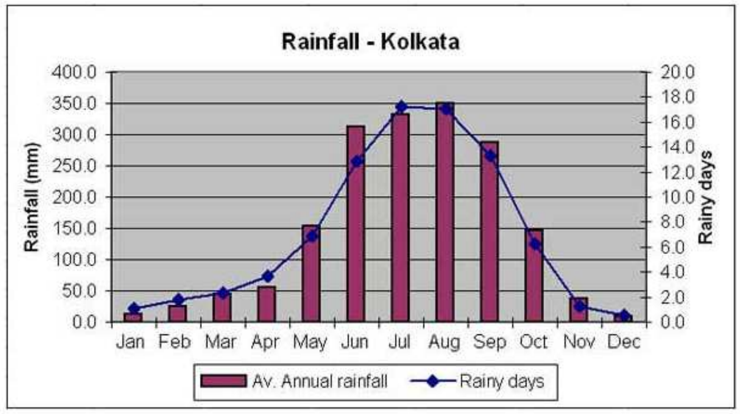


Figure B. 9 Annual Rainfall Distribution of Kolkata

The trend in the relative humidity is quite similar to the other two cites discussed: high RH, during the monsoon period, even during the day. The afternoon hours of February and March are quite dry with RH lower than 40% (Figure B.10).

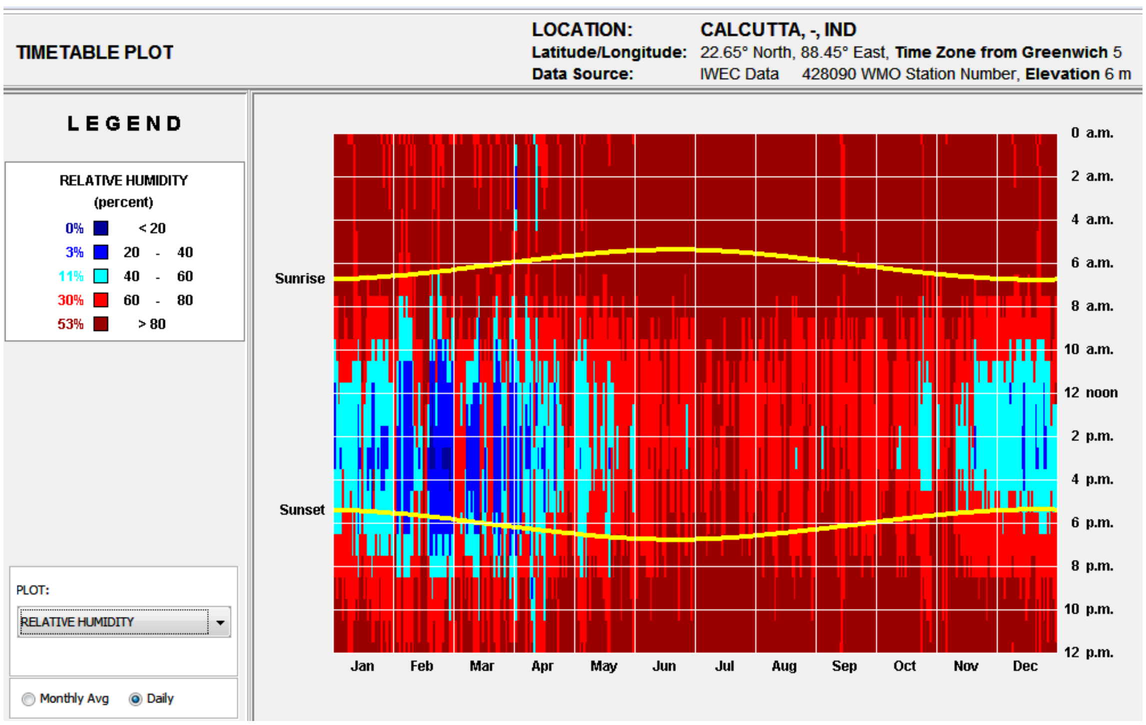


Figure B. 10 Annual Relative Humidity Distribution of Kolkata [Source: Climate Consultant]

The predominant directions of the wind are North and South. As is the case with the other two cities, wind speeds vary during the course of the day as well as with seasons, however much lower levels of wind speeds is observed in the case of Kolkata. The wind speed is lower than 2 m/s for roughly 61% of the year (Figure B.11).

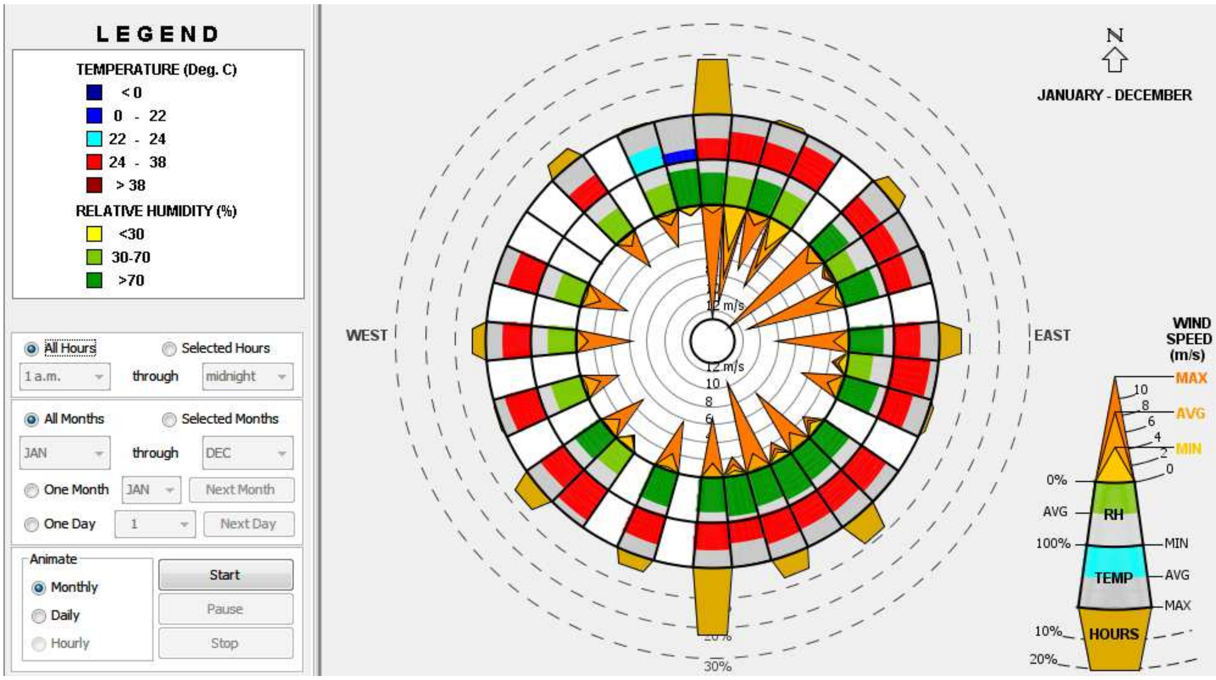


Figure B. 11 Annual Windrose Diagram of Kolkata [Source: Climate Consultant]

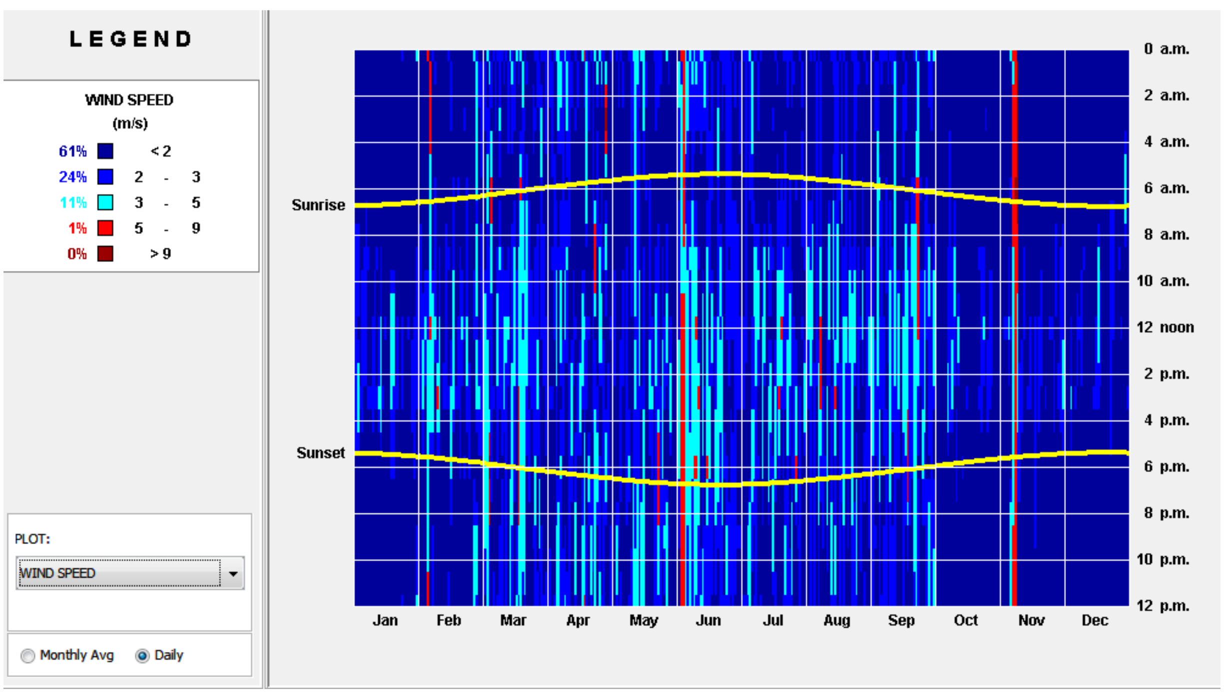


Figure B. 12 Annual Wind Speed Distribution of Kolkata [Source: Climate Consultant]

The psychometric chart for adaptive comfort indicates that ventilation can be an effective strategy to achieve thermal comfort in Kolkata for 45.7 % of the year (Figure B.13).

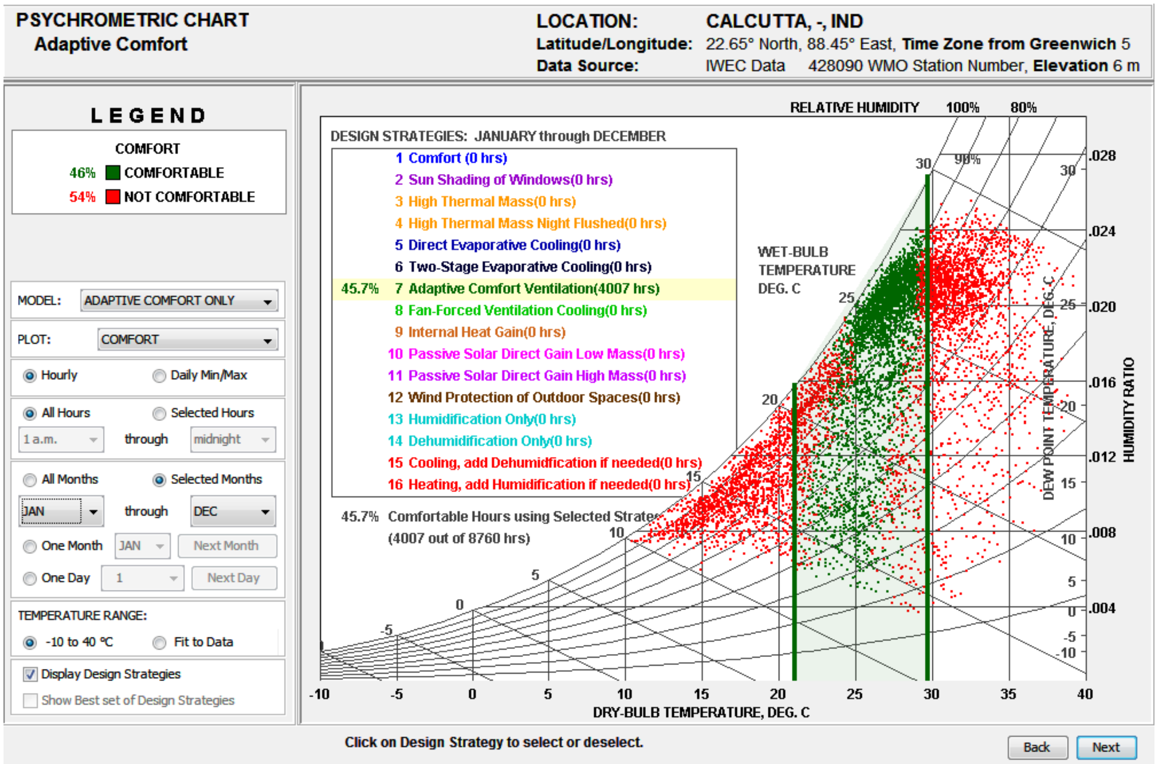


Figure B. 13 Psychometric Chart for Adaptive Comfort: Kolkata [Source: Climate Consultant]

Appendix C

Calculation Excel Sheet:

Since it is not possible to view the effects of interchanging the interior and exterior surfaces using DesignBuilder, an excel spreadsheet was created to observe the same. The base data (interior air temperature and the interior and exterior temperatures were however taken from DesignBuilder.)

One dimensional transient heat transfer is considered. The direction of heat flow is assumed to be perpendicular to the surface of the element (that is, along the thickness of the element). Let 'A' be the surface area and 'd' be the thickness of the element. The element is assumed to be divided into 10 parts of equal thickness. Therefore width of each layer = d/10 m.

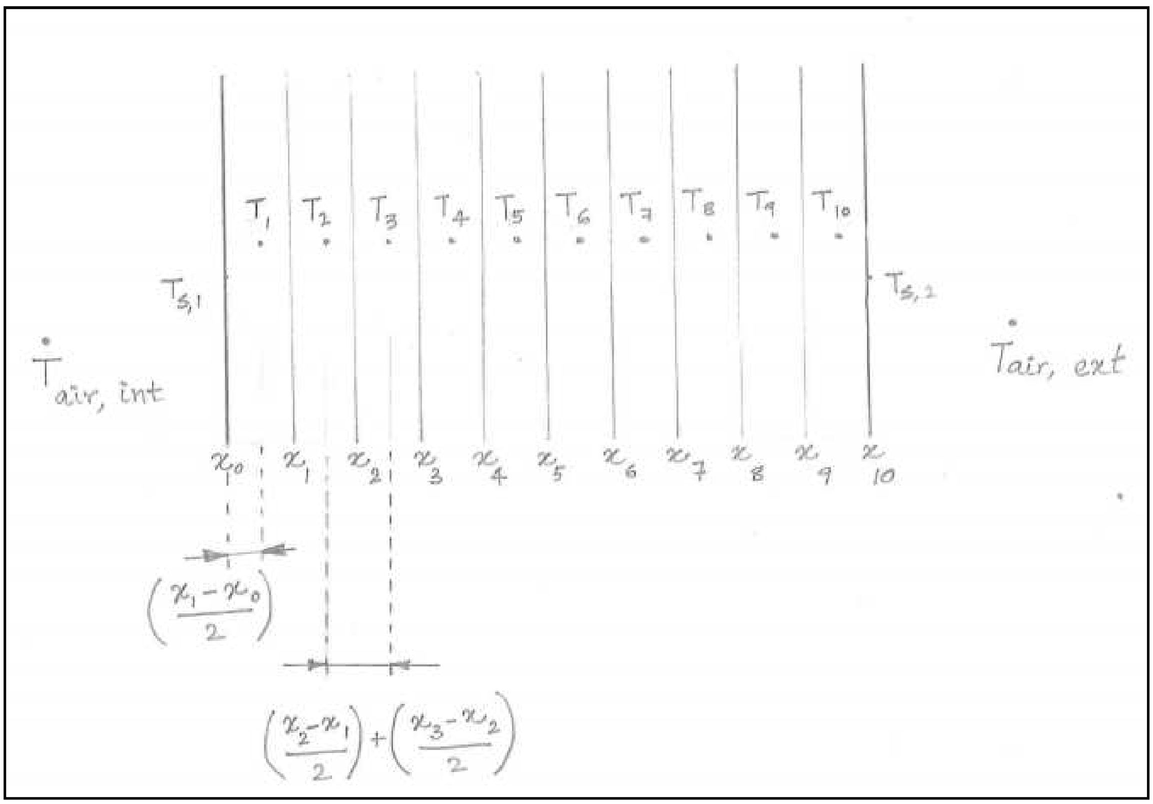


Figure C. 1 Representation of the position of the different nodes

Nodes are considered at the centre of each of the layer and at the two outermost surfaces of the element. One of the surfaces will be facing the room interior while the other one will be facing the exterior space.

	Day	Night
Surface 1	In	Out
Surface 2	Out	In

Time step, t = $\frac{(d/10)^2}{2a}$

Where a: effusivity of the material (m^2/s)

The indoor air temperature, outdoor air temperature and the interior and exterior surface temperatures are represented as cosine curves given as a function of the time. They are represented as follows:

$T(t) = T_{avg} + T_i \, . \cos \omega(t - t_{max})$

Where, T(t) : is the temperature at any given time ‘t’

T_{avg} : daily average temperature (˚C)

T_i : $\frac{(Tmax - Tavg) + (Tavg - Tmin)}{2}$

t_{max} : Time hour at which the maximum temperature is obtained.

Note: If the difference between the maximum temperature and the average temperature is the same as the difference between the average temperature and the minimum temperature T_i can be equated to this value. However, in the climates considered there were large difference between these two values. If T_i was calculated according to the original formula, the minimum temperatures will be overestimated. For this reason an average value of the two was considered. Even though there is slight underestimation of the maximum temperature and overestimation of minimum temperatures, it is being neglected.

The values of T_{avg} , T_{max} , T_{min} and t_{max} are taken from Design Builder after running an initial simulation for the considered cross-section.

Therefore, the respective temperature curves are:

$T_{air, in}(t) = T_{air, in, avg} + T_{air, in, i} \, . \cos \omega(t - t_{air, in, max})$

$T_{air, out}(t) = T_{air, out, avg} + T_{air, out, i} \, . \cos \omega(t - t_{air, out, max})$

$T_{s1}(t) = T_{s1, avg} + T_{s1, i} \, . \cos \omega(t - t_{s1, max})$

$T_{s2}(t) = T_{s2, avg} + T_{s2, i} \, . \cos \omega(t - t_{s2, max})$

The temperature at each of the nodes are given as a function of the temperature of the same node at the previous time step as well as the temperatures of the nodes adjacent to them at the previous time step. The following are the formulas used:

Temperature at node 'n' = $T_{n,t} = T_{n,t-1} + \partial T$

Where ∂T is obtained from the heat balance equation:

Heat Transfer Equation between two adjacent nodes within the wall (nodes 1 to 10) can be given as:

$$\rho.c.V.\frac{\partial Tn}{\partial t} = \lambda.A.\left(\frac{dT}{dx}\right)_{(n-1)\to n} - \lambda.A.\left(\frac{dT}{dx}\right)_{n\to(n+1)}$$

$$A.dx.\frac{\partial T}{\partial t} = \frac{\lambda}{\rho.c}.A.\left(\frac{dT}{dx}\right)_{(n-1)\to n} - \lambda.A.\left(\frac{dT}{dx}\right)_{n\to(n+1)}$$

$$\partial T = \frac{\partial t}{dx}.\ a.\left[\left(\frac{T,n-1-T,n}{x,n-x,n-1}\right) - \left(\frac{T,n-T,n+1}{x,n+1-x,n}\right)\right]$$

$$\partial T = \frac{t,n-t,n-1}{0.5\,(x,n-x,n-1)+0.5\,(x,n+1-x,n)}.\ a.\left[\left(\frac{T,n-1-T,n}{x,n-x,n-1}\right) - \left(\frac{T,n-T,n+1}{x,n+1-x,n}\right)\right]$$

Temperature at node 'n' = $T_{n,t} = T_{n,t-1} + \partial T$

For node 1, n-1 refers to n, s1 and n+1 refers to n2. Similarly for node 10, n-1 refers to n9 and n+1 refers to n, s2.

For an exterior surface, coefficient of convection, $\alpha_{c,ext} = 0.04\ m^2K/W$

For an interior surface, coefficient of convection, $\alpha_{c,in} = 0.13\ m^2K/W$

The heat loss/ gain through the surface is calculated as follows:

$$\frac{Tair,in - T1}{\left(\frac{0.5(x\,1-x0)}{\lambda}\right)+\alpha\ c,in}$$ if surface 1 is facing the interior.

$$\frac{Tair,in - T10}{\left(\frac{0.5(x\,10-x9)}{\lambda}\right)+\alpha\ c,in}$$ if surface 2 is facing the interior.

The net heat loss/ gain was calculated as the area under the curve.

Appendix D

Thermal Properties

M.C. Kiran et. al. carried out investigations to evaluate the thermal conductivity of bamboo mat board (BMB) and to study the influence of density on thermal conductivity of BMB. Effect of thickness on thermal conductivity of BMB (same density) was also studied.

The boundary conditions for the investigation were based on the Indian climatic conditions during summer (temperatures were set at 30°C and 50°C). The samples were prepared and conditioned at 27+/-2˚C and 65+/-5 % RH. The moisture content of the samples was maintained in the range of 8-10%. Calculations were carried out for a range of bulk densities ranging from 750 to 1650 kg/m3. From the observations it was concluded that thermal conductivity of BMB increased with increasing bulk density and it can be expressed in linear trend line relationship as given below:

y = 0.328x - 0.143
Where, y : thermal conductivity in W/mK,
x : Density in gm/cm3.
Thermal conductivity increased from 0·121W/mK for a bulk density of 765 kg/m3 to 0.384W/mK for a bulk density of 1650 kg/m3.

With respect to the effect of thickness on thermal conductivity of BMB (having same density) it was concluded that no considerable difference can be observed.

Effect of Moisture

The moisture content of walls changes with the changes in external temperature and air humidity. Bamboo being an anisotropic porous material has a high moisture absorption rate. Changes in moisture content affect the coefficient of heat conductivity and specific heat capacity of bamboo which in turn affects the dependent physical parameters (e.g., heat transfer capacity, heat storage capacity, temperature distribution, attenuation coefficient of temperature wave, delay coefficient of temperature wave, etc) (Jibo Long et al.).

Jibo Long et al. studied the heat transfer intensity of bamboo structure wall in warm and humid environment. Experiments were conducted on a 20mm thick bamboo plywood wall having a thermal conductivity of 0.3 W/mK, specific heat capacity of 1370 J/kgK, and a density of 732.5 kg/m^3. An effective porosity of 32.6% and rate of moisture absorption of 20(%·h^{-1}) in the beginning was assumed based on previously conducted study. They concluded that under the condition of the same indoor and outdoor temperature and steady state heat transfer, the temperature difference between inside and outside surface of the wall is inversely proportional to the moisture content. The total moisture content also determines the temperature distribution at different positions within the material. The higher the moisture content of the material layer, the smaller is the thermal resistance of the material layer and hence smaller is the temperature gradient within the material.

In this study the effect of moisture was neglected.