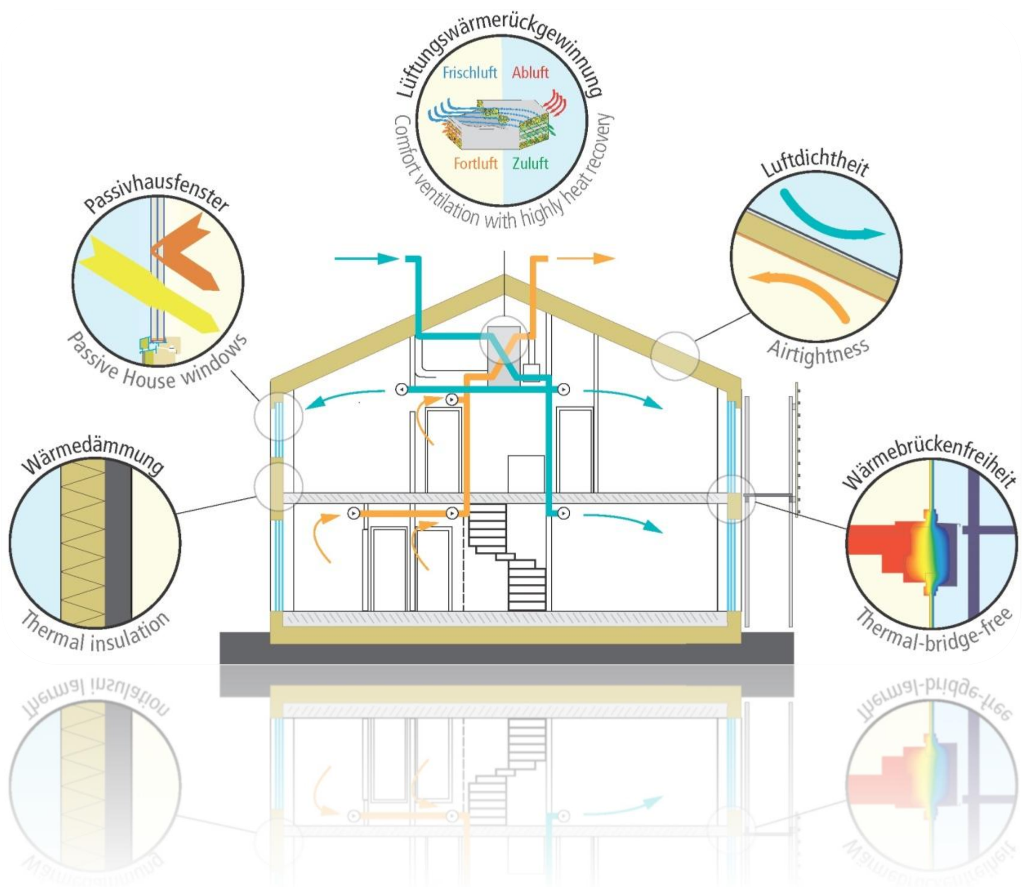

THE ROLE OF PASSIVHAUS PRINCIPLES TO IMPROVE COMORT IN BANGALORE

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"Except where stated otherwise, this Dissertation is based entirely on the author's own work."

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TABLE OF CONTENTS

1. INTRODUCTION

Passivhaus is a construction concept based on building physics. According to the Passive House Institute (2015) it is a building standard which achieves high level of occupant comfort in a low-energy dwelling. It is economical and provides exceptional indoor air quality.

The article by Feist (2015a) explains that the initial development of Passivhaus principles began around the late 1980s between himself and Prof. Bo Adamson. He also states that the construction of the first prototype was based on results from extensive research carried out in eight different projects. It was built and occupied in 1991 in Darmstadt-Kranichstein, Germany and it achieved an ambitiously low space heating load. Schnieders, Feist and Rongen (2015) further mention about the intent of the research project which was to reduce the requirement of the overall energy demand in the building by improving the performance of each component, including household appliances, other electrical back-ups, domestic hot water and efficient lighting. Additionally, the building envelope was optimized based on passive approaches by using insulation, high quality windows, airtightness, ventilation heat recovery, and the exclusion of any thermal bridges.

Building Research Establishment Ltd. (2011) describes that Passivhaus building certification is a thorough process to make sure the built structure meets the quality requirements of the Passivhaus standards of energy assessments based on occupant comfort. A Passivhaus building is a lot more than just a sum of the different components. It involves execution of impeccable details during construction which are put together after a vigorous design process based on the principles of Passivhaus. The key design tool is the Passive House Planning Package (PHPP), which allows careful planning during the design stage and also benefits as a verification of the Passivhaus standard (International Passive House Association, 2015). PHPP uses various reliable and proved calculations to accurately estimate the space heating or cooling demand and the primary energy requirement along with estimating the building's frequency to overheat during the hot periods in a year (International Passive House Association, 2015).

It is important to realize that this was developed in Central European region with extreme detailing of insulation, air tightness, windows and ventilation in order to provide comfortable warm conditions for the occupants in harsh cold exterior climate. International Passive House Association (2013) confirmed in a press release that the principles of Passivhaus also work for buildings in the tropical climate. The dynamic simulations carried out were tested for Mumbai in India among other locations and explained essential design considerations for each region. It goes on to be explained in the press release that this will not be a very direct solution and various adaptation will be required. Fincke (2014) explains that it will be very risky to apply the Central European Passive House design to buildings in the tropical climate without modifications. Every construction detail for the windows, insulation, and ventilation will have to be specifically adapted to suit the conditions of the location. Each country boasts of its own traditional way of construction over centuries. It would take very deep understanding of both methods, thorough analysis and a lot of research to figure out if the Passivhaus principles can help to improve the internal thermal comfort of buildings in the tropical climate.

1.1 AIM

The aim of this paper is to find out if a Passsivhaus building is possible in the tropical wet and dry climate of Bangalore (also referred to as Bengaluru), India.

1.2 OBJECTIVES

The key objectives of this paper are as follows:

- To study the essential requirements for human comfort.
- To study the design recommendations for Passivhaus buildings in tropical climates.
- To analyze the key issues using PHPP for a typical dwelling in the tropical wet and dry (savanna) climate of Bangalore, India.

1.3 RATIONALE

There is a host of information about Passivhaus in the European region in the form of research and more than one million square metres of recorded Passivhaus building's floor area that has been certified by the Passive House Institute in Darmstadt, Germany until the end of 2014 (Schnieders et al, 2015). However, the progress outside of the European region has been very minimum in the past two decades. The proceedings of the International Passive House Conferences between 1996-2014 have discussed some among the 91 Passivhaus buildings that have been built outside of the European region, confirming 47 of these to be located in the US (Schnieders et al, 2015). There was very limited research or sources available to the author during the study for this paper. This makes it clearly evident that there is tremendous scope for exploration of Passivhaus principles worldwide.

The United Nations conference on climate change confirmed the target for maintaining the global temperature rise below 2°C. The discussions among scientists indicated that any further increase in temperature would be highly threatening (COP21, 2015). It is alarming to read the report by Vivan (2016) that there has been a 5°C rise in the average temperatures of Bangalore in India this year as compared to the previous and that the hotter months in a year are increasing. The climate change is making it very uncomfortable for people to stay indoors without artificial cooling or step outside in Bangalore which once boasted of the most pleasant climate in the region. It is essential to explore passive alternatives for comfortable spaces for people worldwide. Hence, this paper is focused on checking the possibility of a Passivhaus in Bangalore, India through a typical dwelling chosen as a case study. The calculations and verifications are carried out using PHPP.

2. BACKGROUND STUDY

Girard and Langlois (2006) have studied on how the impact of sun's energy leads to various climatic zones in the world. It heats up land and water masses on earth very differently due to its material composition, non-uniformity of surfaces in different geographical zones and the earth's rotational axis tilt. Singleton and Tibbs (no date) explain how different external factors and the latitudinal location of a place affect Earth and its uneven landforms; heating or cooling them differently during different times of the day and year. Salvaggio and Futrell (2012) have studied the contrasting elements on Earth's surface and state that dry areas, deserts and oceans usually warm up and cool down rapidly whereas the greens and forests behave uniquely. Generally, sloping lands that face the sun quickly warm up compared to the other side of the hill.

Per cent of Earth surface	Sun rays hit the Earth …	Length of days
5	not at all or at flat angle.	At the North Pole half year day, half year night.
25	at moderate to steep angle.	Long days in summer, short days in winter.
40	at steep to 90° angle.	Always almost 12 hours day and 12 hours night.
25	at moderate to steep angle.	Long days in summer, short days in winter.
5	not at all or at flat angle.	At the South Pole half year night, half year day.

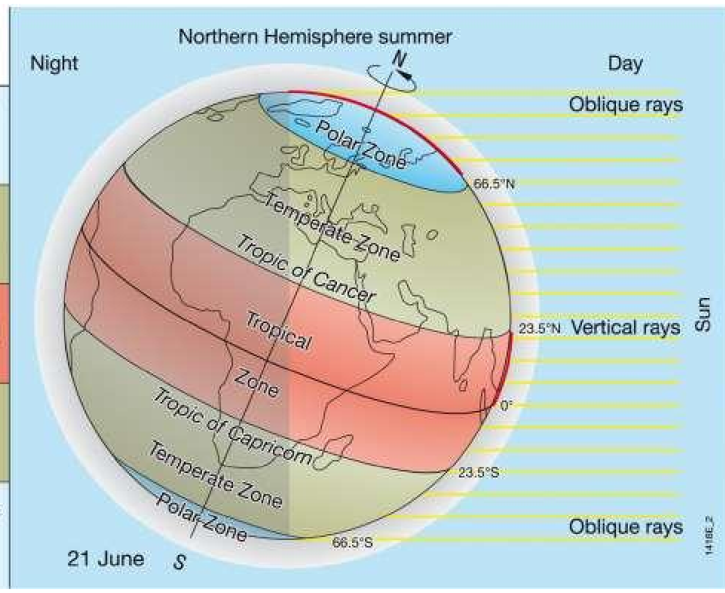

Fig 1: Geographical Zone of Earth (Diercke, 2015)

Climates vary greatly from polar extremes to tropical zones where polar regions literally see six months of daylight and six months of night and the tropics have the sun passing overhead in a year. Fislisbach and Zollikon (1993) admit that it cannot be stated that the climate remains constant at a given point of time in any of these regions in the year because it is affected by patterns of wind and ocean currents, the geomorphology, the existence of vegetation, altitude and overall topography. Needless to say the micro climate has a great impact in its vicinity. The rationale of this research emerged because human beings require comfortable indoor climate inside buildings to protect themselves from the outdoor climatic conditions which are usually harsh and hostile. The internal environment must encourage good health of its inhabitants while providing comfortable conditions to live and work. This brings us to understand how climatic factors could be relevant to construction of the buildings.

2.1 THERMAL COMFORT

Fanger (1970) researched to define a condition which would be most comfortable for a large proportion of people carrying out any activity in different clothing. He developed his own ‘comfort equation’ based on Predicted Mean Value (PMV) and Predicted Percentage (of people) Dissatisfied (PPD) to calculate the optimal temperature for human comfort in a location. It should be noted that most of Fanger’s study in the initial years dealt with factors that influence human comfort such as air temperature, mean radiant temperature, relative air velocity and humidity level. On the other hand, there were other factors explored related to human activity and clothing worn by a person determining the comfort experienced. It should also be noted that Fanger developed PMV and PPD to account for both activity (met) and
clothing (clo) and therefore adaptation through adjusting either or both of these (usually clo).

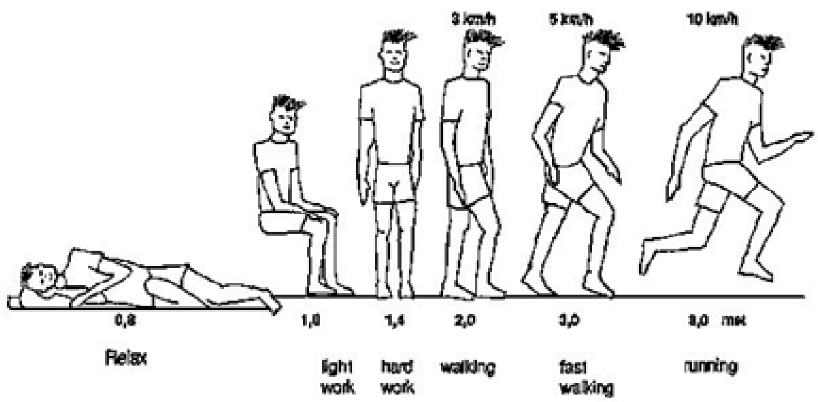

Fig 2: Metabolic Rate of Different Activities (Fislisbach and Zollikon, 1993)

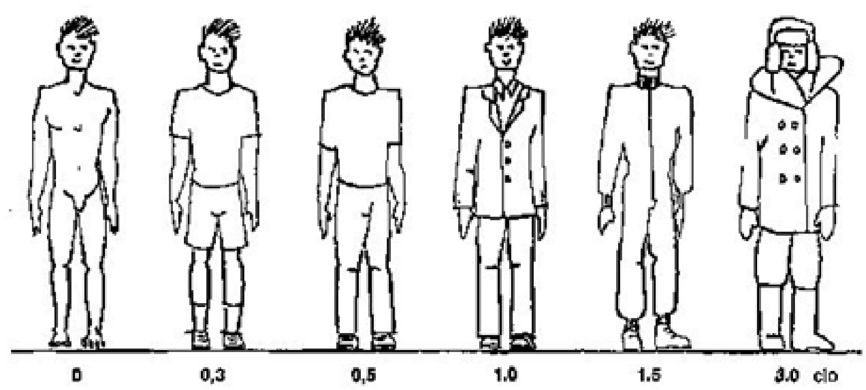

Fig 3: Insulation values of different kind of clothing (Fislisbach and Zollikon, 1993)

In contrast to Fanger’s method of experimental data collected in a controlled climate chamber under steady state conditions, Ellis (1953) and many others as discussed later on in the paper stuck to the adaptive model and carried out many field studies with a notion that it would give the occupants a chance to interact and behave dynamically with their surroundings. Ellis carried out one in Singapore for the tropical climate and found an optimal temperature of 27°C for a relative humidity of 80%; velocity of 0.4m/s and light tropical clothing of 0.4clo. When Fanger's equation was applied for the same location in 1972, it was calculated to give a predicted mean value of 27.5°C for Singapore (Parsons, 2003). Despite the close match among their research results being close, many people who have lived in tropical regions for over the last decade at least, for example in India, will disagree to the idea of this range of temperature being the most comfortable. During the summer months, temperatures climb to 45°C in some regions of the country while the low hardly drops to high twenties for most cities. Although Bangalore enjoys a comparatively moderate climate than most of India all year round, recent recorded temperatures maximums over the summers have been around 38°C (Weather2, 2016).

World Green Building Council (no date) explains that the human experience of thermal comfort is based on their most recent experience. This means to say that people will have a higher tolerant of indoor temperatures when outdoor temperatures are higher. ASHRAE Handbook (2005 cited by IIT Kharagpur, no date) suggests to consider a range between 32.8 to 34.4°C as the upper limit for summer outside conditions while designing for Bangalore among other Indian cities. When people step into an environment which is 5 to 8°C lower from the outside temperature, they immediately feel the difference based on the human experience of thermal comfort depending on their most recent experience. This helps in realizing that Bangaloreans are acclimatized to feeling comfortable between 21 to 31°C, especially while having to deal with high thirties (Weather2, 2016) in recent peak summer times. It would not be wrong to argue that people would begin to feel dissatisfied and uncomfortable due to overheating in a slightly larger PMV stretched range which is more than plus or minus 3. However, it can be admitted here there is huge scope of field studies or the adaptive model research that can be carried out with the rapidly changing temperatures.

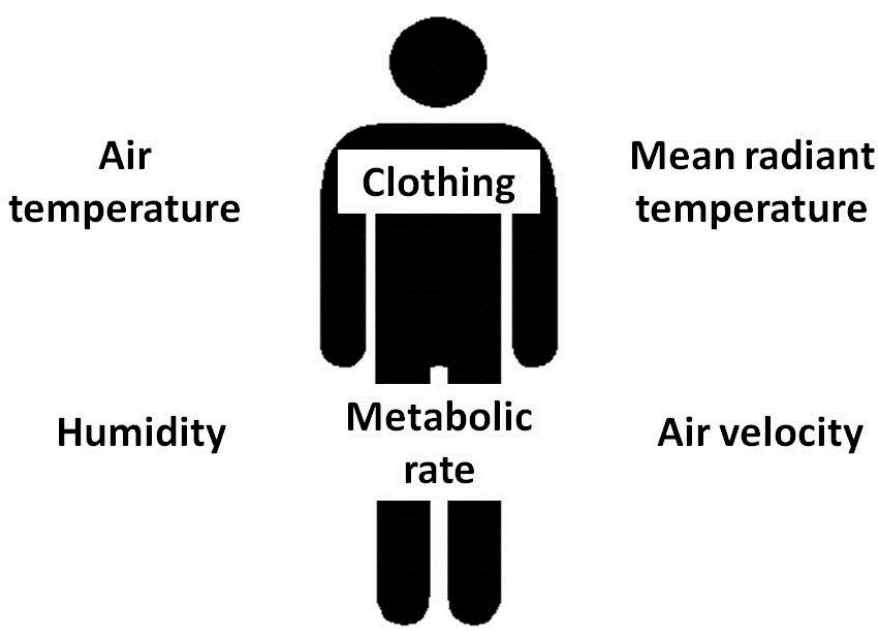

Fig 4: Factors which affect human physiological response to heat (Diamondenv, 2015)

Fislisbach and Zollikon (1993) discuss some of the factors that affect human thermal comfort as below:

- Air temperature - It undergoes extreme changes between day, night and also between different seasons in a year. People adapt themselves to these changes by adjusting their clothing and activity in their particular environment.
- Humidity and Precipitation - Moisture content in the air and evaporative cooling in the form of sweating or perspiration from the skin of a human body are ways in which people tend to make themselves comfortable in any environment.
- Mean radiant temperature - In order to maintain uniform temperature human body radiates heat to transfer it to its cooler surroundings while at the same it is also capable of absorbing radiant heat from hot objects nearby when it feels cold.
- Air movement – Essentially, this is the motion of atoms which move about at a faster pace in hotter temperatures. Hence, a breeze feels cool in conjunction with evaporative cooling over the skin of a human body. This is probably one the reasons why we feel cool when we sit in front of a fan or a cooler on a very hot day.

Thus evaporation, convection, radiation and conduction are different methods by which heat is removed from the skin of a human body which makes a person feel comfortable in a warm environment (Fanger, 1970).

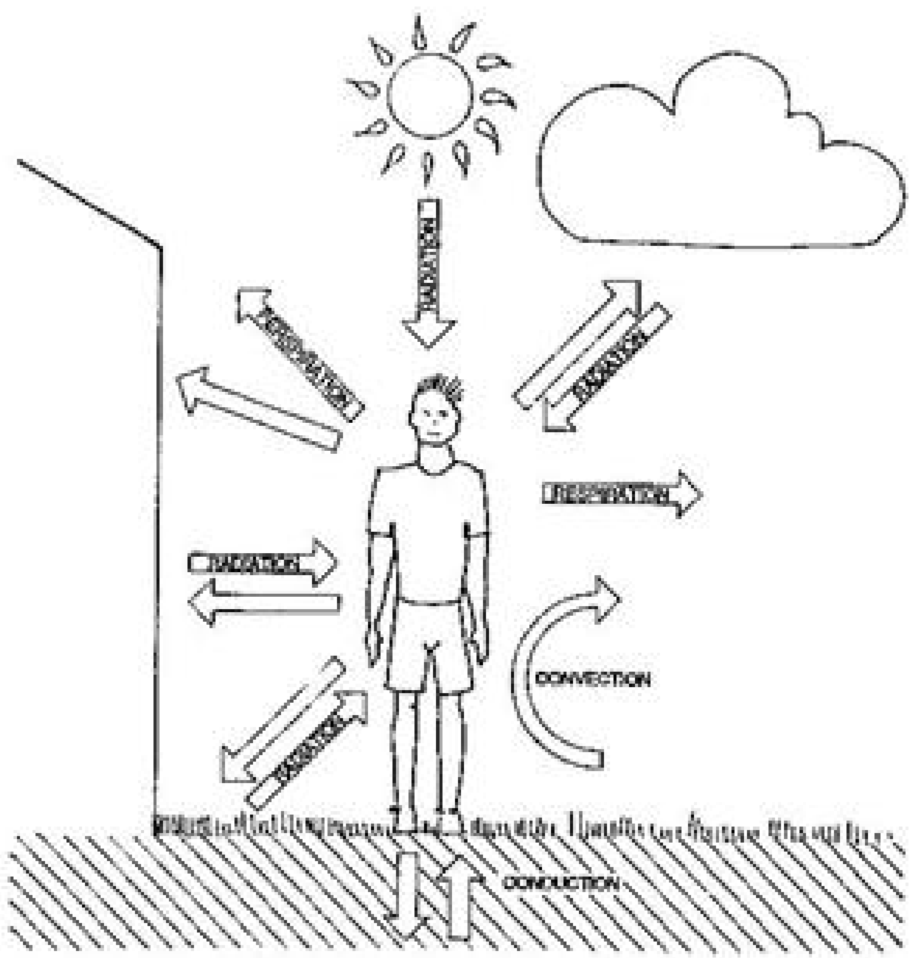

Fig 5: Ways of Thermal Exchange by Human Body (Fislisbach and Zollikon, 1993)

Apart from the natural climatic factors, Fanger (1970) discussed about the activity(met) and clothing(clo) as influencing factors. Fislisbach and Zollikon (1993) additionally discuss acclimatization of a human body as an important factor responsible for comfort:

- Metabolic rate - The kind of work a person is performing and the rate at which he does it also affects his response to the micro climate in his environment. For example, one could feel comfortable which resting in a room whereas feeling warmer in the same environment if he/she was exercising.
- Clothing – Clothing acts as a kind of insulation for the human body to bear up different effects of varying temperature for example, someone wearing a suit has an insulation effect of 1 clo which is 0.155 m^2K/W and someone wearing high boots, winter coat and a thermal cap would have an insulation effect of 3 clo. 'clo-value' is an expression for measuring the insulation effect of clothing.
- Acclimatization – While one person might naturally feel acclimatized to cold climate in higher altitudes, the change of environment to a hotter temperature and humidity could make the same person feel very uncomfortable. On the other hand, another person in this condition might feel perfectly comfortable because they are accustomed to it. In a matter of a few days or weeks, the person from higher altitude will get used to the new environment. Thus it explains human beings are organisms which adapt to changes and the surroundings that they live in.

Nicol and Humphreys (1973) just like Ellis support adaptive comfort where the occupants interact with the outdoor and indoor environment themselves and slowly achieve comfort. It also accounts for observational recordings and the fact that people might not necessarily enjoy a constant temperature. They might instead prefer the thermal environment to waver its temperature over being a constant throughout. Once the adaptive comfort method was brought forward as an acceptable approach for research on comfort, de Dear and Brager (1997) were commissioned by ASHRAE in the mid-1990s to expand this model from quality field data through vigorous research for different climatic zones all around the world. Towards the end of it, a host of valuable data was published in the ASHRAE Handbook 2005 to help architects and other professionals in the built environment to use the most suited design data for their city directly off the handbook. This project brought to light the fact that the occupants of the fully air-conditioned buildings were twice as sensitive to the changes between the indoor and outdoor environments as compared to the occupants who spent most or all of their times in naturally ventilated buildings. The latter category was more adjusting and adapting to changes in the surroundings actively being involved in opening windows or altering clothing to feel better. This clearly indicates that every person reacts and responds differently to the temperature changes according to their individual perception of thermal comfort.

World Green Building Council (no date) have stated in their research note on thermal comfort that the biggest challenge posed by the tropical climates is the idea of designing comfortable indoor environments while still linking them with the outdoor environment via natural ventilation. The outdoor conditions are no more the same. Ill-effects of 'urban heat islands' is increasing in areas with not enough vegetation to block the solar radiation or water bodies to help with evaporative cooling. The alarming rise in recent temperatures pose an issue before researchers today if natural ventilation is as beneficial today as it seemed a few decades ago for the tropical regions.

Daum, Haldi and Nicolas (2010) propose a probabilistic solution for thermal comfort using blind controllers to suit the needs of any user to block the solar radiation during peaks while also allowing for solar heat gain as desired to avoid heating costs during night times or the colder months of the year.

They do propose active methods for cooling as an addition to the blind controller, with the use of air conditioning to increase thermal comfort during the hotter months in the year. However, energy savings would depend on the individual user and in this case another issue to be thought out is that if minimal active cooling would be necessary in the tropics; if there was more that could be done passively to improve the performance of the buildings in order to minimize the need for active methods.

With regards to Human comfort there are many physiological factors which are fundamental. Fislisbach and Zollikon (1993) point out that a human body feels comfortable when its internal temperature is kept within the narrow limit of around 37° C. If there is a rise of 5° C or drop of 2° C of the internal temperature of human body, this fluctuation could lead to death. Despite this sensitivity, the human body is extremely capable to balance its temperature through various methods. On one hand the 'Internal Heat Load' is determined by this thermal balance while on the other, the thermal exchange or energy flow between the body and the environment helps the body stabilize it. As discussed above this thermal exchange between the body and the environment occurs through various processes like evaporation (Perspiration and respiration), convection, conduction and radiation.

Thermal comfort zone is an optimum condition in which a human being needs to make very less or no extra effort to sustain the thermal balance of their human body. The higher the effort the lesser comfortable someone would feel in that climate/environment. It is usually not possible to attain the maximum comfort condition but however the aim of the designer who builds houses should be to provide a comfortable internal environment which is close to an optimum and still within the range where thermal balance of the human body can be easily attained. This range is what we refer to as thermal comfort zone throughout this research paper. The lessons of IIT Kharagpur (no date) define thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment". Thermal comfort zone is bound to differ with different individuals. Fislisbach and Zollikon (1993) say thermal comfort not only depends on their age, health conditions and gender but also on their clothing worn by them and the physical activity they are carrying out at that moment. The geographical location they hail from becomes an important factor to understand the acclimatization capacity of the person although ethnicity is not of much importance.

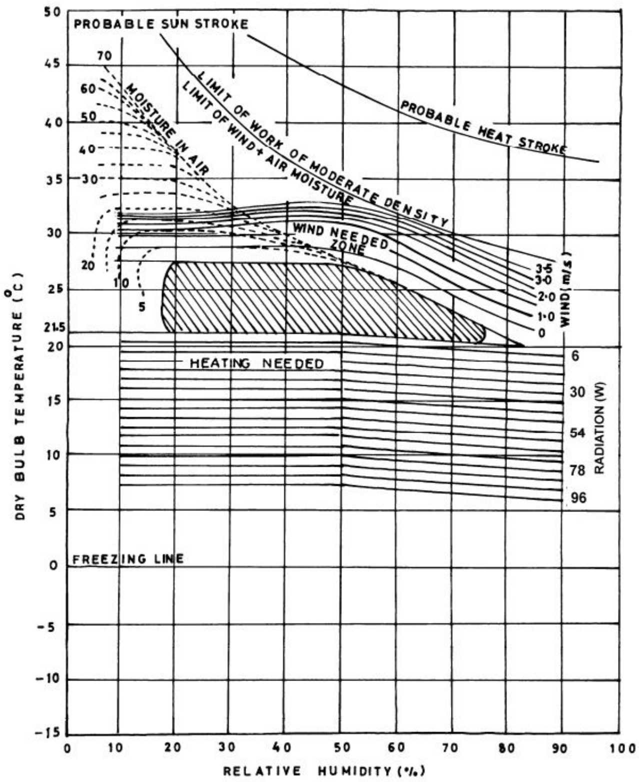

Fig 6: Bio climatic Chart (Olgyay V.,1963)

The bio climatic chart above illustrates the thermal comfort zone based on Ambient temperature and humidity, mean radiant temperature, wind speed, Solar radiation and evaporative cooling based on the dry bulb temperature and humidity of a location. One can easily determine if their existing climatic conditions fall into the comfort zone or not. In cases where it doesn't, design decisions have to be taken accordingly to achieve the requirements of comfort at a particular location. A bio climatic chart can thus be very informative for individuals to take informed decisions. For example, Olgyay (1963) discusses in the case of Central India where generally the temperatures are high and relative humidity is low, air movement will not be of much help to make a person feel comfortable. Instead methods of introducing moisture laden breeze to cool the space and decrease the temperature would help a person feel more comfortable to maintain their thermal balance in this environment. In short evaporative cooling is advisable. We can notice from the chart if the condition of a location lies below the perimeter of the comfort zone, heating would be necessary to negate/neutralize the low temperatures.

2.2 PASSIVHAUS

Feist (2015b) defines Passivhaus as “A Passive House is a building, for which thermal comfort (ISO 7730) can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air.”

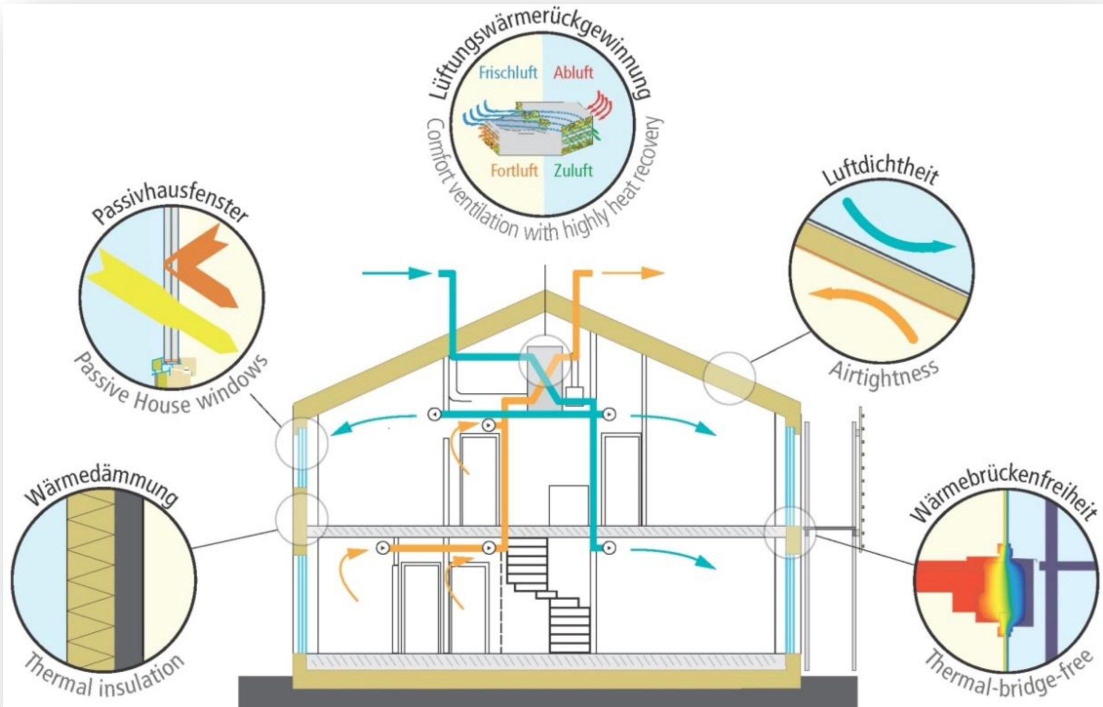

Fig 7: Key principles of Passivhaus

Passive House Institute (2015) describes the key Passivhaus principles adopted for buildings in cold climates of the European region as below:

- Thermal Insulation – Insulation around a space traps heat and increases the time lag of heat transfer from within the internal environment to the colder environment outside.
- Passive House Windows – Glazing in a building helps bring in solar gains easier into the internal environment but at the same time also allows heat transfer to the outside very quickly. Passivhaus windows are thus designed to allow the solar gains which are positive for the living conditions inside while maintaining the surface temperatures at 17° C and negate the loss of heat through well insulated frames and junctions.
- Mechanical Ventilation with Heat Recovery – The MVHR unit helps with continuous fresh air circulation and recovers the heat of the extracted air volume before it is disposed to the external environment.
- Air-tightness – This is a very important aspect of Passivhaus because it ensures there is no heat leakage to the outside and the building is kept air-tight to very high standards in order to keep the energy required to heat the space heat demand minimum.

- Thermal bridge-free design – Heat escapes at every joint in the construction materials. Thermal bridge-free design aims to recognize all such junctions and detail them very specifically to avoid leakage of heat through these junctions.

It is essential to understand the main criteria a Passivhaus is required to meet before further research can be carried out. The criteria a building is expected to meet to be considered a Passivhaus as per the Passive House Institute (2015) are as follows:

1. The maximum space heating or cooling demand of the treated floor area is set at 15 kWh per square meter or 10W per square meter peak demand. In case of a cooling requirement, there is an additional allowance for dehumidification.
2. The total energy that is used for all other domestic appliances including heating or cooling, hot water and electricity must not exceed beyond 120 kWh per person occupying the net living space per year.
3. The building must be air-tight. The exchange of air is capped at 0.6 air charges per hour at 50 Pascal air pressure which is tested on-site through both states of pressurization and depressurization of internal air volume.
4. Thermal comfort must be met of not exceeding over 25° C in all net living spaces with an allowance of temperature exceeding over 25° C only in 10% of the hours in a given year.

Today, Europe boasts of more than one million square meters of Passive House floor area, recorded until the end of 2014 (Schneider *et al.,* 2015). If all houses of varying styles and sizes located anywhere in the world were to be designed and built to the standard mentioned above; it would reduce most of the energy consumption by buildings and make way for excellent health and comfort for people all over the world. Despite the necessary modifications to the design of Passivhaus to suit the differing circumstances in tropical climates, this field requires many professionals to add their contributions through a lot of research and innovations.

2.3 PASSIVHAUS IN DIFFERENT (NON-EUROPEAN) CLIMATES

As mentioned earlier on in the paper, there is very limited research carried out about Passivhaus in the tropical climate. According to Schneider and others (2015), Passivhaus is a definite possibility in any part of world. They carried out further research in different climatic zones to study the global feasibility of Passivhaus. Two methods were used for this purpose. One method was the DYNBIL hydro-thermal dynamic simulation to understand the technical possibilities at different locations where the typology of small row houses was tested where the heating/cooling load was not more than 10 W/m^2 of the treated floor area. Practically anywhere across the world with the right component and suitable modifications, the findings showed that a properly functioning Passivhaus could be constructed.

The research by Schneider and others (2015) concluded that the resulting annual energy demand for space conditioning of the Passive House is 75-95% lower when compared to a traditionally insulated building of the same geometry. In regions which shared hot and humid conditions like Shanghai or Singapore, humidity was a major concern and it was found that the total useful energy demand for sensible and latent cooling might exceed 70kWh/(m^2a) in a Passive House building as well. However, in extreme climatic conditions with huge temperature differences compared to the regions where Passivhaus exists there were some other difficulties encountered and possible solutions were mentioned. These solutions need to be explored for individual cases through further research.

The article (Fincke, 2014) discusses some interesting findings concerning the cooling aspect that, where it was really easy to determine that active cooling was necessary it was premature to presume that Passive cooling methods with excessive shading and overnight ventilation to escape the additional heat wasn't close to reality. Thus indoor temperatures exceeded over 25°C in all the hours in a day and in a year bordering between the range of 5 to 20% increase with a slight fluctuation of the case studies located with a few hundred kilometers away. When temperatures go very high there is absolutely no way that even active cooling will be sufficient in buildings that have been specially designed and built for passive cooling. In a nutshell in cooler climates indoor temperatures exceed the limit easily and it is easier to avoid active cooling completely and adopt passive cooling methods for good. Although keen focus has to be given to improvising the passive cooling strategies and dealing with humidity recovery to provide a comfortable indoor environment in tropics.

The other method (Anon., 2014a) that was carried out was an independent research related to the economics of different construction techniques. Passivhaus can become prevalent system only when funded by the home owners, as witnessed in central Europe. A financially optimum building is therefore specified irrespective of the Passivhaus standard because of the cost of the construction and operation was noticed significantly high when compared using net present value method. The cost for these studies were carried out on estimates of average prices during the time of the study. The evidence claims (Schneider *et al.,* 2015) that at a minimal extra building costs of 5 to 10%, Passive Houses generally consume 80 to 90% less heating energy their counter-part conventional new buildings of the same geometry.

From the study (Schneider *et al.,* 2015), Tokyo has very similar humidity ratio to Bangalore. The solutions offered to deal with the humidity issues in Tokyo was that active cooling was a must; but not necessarily air conditioning units but just the dehumidification would suffice. This is one of the pointers to be examined for the climate of Bangalore. In Shanghai, where the maximum daily average temperatures are recorded similar to Bangalore's recent summer time recordings; the buildings are advised to remain largely closed so as to reduce external humidity or heat loads from fluctuating the internal environment. Bangalore's latitudinal location is set between Abu Dhabi and Singapore. All three locations experience similar maximum and minimum annual average temperatures with Bangalore being the most pleasant than the two other. However, because of the temperature range similarities, it would be helpful to compare the solutions offered for Passive Houses to deal with the heat gain in these locations. The recommendations for these locations was to protect the building from heat to minimize transmission loads to a manageable level. Good airtightness was necessary to reduce infiltration of excess heat from the outside to the internal environment. To also decrease the ventilation load, the use of an extremely energy efficient recovery ventilator was suggested. It was confirmed by Schneider and others (2015) in their results that cooling the passive houses through supply air alone was a definite possibility. This being owed to the fact that there was minimum fluctuation in the ambient temperatures of both these locations throughout the year. This would be good news for Bangalore as the fluctuation in ambient temperature is even more minimum of only 5.3°C (Weber, 2015). The highlighting difference in the suggestions for the two locations of Abu Dhabi and Singapore was relating to the windows. Triple solar protective glazing with a low g-value of 0.25 was recommended for Abu Dhabi so as to lessen the solar transmission and loads into the building via windows. Movable shading was not found to be necessary. In contrast, double solar protective glazing also with a very low g-value of 0.23 was found to be sufficient for Singapore to reduce solar loads through windows. For the Singapore module, there was also excessive shading suggested with a roof projection of 1.5m horizontally to particularly shade the exterior walls from direct solar radiation.

In conclusion of the technical and economic factors of the study, for climates that needed only cooling it was noted that protection from the sun was crucial throughout the year for not only the glazing units but also the walls and roofs. The primary energy demands were easily met below 120 kWh/(m^2a). Cooling and dehumidification with high values were in some cases needed throughout the year in the tropical regions, even if the location was situated at higher altitudes with slightly lower temperatures. This is an issue which needs to address specifically with case studies in future researches.

Building services are an important aspect for any building. The study (Anon., 2014b) showed with respect to building services of Passivhaus of different climatic zones a ventilation system with fresh air and extract air would be suitable with or without heat recovery depending on individual cases. In locations where the need for air conditioning is rather low it would be fine even without the ventilation heat recovery. However, in such cases an addition of humidity recovery into this system would help increase the indoor air humidity or prevent the high levels outdoor air humidity from additionally rising the dehumidification demand for the building. It was mentioned in this study that this would be a tough call to make whether humidity should be recovered or more energy should be consumed with or without it. As discussed above, in Tokyo, a promising solution was found that a bypass which would automatically adjust based on the difference between absolute humidity levels in summer would be ideal.

2.4 KEY ISSUES

For the purpose of this research, the focus is the tropical wet and dry climate of Bangalore, India. The key issues recognized from the above understanding are listed below.

I. Insulation: The composition of the wall, roof and floor play a very important role in the performance of a building. The building materials used impact the inside and outside environment especially when there is high relative humidity of outdoor air during hot and humid periods and cooling or dehumidification of the indoor air at the same time. This is because the difference in the vapour pressure and temperatures between the inside and the outside widen. When a material with low resistance to vapour diffusion, like mineral wool is used for insulation, it can be concerning if it would accumulate water during rains or through the night. External render of porous cement/plaster is usually used for warm climates in order to allow for vapour diffusion to dry the layers behind. Porous concrete has a hygroscopic property to deal with large amounts of condensation by absorbing it as well as supporting the drying of this matrix. Therefore, the choice of building materials for construction in warmer climates become a major deciding factor and require careful investigation and probably a lot more experimental evidence.

II. Shading: This is so far the easiest way to avoid excessive solar heat gain into the building. Also, shading for the glazing units would avoid direct solar radiation into the building.

III. Windows: Single glazed non insulated windows definitely require replacement. Deeper analysis needs to be done to identify the best suited windows for this location; whether it would be double or triple glazing units with high or low g-values.

IV. Thermal Bridges: When insulation becomes essential, air tightness and thermal bridges become very important. Every junction of the building needs to be detailed such that thermal bridges are avoided and the same should be achieved during construction.

V. Ventilation: It can be observed that cost optimized buildings do not necessarily need a ventilation system with heat recovery. The concern of dehumidification or humidity recovery will have to be solved to provide a comfortable living environment. If cooling and dehumidification are required, it would be wise to provide separate controls for each of these functions in order to reduce the overall energy consumption. There could be another way of looking at this where outdoor air could be directly used to cool the indoor environment and the process of dehumidification could take place without heat recovery. Thus a controlled adjustable bypass could be suggested to optimize the longevity of the ventilation system as well as the controlling of the air conditioning. These points regarding ventilation and cooling units will have to be further analyzed through this project to offer suitable recommendations particularly for the dwellings of Bangalore.

3. METHODOLOGY

Research methods involve various forms of data collection, analysis, and interpretation. This research paper follows the Mixed Method Strategy as it seemed to be the best suited for the discussion as it had different forms of data and interpretations drawn on various possibilities over a wider timescale. There are three different strategies under mixed methods. All three of them are slightly different and the research method plans to overlap them as needed by each progressive step in the project. The crisscross questioning between these three strategies is expected to provide a pattern to discovering a useful piece of information and questioning it further to arrive at a more informative and fruitful conclusion. The different mixed strategies adapted have been described below.

3.1 MIXED METHOD STRATEGY

Data is collected in a mixed system, both qualitative and quantitative to study different aspects of the main requirements to answer the research question. Johnson and others (2007) explain that while considering a wide range of data collection, it needs to be organized by a degree of predetermined nature for various procedures. A system of closed-ended versus open-ended questioning with the focus split unevenly on numeric versus non-numeric data analysis. In this case non-numeric data mainly comprised of data collection from the architect and contractor of the case study selected and also a few brief sessions of discussing the thermal comfort experienced by the users in the space. The ideas that emerged from this step were adopted to be filled in as numeric data into the Passive House Planning Package(PHPP). Thus a mixed-method matrix was adapted to examine approaches to data collection.

The case study selected is indicative of a typical building in Bangalore. This behaves as a sample data for this research project to carry out further analysis. It is presumed that the result of these case studies through PHPP can be used to indicate the typical behavior of other structures in Bangalore with the most direct solutions of this research for adaptation of Passivhaus principles. Sampling, permissions, data sources, data recording and administering data collection (Johnson, *et al.,* 2007) are different phases that would be encountered in this method for process of this research.

Table 6.1 Phases in the Data Collection Process for Qualitative and Quantitative Research

Qualitative Data Collection	*Phases in the Process of Research*	*Quantitative Data Collection*
• Purposeful sampling strategies • Small number of participants and sites	Sampling	• Random sampling • Adequate size to reduce sampling error and provide sufficient power
• From individuals providing access to sites • Institutional review boards • Individuals	Permissions	• From individuals providing access to sites • Institutional review boards • Individuals
• Open-ended interviews • Open-ended observations • Documents • Audiovisual materials	Data sources	• Instruments • Checklists • Public documents
• Interview protocols • Observational protocols	Recording the data	• Instruments with scores that are reliable and valid
• Attending to field issues • Attending to ethical issues	Administering data collection	• Standardization of procedures • Attending to ethical issues

Table 1: Phases in the Data Collection Process for Qualitative and Quantitative Research (Creswell, 2006)

The buildings selected for the case study is a typical construction residence building in Bangalore. This detached dwelling was built around 25 years ago as a load-bearing structure with reinforced concrete slabs. In order to support the weight of the massive spans, composite masonry walls were constructed with 4.5" brick and 4.5" stone in a 9" thick masonry wall. Timber doors and windows are fitted in every floor. The climate data tool for PHPP (Weber, 2015) was carefully selected for Horamavu, Bangalore where this detached dwelling is situated.

3.2 TRIANGULATING DATA SOURCES

Using qualitative and quantitative research methods together, Triangulation is a common approach to back up one set of findings from one method of data collection underpinned by one methodology, with another very different method underpinned by another methodology (Tashakkori & Teddlie, 1998). In this research, the questions that were brought about through the analysis of the data collected based on the behavior of the building with the construction technique adapted and the further review of general structures in tropical climate but more specifically to the temperate uplands of Bangalore was matched by the warnings from PHPP. Cross-questioning during the analysis phase was supported by the results of PHPP. This clarified that the indication of the doubts that cropped up during the process of the research were validating each other. Whilst one method provided in depth clarity the other method of theoretical analysis remains an on-going process through and beyond this research paper.

The results from one method help researchers identify questions for the other method (Tashakkori & Teddlie, 1998) Alternatively, the qualitative and quantitative data can be merged into one large database or the results used side by side to reinforce each other (Creswell *et al.*, 2003). Triangulation can serve to be a very important step in the process of research to improve the accuracy of judgements by collecting different kinds of data based on the same phenomenon. Cross-validation can reinstate assurance to the researcher at times and sometimes perhaps, serve as a milestone to track the process of where the research is after all headed. This strategy will be extremely useful while navigating through PHPP to optimize the results for quick decision making based on the qualitative research data or key issues.

3.3 CONCURRENT PROCEDURE

Concurrent procedure in mixed methodology eventually ties together the quantitative and qualitative data to provide a comprehensive analysis of the research problem. Both types of data are collected at the same time and then integrated with all the information. This consolidated data is then used for interpretations and discussions of the overall results (Creswell *et al.*, 2003). It helps to improvise on the attained results for a sound and genuine result of the research problem. This type of method gives one the freedom to have one form of data collection larger than the other and collected at different or overlapping times through the timescale of the project. This is essential as it gives the freedom to explore new ideas and questions along the way.

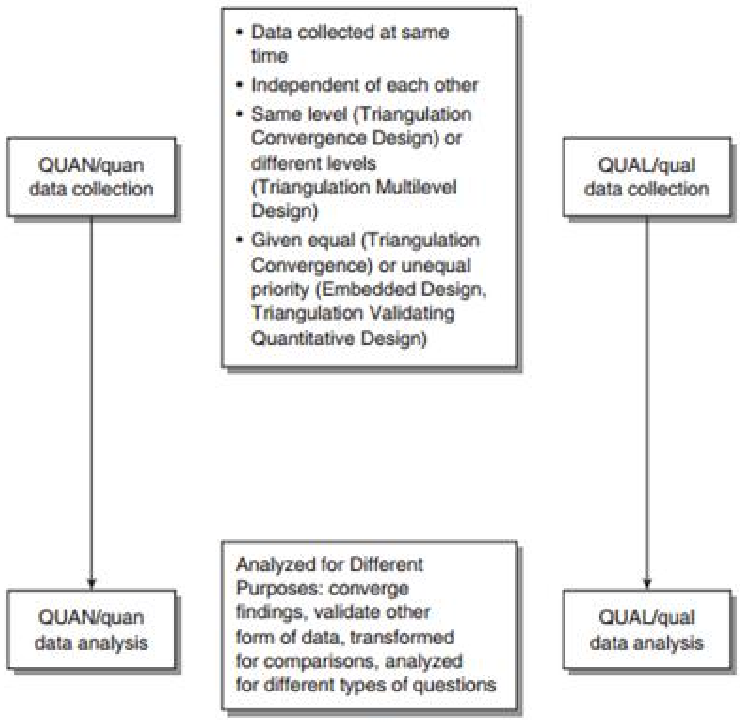

Fig 8: Concurrent forms of Mixed methods data collection (Creswell, 2006)

The literature studies comprising of both qualitative and quantitative data would lead to key issues. These are to be examined for the selected case study through PHPP to produce quantitative results and produce valid verification data for the case study. The key issues are to be further studied and discussed qualitatively. The inputs from the discussions are then to be modified on the PHPP file for the case study. Back and forth a few times between the two methods backed by vigorous discussions eventually would lead to a sound understanding of the key issues that affect the possibility of Passivhaus in Bangalore. The results would determine the turn of further discussions and conclusion of this research project.

4. ANALYSIS

4.1 CASE STUDY

4.1.1 LOCATION

Bengaluru, previously known as Bangalore, is located in the central part of the southern tip of India approximately 300 kilometers from both the east and west coast. Its geographical location can be traced to the latitude of 13.2 ° N and 77.4 ° E.

4.1.2 CLIMATE

Bangalore experiences tropical wet and dry (savanna) climate. This city is possible one of the most pleasant cities throughout India and usually remains under moderate conditions. It is because it is located up on a high plateau region with a lot of vegetation. It is located close to the Tropic of cancer and hence the climate is neither consistently high nor warm and humid. The characteristics of the climate here changes from season to seasons alternating between hot, dry periods and periods of concentrated rainfall and high humidity.

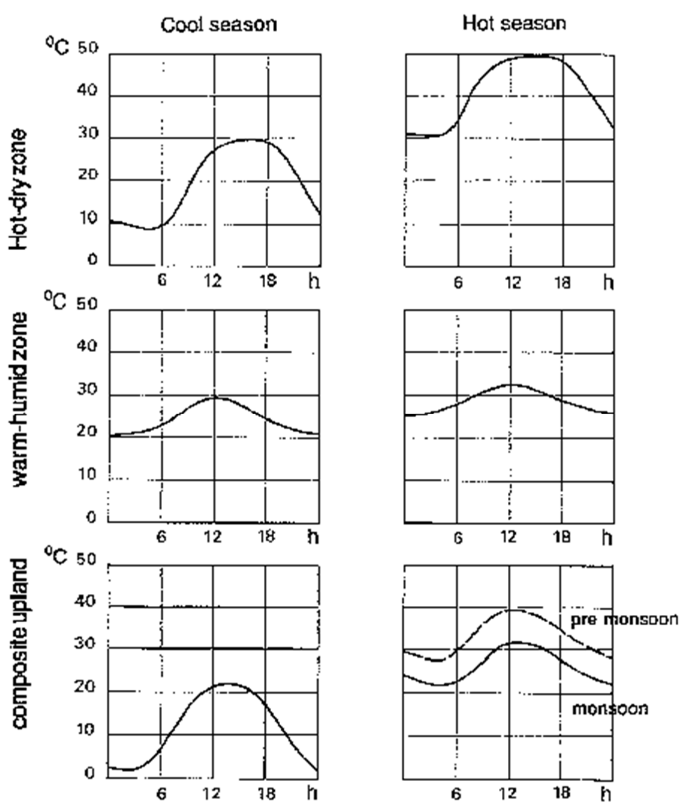

Fig 9: Temperature variations in composite climate (Fislisbach and Zollikon, 1993)

The solar radiation for Bangalore is more or less is same throughout the year. It experiences lower temperatures compared to the hot dry regions surrounding it due to being located at a relatively higher elevation of 900m (IISc, 2015) above sea level. The climate here is neither too hot nor too cold. During winter season the range of temperatures varies between 8 to 18°Celsius during night time and between 24 to 33°Celsius during the day time (Fislisbach and Zollikon, 1993). Similarly, during the summer season, the air temperature rises to above 20 to 22°Celsius during the night time and ranges somewhere between 27 to 38°Celsius during the day time. The relative humidity of this region is comparatively low during summers and winters, recorded to be between 50 to 70% and rising as high as 45 to 80% during the rainy seasons or the monsoons. Bangalore experiences heavy rainfalls with the total rainfall exceeding 100 cm per year usually.

Wind speeds vary depending on the topography of the plateau regions but are generally high during the summers. The predominant wind direction is south west to north east and north east to south west during the monsoons. Skies stay mostly clear with occasional presence of low dense clouds especially during summers. During the dry periods winds are dusty and hot in the lower areas whereas strong and very regular around the mountainous regions. In the upland areas night frost can sometimes be experienced during winters similar to its occurrence in continental areas.

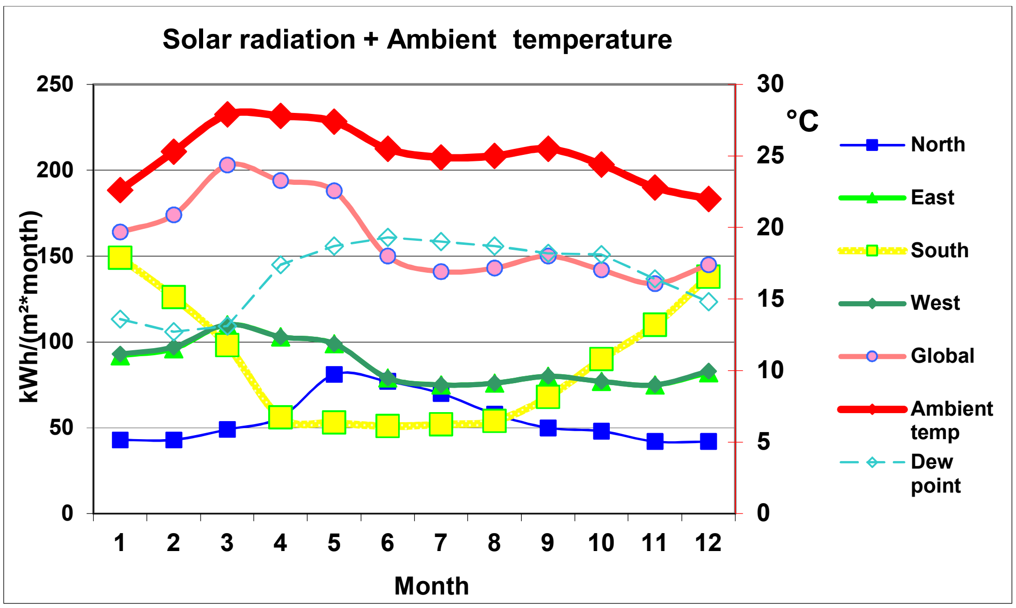

Fig 10: Climate data from the Passive House Institute for Horamavu, Bangalore, India

Overall, Bangalore can be stated as a tropical wet and dry (savanna) climate located in the tropical zone. The climate data used from the Passive House Institute (Weber, 2015) for PHPP is depicted in the graph above. For the calculations of PHPP, the Interior temperature for winters has been considered 21°C and for summers as 30.8°C. Bangloreans are acclimatized to feel comfortable between 21 to 31°C as discussed in Section 2.1 above. Hence, overheating for the space is only considered to be when above 30.8°C. It is probably necessary to check this temperature for each location specifically because many people in different cities of India are accustomed to an annual average temperature of 35°C and are now complaining about the rise in maximum temperature in recent years above 40°C.

4.1.3 URBAN SCENARIO

Urban structures depend strongly on climate and are sketched out distinctly in each climatic zone with the fundamental concerns being the provision of shading and air movement by varying methods. The urban form contributes to the nearby environment affecting the city's microclimate.

The effect of the climate on the outside space of traditional settlements can be explained by the following examples:

- Settlements in urban areas are characterised by perfect protection against solar radiation by mutual shading which prompts compact settlements, narrow streets and many small public squares which are usually shaded by dense and tall vegetation. This is the case for the city centres of Bangalore.

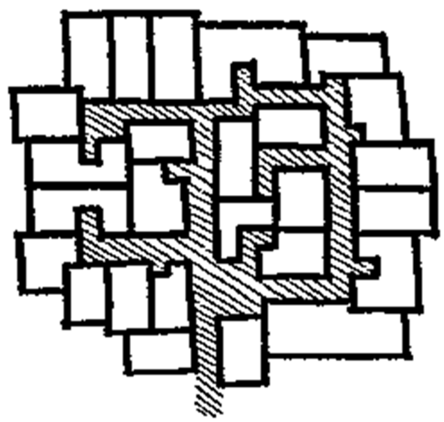

Fig 11: Typical settlement for urban areas and city centers (Fislisbach and Zollikon, 1993)

- Settlements in spacious peripherals of the city are set in a way to maximise the use of prevailing winds and thus buildings are scattered. The vegetation is planted accordingly in order to provide more share without obstructing the natural ventilation. This is the case in the suburbs of Bangalore.

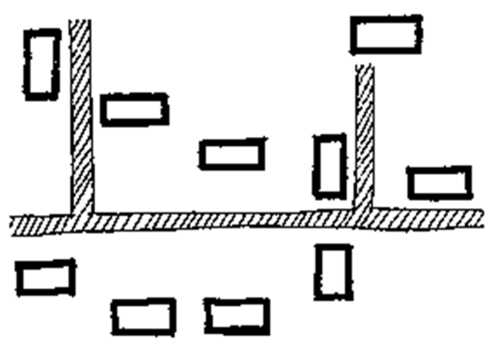

Fig 12: Typical settlement for city suburbs (Fislisbach and Zollikon, 1993)

Modern requirements in cities like Bangalore have been adopted in contradiction to the traditional old patterns like in the case of the arrangements of the dwellings in the city's periphery. However, advantages of the traditional patterns should be supported where possible. In city centres and the growing areas where this would not match the economic growth, solutions like Passivhaus with technical soundness become more important as most these buildings get insufficient sunlight on selective facades. This can also be noted as a flaw in the governments urban development standards which allow all buildings to be built at just six feet distance between them. Such narrow gaps become dingy spaces and do not provide hygienic conditions either. This makes it evident that although one is designing solutions for Bangalore's climate the contextual scenario is of prime importance.

The central business district and city centre of Bangalore are hence experiencing much higher temperatures than the other parts. This can also be pointed out to the concrete buildings in the central business district and asphalted roads which heats up very quickly from the active solar radiation making the external environment warmer than it is meant to be. Most of this acquired heat ends up being stored in the thermal mass of the concrete building and doesn't escape overnight as usually planned for in concrete structures. This leads to the daily minimum temperature to be higher than expected. Although this might be suited as a pleasant scenario during winter season; it does make life unbearable especially during the summer day time in the central business district and the city centre of Bangalore. Such a cycle repeats and becomes more evident during summer nights. The city is experiencing loss in vegetation and increase in pollution. Undeveloped land in these pockets or at the periphery of this city could act a source of cool air if vegetated, and facilitate healthy wind movement.

4.1.4 DESIGN STRATEGY AND THERMAL ZONES

The main points to be kept in mind while designing buildings for the tropical wet and dry climate in order to achieve a good thermal comfort level are as follows:

- Maintain a balance – There will be conflicting requirements for different seasons in this climate. It is essential to remember that the temperatures are not extreme in every season. It would be best suited to find balanced solutions to suit most of the year and provide additional alternatives which could be used during peak times.
- Promote solar radiation gain in winters but avoid the same in summers by providing shading.
- Plan for wind protection during winters and for good cross ventilation in summers. Provide moderate heat storage capacity for all buildings as time lag for thermal exchange is beneficial. Windows neither too big nor too small but mediums sized should be used.
- Orientation should be such that benefits can be gained from the winter sun.
- Semi compact built form are advised; roof type depending on the precipitation pattern of the place. In case of Bangalore flat roofs with mild slopes are quite common.
- Ventilation should be controlled while protecting from the winter winds.
- Thermal insulation is beneficial for Bangalore.
- Reflectivity and emissivity are less important.

Buildings of this climate are one of most complex ones to design due to the reason that they must satisfy the needs of the cold dry, hot and cold humid periods in the same structure. In addition, heat conservation although essential in winters; solar heat gains are to be avoided during the rest of the year. A careful analysis of the duration of the seasons and their severity should be taken in to account while providing solutions between conflicting needs to reach a balanced design.

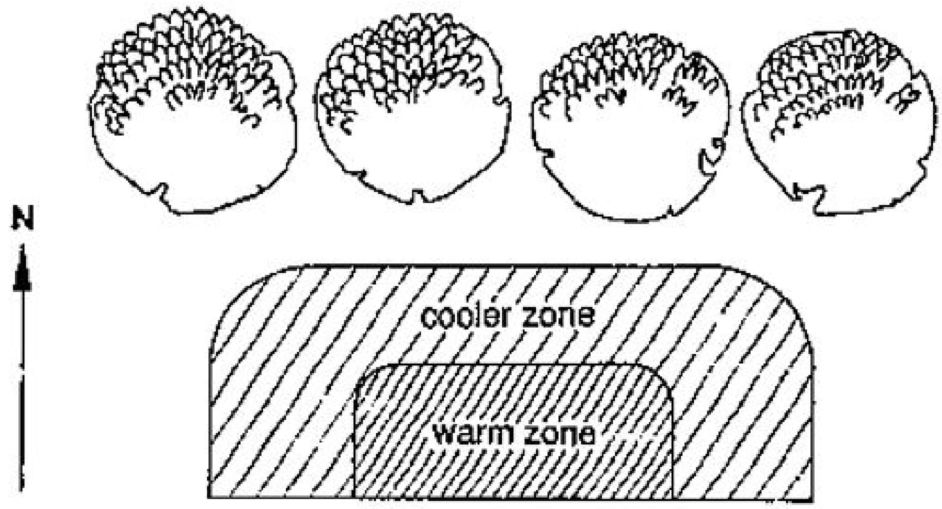

Fig 13: Thermal Zone layout for Warm and Cold Zones (Fislisbach and Zollikon, 1993)

The figure above indicated the usual suggestion for designs in Bangalore where a part of the house is designed as a warm zone and the other part is designed as a cooler zone in order to meet the comprise between the conflicting needs of this climate. The functions of the house are accordingly arranged. Living rooms, Verandas and other common spaces which have higher heat demand are placed facing towards the winter sun which is towards the south. The other areas such as the kitchen, store and bedrooms are generally arranged surrounding the warm zone on the west, north, east sides in the cooler zone. It also acts as the buffer zone to protect against heat loss and wind. Sometimes a line of vegetation is planted to provide additional protection to the thermal buffer zone.

4.1.5 BASE CASE FOR PHPP

The detached dwelling shown in the image below is selected for the base case for PHPP. It is a 3-storey structure facing the road on the north side, built in 1990, in Horamavu, Bangalore, India. The total treated floor area for all floors within the thermal envelope is 413 square metres.

Fig 14: Front North Elevation of the dwelling

The reason for selecting this building for the base case study of this research was because it is a representation of the typical construction for the region. It can be used as a sample case to generate results from PHPP. It also largely represents buildings in many other regions in India. It is a load bearing structure with reinforced concrete floor slabs. As indicated in Appendix-C the thermal conductivity of the brick wall is 1.2 W/(mK) and the stone wall is 3.5 W/(mK). These are very high to be thermally resistant of the solar heat gain. However, the exceptionally deep overhangs protect a large portion of the wall and most windows from direct solar heat gains. This helps keep the place much cooler passively.

The residence is overshadowed by tall structures on the South-west and West sides of the building making it very difficult for solar penetration. Even on the East and North sides, the deep overhangs shadow the wall and windows and there is very less direct solar radiation on them.

Roofs are mainly constructed of reinforced concrete and are generally observed to be flat in this region. The sun is right over head during mid-day and falls normally on the flat roofs in Bangalore and many other places in the tropical zone. This extensively heats the concrete slabs increasing the heat gain massively.

Fig 15: Images showing the exterior and interior of the case study dwelling in Horamavu, Bangalore, India

Windows in the base case are single glazed with timber frames which are fixed with the steel hold-fast into the masonry walls. The glazing units are one of the main reasons for massive heat gains throughout the year. As can be seen in Appendix-A Bangalore experiences approximately 2800 annual sunshine hours. In fact, this is comparatively less for a tropical region but still has a significant indication of heat gain throughout the year. It is to be noted that the temperatures in Bangalore did not fluctuate much during different seasons but in recent years range within an average of 18-30°Celsius.

Specific building demands with reference to the treated floor area					
	Treated floor area	413.2	m²	**Requirements**	**Fulfilled?***
Space heating	Heating demand	**0**	**kWh/(m²a)**	15 kWh/(m²a)	**yes**
	Heating load	**5**	**W/m²**	10 W/m²	**yes**
Space cooling	Overall specif. space cooling demand	**51**	**kWh/(m²a)**	45 kWh/(m²a)	**no**
	Cooling load	**36**	**W/m²**	10 W/m²	**no**
	Frequency of overheating (> 30.8 °C)	12.1	%	-	-
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances		**kWh/(m²a)**	120 kWh/(m²a)	
	DHW, space heating and auxiliary electricity		kWh/(m²a)	-	-
	Specific primary energy reduction through solar electricity		kWh/(m²a)	-	-
Airtightness	Pressurization test result n_{50}	**10.0**	**1/h**	0.6 1/h	**no**
				* empty field: data missing; '-': no requirement	

Fig 16: PHPP Verification – Base case

It can be observed from the image above and the details in the Appendix-C that PHPP shows the very low heating load. However, the space cooling demand is 51 kWh/(m^{2}a) which is much higher than that limited by Passivhaus standards. The cooling load is 36 W/m^2 which is more than 3 times of the permitted limit. Frequency of overheating is also slightly high at 12.1%. This building would require extensive refurbishment to meet the Passivhaus comfort standards. The key issues as discussed in Section 2.4 would be factors to alter in PHPP to analyze if it would help reduce the space cooling demands and the frequency of overheating.

4.2 PHPP ANALYSIS

There was a vigorous process carried out through PHPP calculations along with many discussions along the way to optimize this dwelling. The changes and behaviour of the building through the process is discussed in detail through the key issues stated in Section 2.4.

4.2.1 INSULATION

The dwelling's present construction was basic without insulation. Firstly, the U-values of all the elements of the building would be optimized with insulation and air-tightness layer.

Wall insulation was added with not very high thermal conductivity of 0.038 W/(mK) along with a good quality soft board with thermal conductivity of 0.50 W/(mK). External render could be added back on the soft board to match the previous look making sure the material used for rendering would be waterproof in order to protect the layer of insulation behind. Oriented Strand Board (OSB) with thermal conductivity of 0.13 W/(mK) would be added internally as the air tightness layer for the dwelling. The wall thickness increased but was kept to the minimum possible. Roof was not modified too much. Internally, a good roofing board with thermal conductivity of 0.025 W/(mK) would be added outside the airtightness layer of OSB. Flooring had to be completely redone above the reinforced concrete layer. It would mean the staircase would need to be reworked to adjust the increase of a substantial 238mm increase. This would be a lot of work but essential to meet the comfort standards. Rigid Polyurethane Foam was chosen with thermal conductivity of 0.025 W/(mK) placed between softwood timber studs with thermal conductivity of 0.13 W/(mK) as flooring insulation. Structural thermal breakers would be used all around below external and internal walls as they are all load bearing and up to a height of 300mm to climb above the increase in floor height. However, the airtightness layer detail will need to be detailed out cautiously around every wall. Chipboard with thermal conductivity of 0.018 W/(mK) would also to provide evenness below the OSB and to improvise the thermal tightness of the dwelling in order to nullify the thermal exchange through the floor. The U-values achieved for the wall is 0.201 W/(m^{2}K); roof is 0.524 W/(m^{2}K) and floor is 0.108 W/(m^{2}K). The comparative improvements in the U-values from the original base case are depicted in the table below.

U-values W/(m^{2}K)			
	Original value	Optimized value	Percentage (+/-)
Wall	*2.728*	*0.201*	*-92.63%*
Roof	*3.933*	*0.524*	*-86.68%*
Floor	*3.608*	*0.108*	*-97.01%*

Table 2: Improvements in U-values for the case study in Bangalore

4.2.2 SHADING

The dwelling is overshadowed on the South-West and West facades by adjacent structures. However, after a lot of quantitative data analysis with PHPP, it can be confirmed that the shading plays a very important role on all sides of the building to promote passive cooling techniques. This in turn had a massive impact on the space cooling demand of the dwelling. Shading influence in descending order can be explained ad South, North, West and East. Thus, minimum openings (windows) in the S and N help for this location. Solar gains on the south side happen even with the direct radiation of sun on the south walls. To minimize the impact of this, 70% of the south would need to be shaded. It could be worked out in a combination of fixed shading for the walls and movable shading for the windows so the user can have flexibility as desired. The shading on the west is not considered in this case study as it is overshadowed by 45% in the base case as well. North and East facades also are not altered much; shading is equalized on these sides to 20% on both sides.

4.2.3 WINDOWS

Like most dwellings in Bangalore built two decades ago, this also has single glazed windows with timber frame. This wasn't the most impacting factor like Insulation or shading. However, replacing them showed improvements in the space cooling demand of the dwelling. Double glazed windows with low-E; g-Value 0.64; U-Value 1.30W/(m2K) and well insulated REHAU frames with U-value 0.79W/(m2K); psi-value of glazing edge 0.30W/(mK) would be recommended as the best suited for this dwelling. Quantitative data analysis with regards to window showed that Bangalore would not require triple glazed windows as they don't benefit in any way more than the double glazed windows for this case study.

4.2.4 THERMAL BRIDGES

The refurbished dwelling is assumed to be almost free of thermal bridges. A little leverage is given for a few though. This impacts the overall space cooling demand or overheating very mildly. However, the airtightness for the structure is considered to be high and within the quality requirement of the standard of 0.6 1/h for the test results under air pressurization of 50Pa.

4.2.5 VENTILATION

Humidity control is a very important aspect for a Passivhaus in Bangalore. The basic ventilation for the dwelling would be the balanced Passivhaus ventilation system which is considered at 75% efficiency. There is no requirement of heating coil for this location. The cooling units selected to meet the cooling requirements for the case study in the climatic conditions of Bangalore would be to allow for supply air cooling, additional dehumidification and panel cooling when required. It should be noted that these additional cooling units are required variedly through the year as shown in the figure below. Supply of fresh air is to be adopted with automatic by pass for temperature and humidity control as programmed.

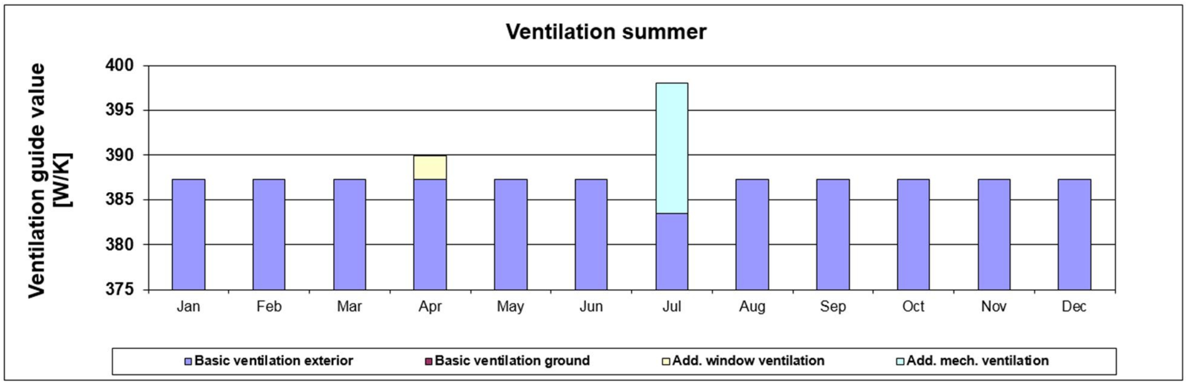

Fig 17 : Ventilation graph for the case study at Horamavu, Bangalore, India.

4.2.6 RESULTS

Further to all the alterations, PHPP verified that a Passivhaus is possible in Bangalore. The results from the optimized PHPP file are shown in the image below and the details can be referred to in the Appendix-C. The observations from this show that there is no more heating load which means it is very comfortable during winters. The space cooling demand has now dropped to 25 kWh/(m^2a) which is now within the requirements of the Passivhaus standards. The cooling load is also lowered to 7 W/m^2. Frequency of overheating had reduced tremendously to 1.4%. The extensive refurbishment of this dwelling to meet the Passivhaus comfort standards would be worth it considering the comfort indoors with the changing climate.

Specific building demands with reference to the treated floor area				Requirements	Fulfilled?*
	Treated floor area	413.2	m^2		
Space heating	Heating demand	**0**	**kWh/(m^2a)**	15 kWh/(m²a)	**yes**
	Heating load	**0**	**W/m^2**	10 W/m²	**yes**
Space cooling	Overall specif. space cooling demand	**25**	**kWh/(m^2a)**	45 kWh/(m²a)	**yes**
	Cooling load	**7**	**W/m^2**	-	**-**
	Frequency of overheating (> 30.8 °C)	1.4	%	-	**-**
Primary energy	Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances	**100**	**kWh/(m^2a)**	120 kWh/(m²a)	**yes**
	DHW, space heating and auxiliary electricity	22	kWh/(m^2a)	-	**-**
	Specific primary energy reduction through solar electricity	48	kWh/(m^2a)	-	**-**
Airtightness	Pressurization test result n_{50}	**0.6**	**1/h**	0.6 1/h	**yes**

* empty field: data missing; '-': no requirement

Fig 18: PHPP Verification – Optimized case

The comparative improvements in the overall PHPP verification results from the base case are depicted in the table below.

Space Cooling			
	Original value	**Optimized value**	**Percentage (+/-)**
Space Cooling Demand kWh/(m^2a)	*51*	*25*	*-50.98%*
Cooling Load W/m^2	*36*	*7*	*-80.56%*
Freq. of Overheating %	*12.1*	*1.4*	*-88.43%*

Table 3: Space Cooling requirements

Clearly there is huge improvement in the reduction of Space cooling requirement of the dwelling. It is confirmed that passive strategies of Passivhaus principles can be adopted to the buildings in Bangalore to improve human thermal comfort.

5. DISCUSSION

The backbone of designing efficiently with minimum energy utilization during the usage of the building is to first minimize the heat gains and maximize the losses in the tropical region. In the above case study, it is to minimize the space cooling demand of the building as shown by the PHPP results. Passive cooling strategies are highly improved and all solutions should be adopted in order to meet Passivhaus standards and gain extreme thermal comfort. Although active systems like dehumidification would be required, the overall load of the additional cooling units is very minimal. Insulation is adopted very minimally to walls, roof and floor to decrease any further heat gains which would have increased the cooling load significantly. It is important to retain the coolness while disposing any additional unnecessary heat in these buildings. The balanced Passivhaus mechanical ventilation suffices this need. It would be 24/7 and be supplied to all the rooms in the dwelling as one single zone.

The objectives while designing buildings in such a region should be to:

- Resist heat gain
  - Decreased exposed surface area – Orientation and shape of the building should be the first consideration while designing Passivhaus standard houses in these areas
  - Increase thermal resistance – Floor, Roof and Wall insulation.
  - Increase shading – Glazed areas of the windows must particularly be protected by the overhangs or movable shading; the south and west wall must be excessively shaded to avoid any direct solar gain on these surfaces.
  - Increase surface reflectivity – All surfaces which have direct solar radiation on them must be pale or light colored and alternatively reflective surfaces like glazed china mosaic tiles could be used to reduce the intensity of solar radiation that would enter the building and reflect back most of it to the external environment
  - Air tightness – Replacement of windows make a good difference to the energy demand of the dwelling. However, it is important to fix the windows in an air-tight manner following the usual Passivhaus methods.

- Promote Heat Loss
  - Mechanical ventilation – Passivhaus has a balanced ventilation system which takes care of getting rid of all the excess heat throughout the day. It supplies fresh air throughout the day and hence also avoid the issue of excessive CO_2 in circulation. It also promotes healthy indoor air quality.
  - Opening of windows – Against the usual assumption that opening windows will promote cross ventilation and make one feel more comfortable; PHPP advices this only for the month of April for the dwelling in Bangalore. The assumption is proven wrong due to the change in climatic conditions from what it was a decade back and also because of high humidity in Bangalore. Opening the window in moths other than April is inviting more heat gains into the internal environment and increasing the internal humidity as well. This would indirectly create more pressure for the cooling units to cool the space after increasing the heat and increase the load usage of the dehumidifier.
  - Ventilation of Appliances – Extract vents would be appropriately placed according to the location of the appliances among other factors.

- Maintain air tightness and air exchange rate – The air exchange rate is calculated to be 0.6 ac per hour. The dwelling is made air tight to maintain this air exchange rate. Anything above or a hole through the air tightness layer will disturb the Passivhaus requirements. Incresing the air exchange rate or a damage to the air tightness layer would result in higher heat and humidity gains from the outside environment and increase the cooling load of the space.
- Designing of plumbing and electricals – These details must also be carefully insulated and done with minimum penetration through the air tightness layer.

Passivhaus design intelligently using passive strategies. It avoids its dependence on energy consumption mechanically and keeps it to the minimum if required. Proper orientation for a Passivhaus would reduce the cooling demand and minimize the heat gains in the tropics. Further reductions in cooling demand to meet the Passivhaus standard could be taken care through the wise choices of building materials with low thermal conductivity and a really good ventilation system. Passive design and low energy strategies have been examined, built and successfully put into practice in buildings and the adequacy of these methodologies is firmly connected to the particular climate in which they are utilized. Irrespective of the location, Passivhaus buildings can be optimised and built anywhere in the world. It would also have substantial savings for the energy bill along with excellent indoor thermal comfort.

Passivhaus principles have been well developed for high performance in temperate climates and have also attained a significant in Europe due to the massive energy reductions in buildings. When properly designed and executed the Passivhaus uses a lot less energy than a normal building and performs optimally in temperate to cold climates. The Passivhaus standard has been proved effective in several European countries and in 91 cases even in Non-European locations which have much warmer climatic conditions.

Eventually the hierarchical importance of the key issues for Passivhaus dwellings in Bangalore are as stated below, the most influencing being first:

1. Insulation
2. Shading
3. Windows
4. Thermal Bridges

The table below shows the reasoning behind this order.

VARIATIONS - KEY ISSUES		Space Cooling Demand	Cooling Load	Freq. of Overheating
	Original Value	20 kWh/(m^2a)	7 W/m^2	1.4%
U- Values W/(m^2 K) **U_w = 0.201 ; U_r = 0.524 ; U_f = 0.108**	**INCREASE (+)** **DECREASE (-)**	45% 0%	143% -29%	485% -100%
SHADING **S: 70% ; N: 20% ; W: 45% ; E: 20%**	**INCREASE (+)** **DECREASE (-)**	0% 0%	14% 0%	121% -57%
WINDOWS **Double glazed ; low E ; g - Value = 0.64 ; U- Value = 1.30 W/(m^2K) ; Uf = 0.79 W/(m^2K)**	**SINGLE** **TRIPLE**	0% 0%	14% 0%	-76% 0%
THERMAL BRIDGES **Plinth-Foundation; Ext. Wall Edge ; Ext. Wall -Roof**	**INCREASE (+)** **DECREASE (-)**	0% 0%	0% 0%	21% -7%

Table 4: Variations of key issues for Passivhaus in Bangalore to determine hierarchy of their importance

6. CONCLUSION

There is clearly a substantial need for improving thermal comfort in buildings of the tropical zone. There have been many passive cooling design strategies adopted through the past centuries. It is important to study and be aware of what affects thermal comfort for humans. An understanding of the climatic conditions and design strategies used in tropical wet and dry climate of Bangalore is also essential to analyze and recommend the right solution for the case study considered. Deep understanding of the Passivhaus principles adapted in cold climates is also required to critically analyze and interpret the results of the Passive House Planning Package. There were many factors about insulation, shading, windows, thermal bridges, ventilation and dehumidification which led to the core issue that solar heat gains were too high and thus increased space cooling demand and frequency of overheating. PHPP was very helpful to understand and make design decisions that actually made significant difference. Clearly, Passivhaus concept helps buildings perform better even in the tropical region. It would be beneficial to take it further and construct a new build Passivhaus and monitor it. This research has confirmed the possibility of Passivhaus principles to improve comfort for the dwellings in Bangalore, India.

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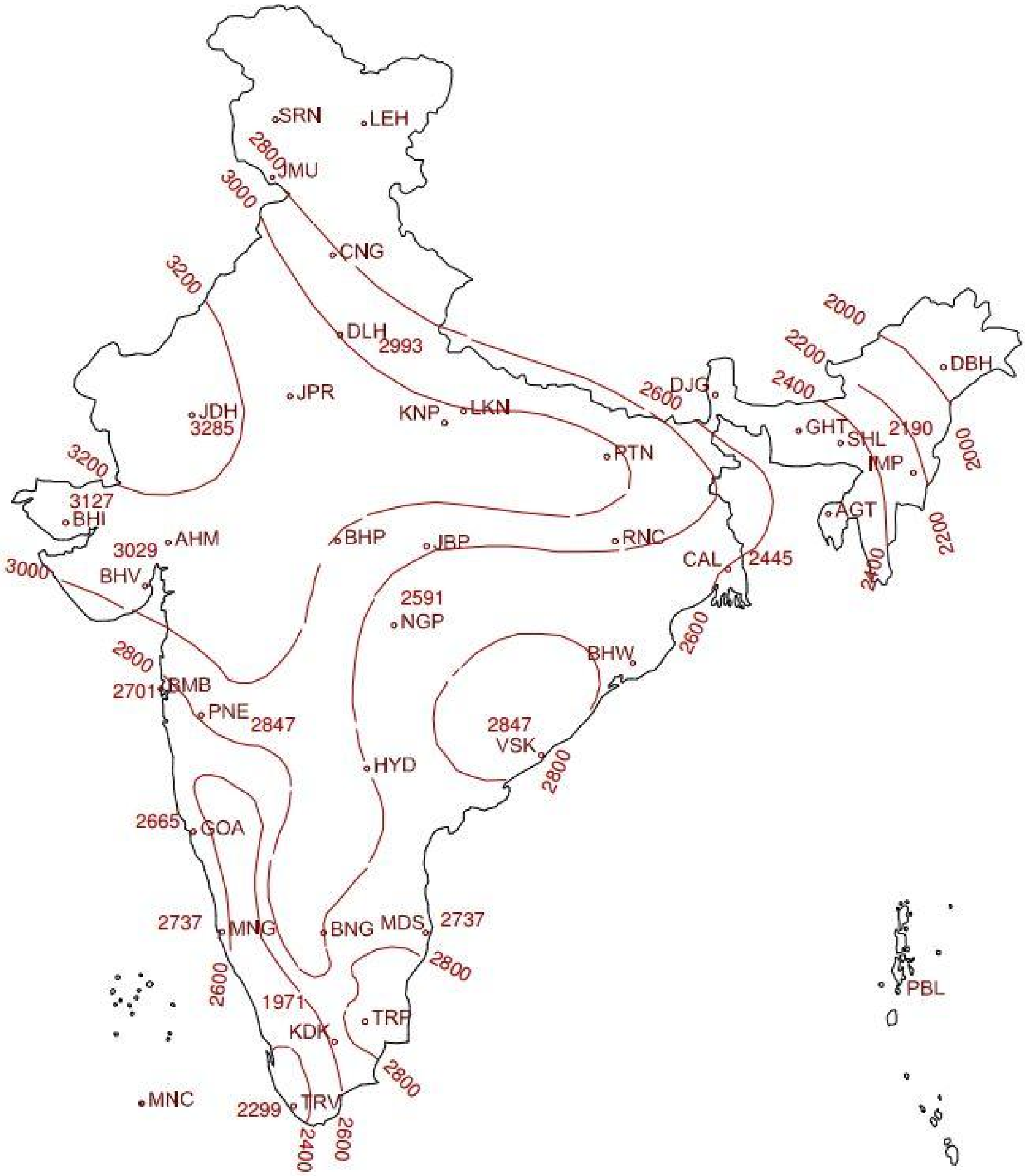
APPENDICES

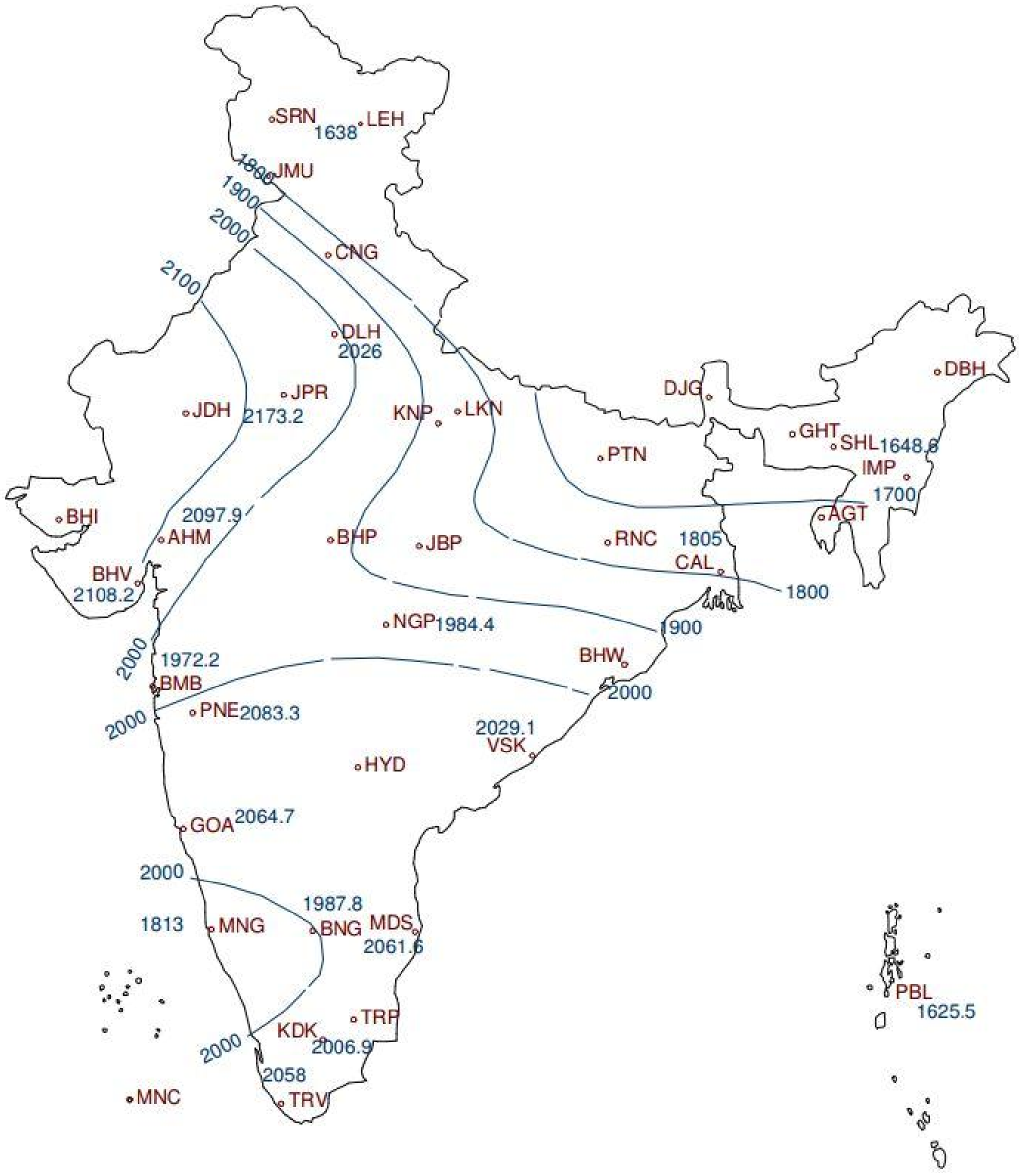
APPENDIX – A

1. Location of Bangalore in India

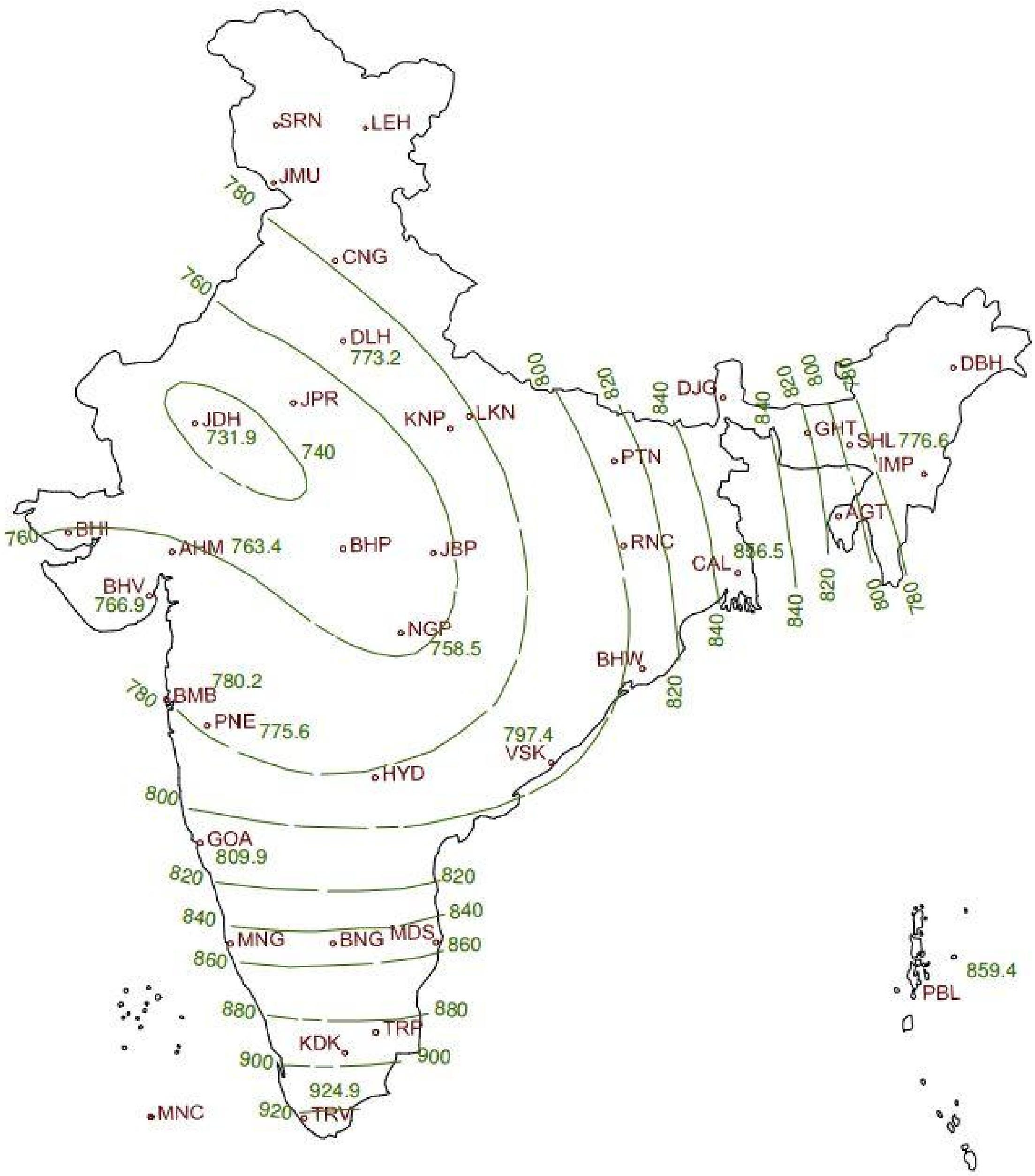
2. Distribution of annual sunshine hours in India



3. Distribution of annual global solar radiation (kWhm2-year) in India

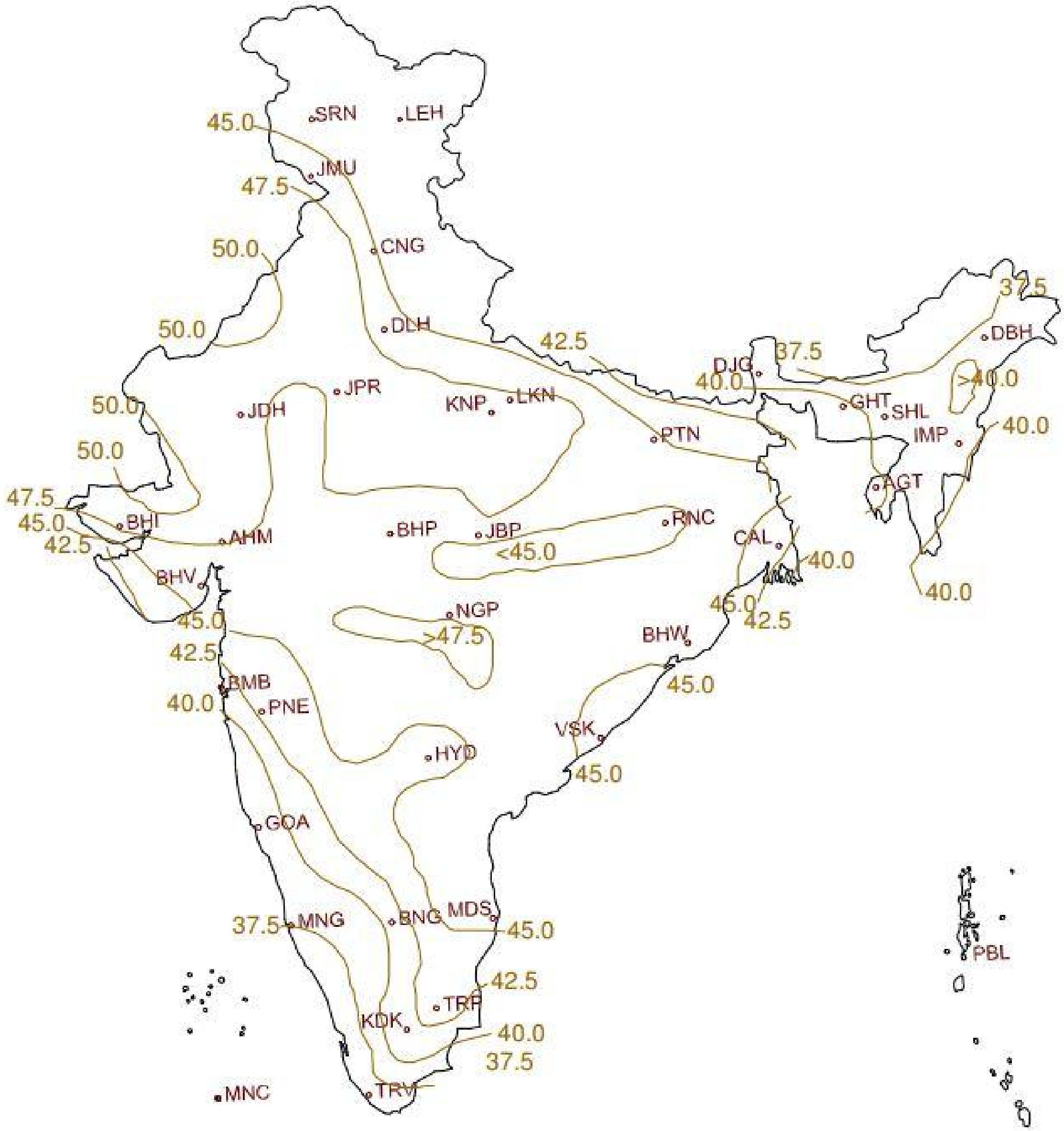


4. Distribution of annual diffuse solar radiation (kWhm2-year) in India

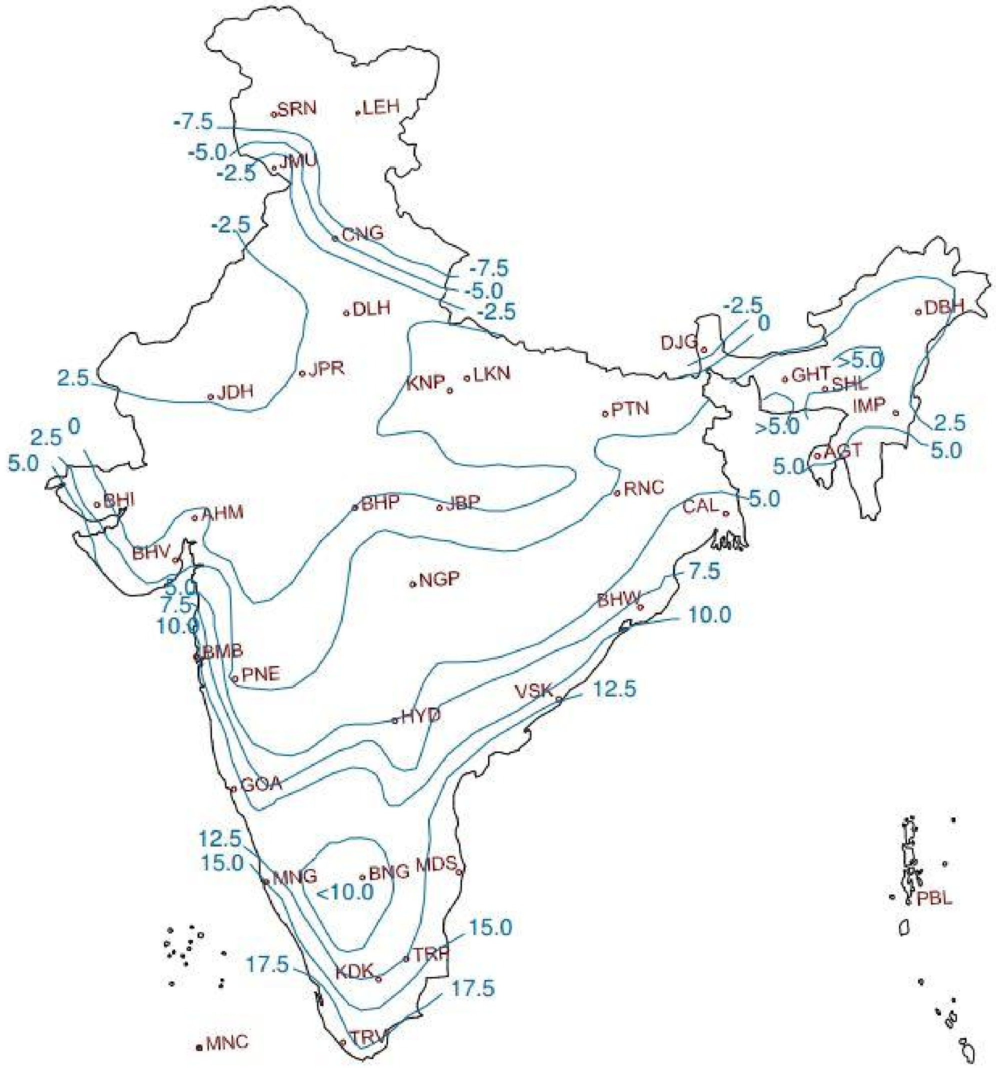


(2. Mani A., Handbook of solar radiation data for India, Allied Publishers, New Delhi, 1981.)

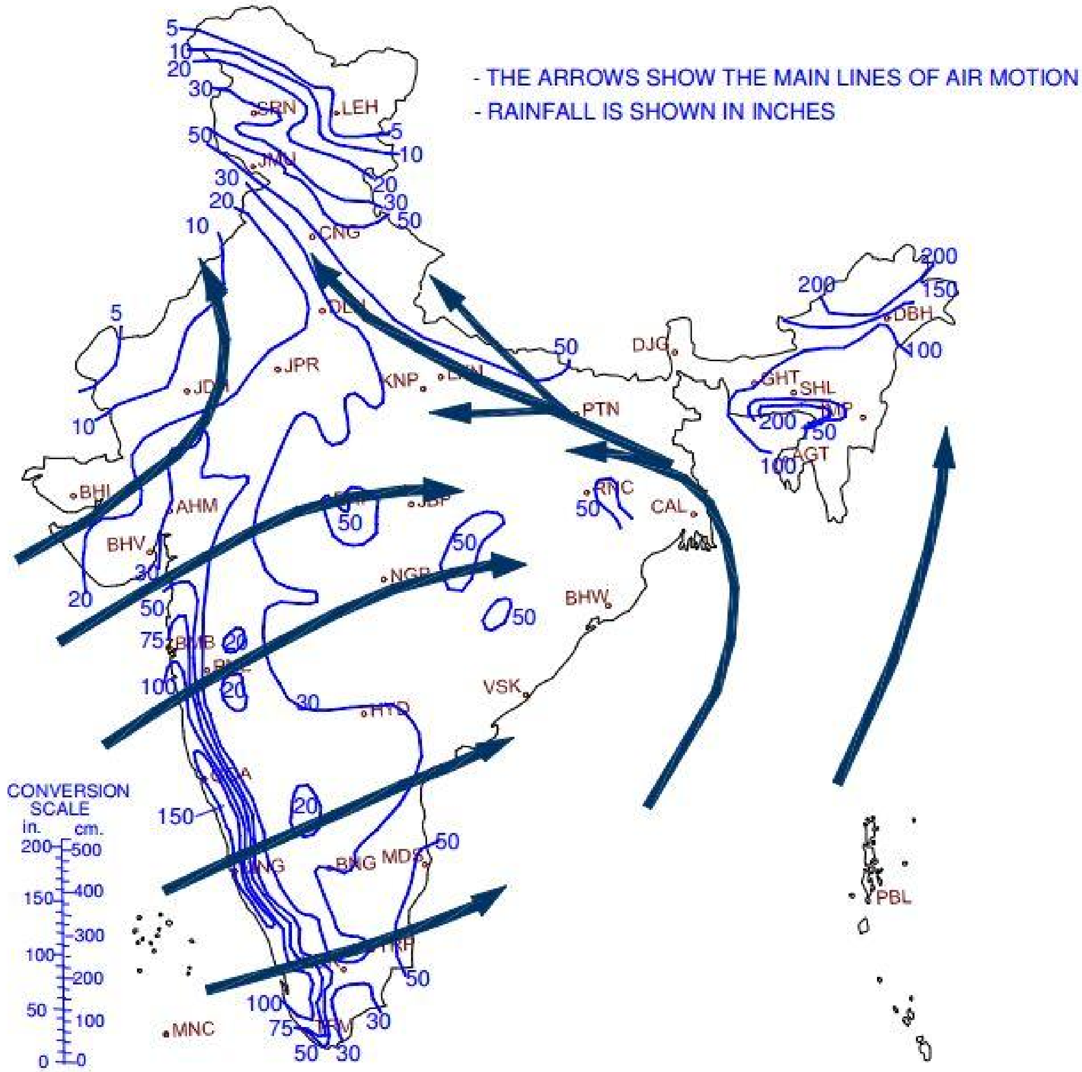
5. Maximum temperature Isopleths in India



6. Minimum temperature Isopleths in India

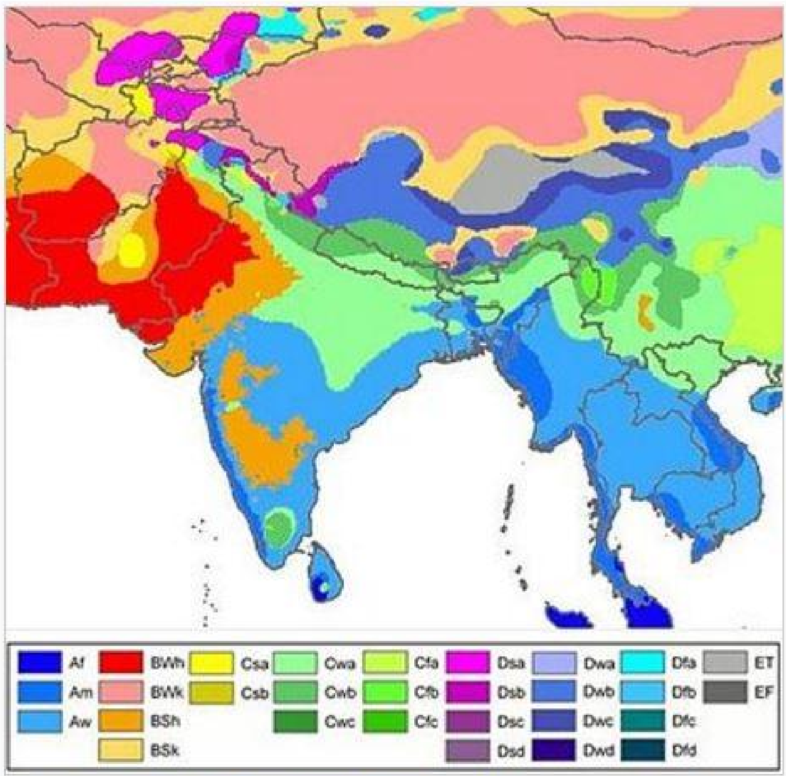


7. Average rainfall and main wind direction in India



(8 Bureau of Indian Standards, National building code of India 1983 – incorporating amendments No.1 and 2, Bureau of Indian Standards, New Delhi, 1990.)

8. Climate Classification of India (by Peel, M. C., Finlayson, B. L., and McMahon, T. A. (University of Melbourne) Hydrology and Earth System Sciences- Updated world map of the Köppen-Geiger climate classification - in 2007)

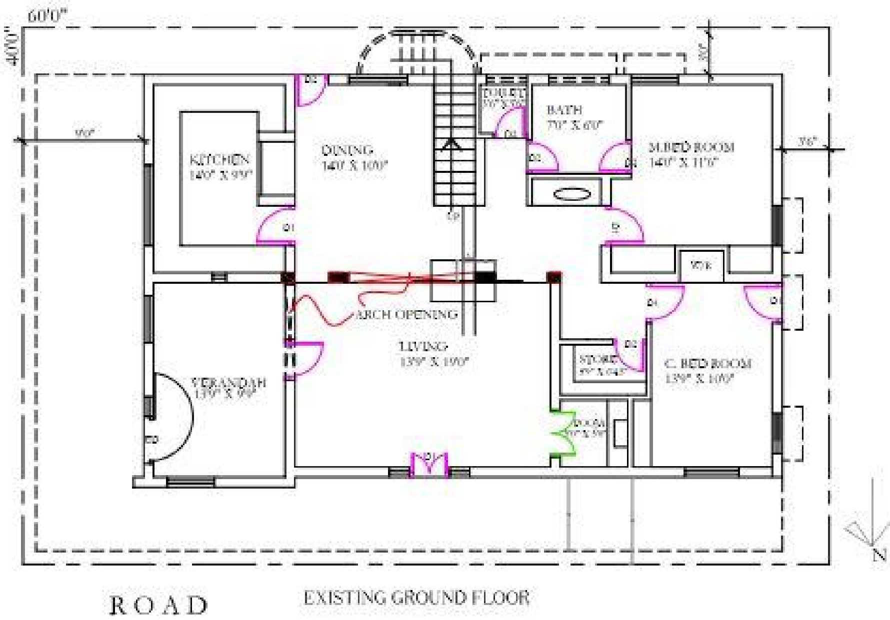


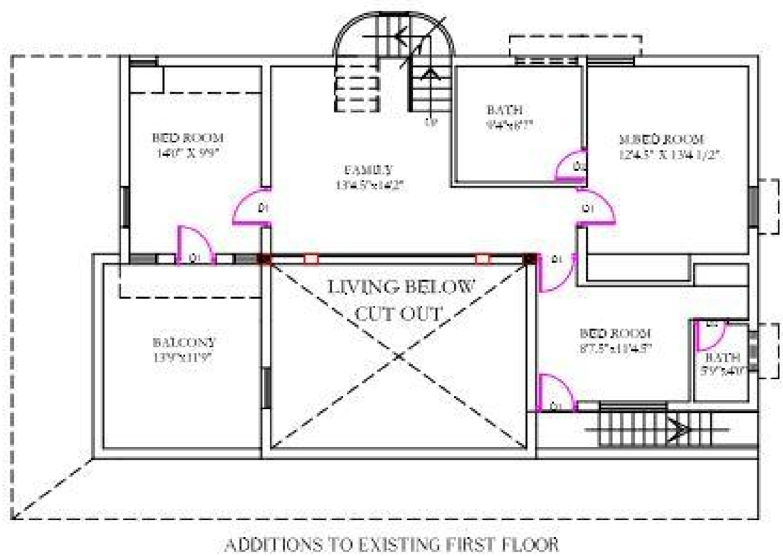
India's Köppen climate classification map[1] is based on native vegetation, temperature, precipitation and their seasonality.

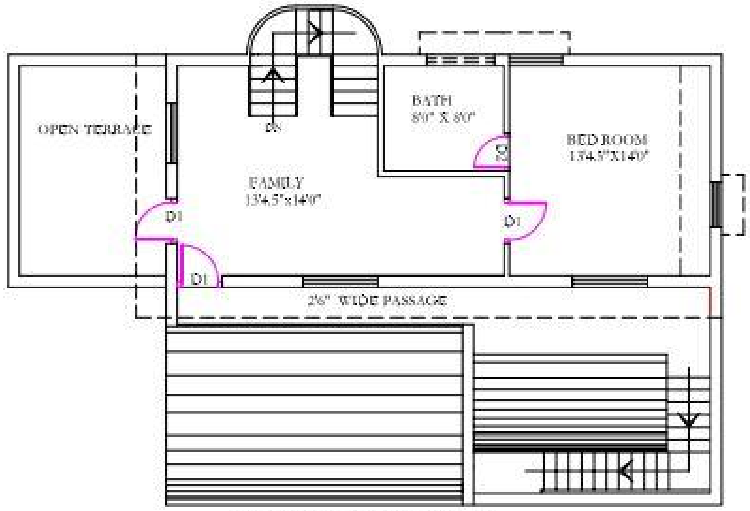
- (Af) Tropical rainforest
- (Am) Tropical monsoon
- (Aw) Tropical savanna, wet & dry
- (BWh) Hot desert
- (BWk) Cold desert
- (BSh) Hot semi arid
- (BSk) Cold semi arid
- (Csa) Mediterr. dry, hot summ.
- (Cwa) Subtropical humid summ, dry winter
- (Cwb) Subtropical highland, dry wint
- (Cfa) Subtropical humid summ (no dry)
- (Dsa) Continental hot summ
- (Dsb) Continental warm summ
- (Dwb) Continental dry wint
- (Dwc) Contin subarctic, dry wint

APPENDIX – B

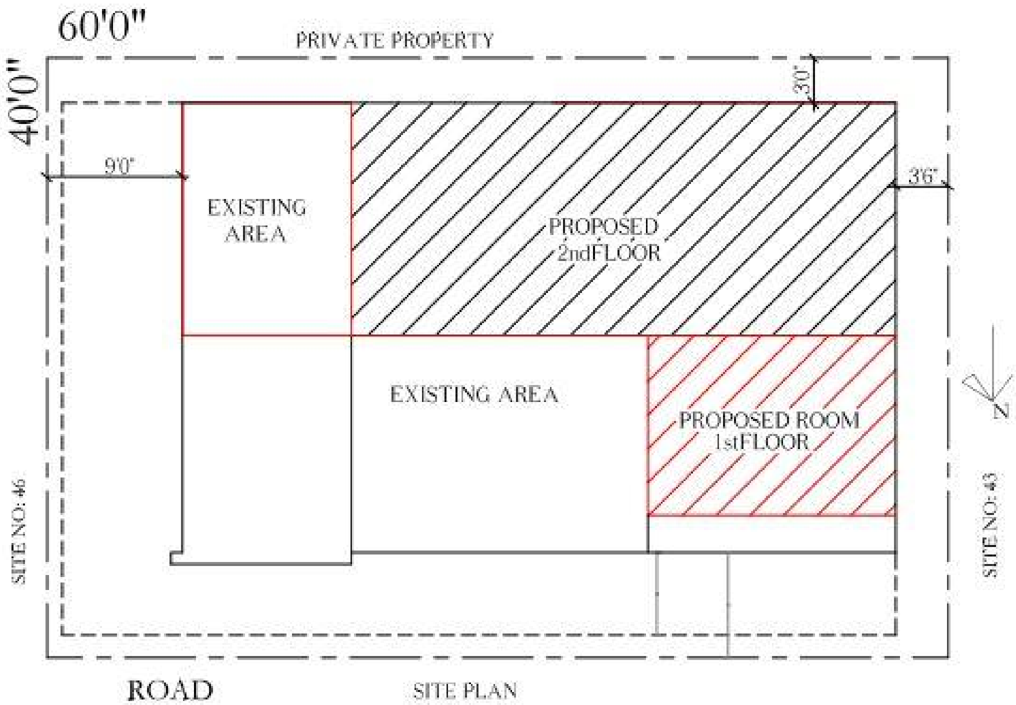
Drawings of the cast study dwelling





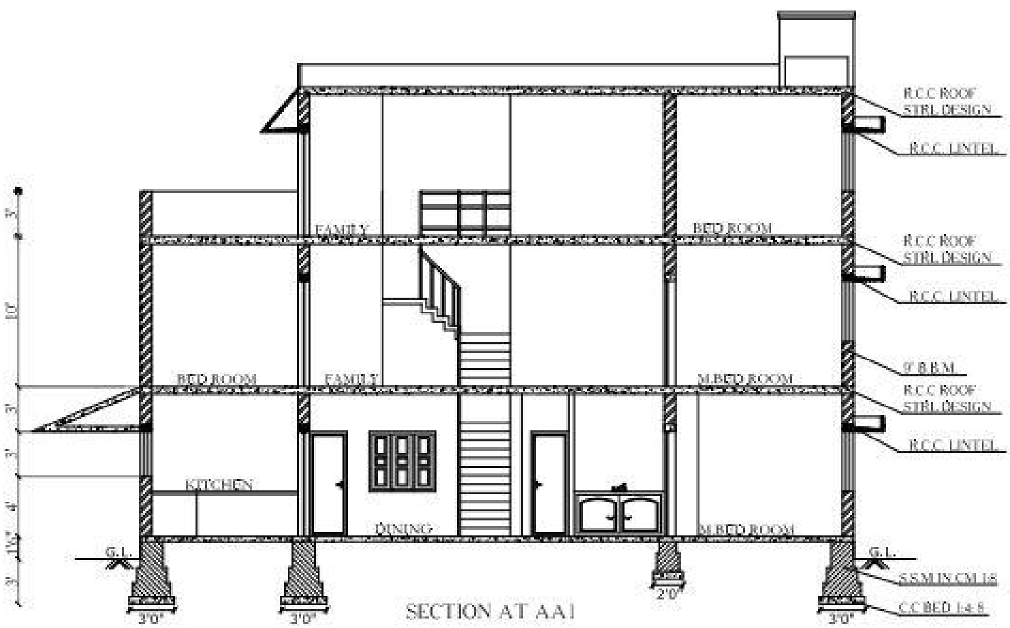


PROPOSED SECOND FLOOR



SITE PLAN

FRONT ELEVATION

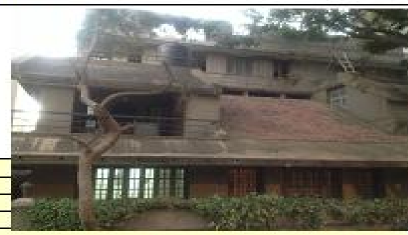


SECTION AT AA1

APPENDIX – C

PHPP result

Passive House verification



Building:	Detached Residence
Street:	8th Main, Horamavu Main Road, Banaswadi
Postcode / City:	560043 - Bangalore
Country:	India
Building type:	Detached
Climate:	Horamavu, Bangalore
Altitude of building site (in [m] above sea level):	729
Home owner / Client:	Dharmaraj S Balla
Street:	8th Main, Horamavu Main Road, Banaswadi
Postcode/City:	560043 - Bangalore
Architecture:	Balla Associates
Street:	8th Main, Horamavu Main Road, Banaswadi
Postcode / City:	560043 - Bangalore
Mechanical system:	Balla Associates
Street:	8th Main, Horamavu Main Road, Banaswadi
Postcode / City:	560043 - Bangalore

Year of construction:	1990	Interior temperature winter:	21.0	°C	Enclosed volume V_e m³:	885.0
No. of dwelling units:	1	Interior temperature summer:	30.8	°C	Mechanical cooling:	no
No. of occupants:	8.5	Internal heat sources winter:	2.1	W/m²		
Spec. capacity:	204 Wh/K per m² TFA	Ditto summer:	2.1	W/m²		

Specific building demands with reference to the treated floor area

				Requirements	Fulfilled?*
	Treated floor area	413.2	m²		
Space heating	Heating demand	0	kWh/(m²a)	15 kWh/(m²a)	yes
	Heating load	0	W/m²	10 W/m²	yes
Space cooling	Overall specif. space cooling demand	25	kWh/(m²a)	45 kWh/(m²a)	yes
	Cooling load	7	W/m²	-	-
	Frequency of overheating (> 30.8 °C)	1.4	%	-	-
Primary energy	Heating, cooling, auxiliary electricity, dehumidification, DHW, lighting, electrical appliances	100	kWh/(m²a)	120 kWh/(m²a)	yes
	DHW, space heating and auxiliary electricity	22	kWh/(m²a)	-	-
	Specific primary energy reduction through solar electricity	48	kWh/(m²a)	-	-
Airtightness	Pressurization test result n_{50}	0.6	1/h	0.6 1/h	yes

* empty field: data missing; '-': no requirement

Passive House?	yes

We confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this application.

Name:		PHPP Version 8.5	
Surname:		Issued on:	
Company:		Signature:	

PHPP, Verification v7.PHPP_EN_V8.5_dwelling_bangalore_india_Apr2016_MScDissertation_ChetnaDharmarajBalla.xlsm

PHPP - Base case

Passive House verification

Building:	Detached Residence						
Street:	8th Main, Horamavu Main Road, Banaswadi						
Postcode / City:	560043 - Bangalore						
Country:	India						
Building type:	Detached						
Climate:	Horamavu, Bangalore				Altitude of building site (in [m] above sea level):	729	
Home owner / Client:	Dharmaraj S Balla						
Street:	8th Main, Horamavu Main Road, Banaswadi						
Postcode/City:	560043 - Bangalore						
Architecture:	Balla Associates						
Street:	8th Main, Horamavu Main Road, Banaswadi						
Postcode / City:	560043 - Bangalore						
Mechanical system:	Balla Associates						
Street:	8th Main, Horamavu Main Road, Banaswadi						
Postcode / City:	560043 - Bangalore						
Year of construction:	1990	Interior temperature winter:	21.0	°C	Enclosed volume V_e m³:	885.0	
No. of dwelling units:	1	Interior temperature summer:	30.8	°C	Mechanical cooling:	no	
No. of occupants:	8.5	Internal heat sources winter:	2.1	W/m²			
Spec. capacity:	204 Wh/K per m² TFA	Ditto summer:	2.1	W/m²			

Specific building demands with reference to the treated floor area

				Requirements	Fulfilled?*
	Treated floor area	413.2	m²		
Space heating	Heating demand	0	kWh/(m²a)	15 kWh/(m²a)	yes
	Heating load	5	W/m²	10 W/m²	yes
Space cooling	Overall specif. space cooling demand	51	kWh/(m²a)	45 kWh/(m²a)	no
	Cooling load	36	W/m²	10 W/m²	no
	Frequency of overheating (> 30.8 °C)	12.1	%	-	-
Primary energy	Heating, cooling, auxiliary electricity, dehumidification, DHW, lighting, electrical appliances		kWh/(m²a)	120 kWh/(m²a)	
	DHW, space heating and auxiliary electricity		kWh/(m²a)	-	-
	Specific primary energy reduction through solar electricity		kWh/(m²a)	-	-
Airtightness	Pressurization test result n_{50}	10.0	1/h	0.6 1/h	no

* empty field: data missing; '-': no requirement

Passive House?	

We confirm that the values given herein have been determined following the PHPP methodology and based on the characteristic values of the building. The PHPP calculations are attached to this application.

Name:		PHPP Version 8.5	
Surname:		Issued on:	
Company:		Signature:	

PHPP, Verification v8.PHPP_EN_V8.5_dwelling_bangalore_india_Apr2016_MScDissertation_ChetnaDharmarajBalla.xlsm

Ventilation Data

Passive House planning: **VENTILATION DATA**

Building:	Detached Residence		
Treated floor area A_{TFA}	m²	413	(Areas worksheet)
Room height h	m	3.00	
Volume for ventilation (A_{TFA}*h) = V_V	m³	1240	(Worksheet Annual heating)

Type of ventilation system

x	Balanced PH ventilation	Please check
	Pure extract air	

Infiltration air change rate

Wind protection coefficients e and f		
Coefficient e for screening class	Several sides exposed	One side exposed
No screening	0.10	0.03
Moderate screening	0.07	0.02
High screening	0.04	0.01
Coefficient f	15	20

			For annual demand:	For heating load:					
Wind protection coefficient, e			0.07	0.18					
Wind protection coefficient, f			15	15	Net air volume for press. test	V_{n50}		Air permeability q_{50}	
Air change rate at press. test	n_{50}	1/h	0.60	0.60	885	m³		0.92	m³/(hm²)

			For annual demand:	For heating load:
Excess extract air		1/h	0.00	0.00
Infiltration air change rate	$n_{V,Res}$	1/h	0.030	0.075

Selection of ventilation data input - Results

The PHPP offers two methods for dimensioning the air quantities and choosing the ventilation unit. Fresh air or extract air quantities for residential buildings and parameters for ventilation systems can be determined using the standard planning option in the 'Ventilation' sheet. The 'Additional Vent' sheet has been created for more complex ventilation systems and allows up to 10 different ver Furthermore, air quantities can be determined on a room-by-room or zone-by-zone basis. Please select your design method here.

Ventilation unit / Heat recovery efficiency design

x	Standard design	(Ventilation worksheet see below)
	Multiple vent. units, non-res buildings	(Worksheet Additional vent)

Average air exchange	Average air change rate	Extract air excess (Extract air system)	Effective heat recovery efficiency unit	Specific power input	Heat recovery efficiency SHX
m³/h	1/h	1/h	[-]	Wh/m³	
372	0.30	0.00	75.0%	0.33	0.0%

SHX efficiency η^*_{SHX} 0%

Summer Ventilation Data

Passive House planning: **SUMMER VENTILATION**

Building:	Detached Residence		Building type:	Detached	
Building volume:	1240	m³	Heat recovery η_{HR}:	75%	
Max. indoor absolute humidity:	12	g/kg	Energy recovery η_{ER}:	0%	
Internal humidity sources:	2	g/(m²h)	Subsoil heat exchanger η^*_{SHX}:	0%	

Results passive cooling			Results active cooling		
Frequency of overheating:	1.4%	at the overheating limit ϑ_{max} = 31 °C	Useful cooling demand:	0.5	kWh/(m²a)
Frequency of exceeded humidity:	66.8%		Dehumidification demand:	24.7	kWh/(m²a)
max. humidity:	14.4	g/kg			

Summer background ventilation to ensure adequate air quality

Air exchange via vent. system with supply air:	0.39	1/h	HRV/ERV in summer (check only one field)		
			None		
			automatic bypass, controlled by temperature difference	x	
			automatic bypass, controlled by enthalpy difference		
			always		
Air exchange via extract air system	0.39	1/h	Specific power consumption (for extract air system)	0.20	Wh/m³
Window ventilation air exchange	0.14	1/h			

effective air exchange

	$n_{V,system}$ 1/h		η^*_{SHX}		η_{HR}		$n_{V,equi,fraction}$ 1/h
exterior $n_{V,e}$	0.390	*(1-	0%	)*(1-	0.75	) =	0.098
without HR	0.390	*(1-	0%	)		=	0.390
ground $n_{V,g}$	0.390	*	0%	*(1-	0.75	) =	0.000
without HR	0.390	*	0%			=	0.000

Ventilation conductance

	V_V m³		$n_{V,equi,fraction}$ 1/h		c_{Air} Wh/(m³K)			
exterior $H_{V,e}$	1240	*	0.098	*	0.33	=	39.9	W/K
without HR	1240	*	0.390	*	0.33	=	159.5	W/K
ground $H_{V,g}$	1240	*	0.000	*	0.33	=	0.0	W/K
without HR	1240	*	0.000	*	0.33	=	0.0	W/K
Infiltration, window, extract air system	1240	*	0.557	*	0.33	=	227.7	W/K

Additional Summer Ventilation for Cooling

Additional ventilation regulation

Minimum acceptable indoor temp. 27.0 °C

Type of additional ventilation

Window night ventilation, manual	Night ventilation value	0.05	1/h		
Mechanical, automatically controlled ventilation	Corresponding air change rate during operation, in addition to base air change	0.40	1/h	Controlled by (please cl	
				Temperature diff.	x
	Specific power consumption	0.50	Wh/m³	Humidity diff.	

PHPP, SummVent v7.PHPP_EN_V8.5_dwelling_bangalore_india_Apr2016_MScDissertation_ChetnaDharmarajBalla.xlsm

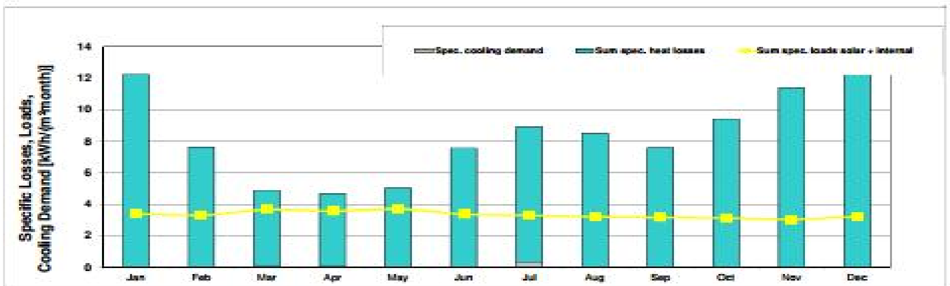
Specific Cooling Demand Data

Passive House planning: **SPECIFIC USEFUL COOLING DEMAND**

Climate: Koramavu, Bangalore
Building: Detached Residence

Interior Temperature: 20.8 °C
Building type: Detached
Treated Floor Area A_{TFA}: 413 m²

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	
Heating degree hours - Exter	7.3	4.9	3.5	3.1	3.3	4.4	5.0	4.9	4.5	5.5	6.6	7.6	61	kKh
Heating degree hours - Grou	6.1	3.7	2.2	2.2	2.5	3.8	4.4	4.3	3.8	4.8	5.8	6.5	50	kKh
Losses - Exterior	3875	2448	1556	1467	1668	2394	2743	2693	2404	2981	3592	4113	31933	kWh
Losses - Ground	-11	-7	-4	-4	-5	-7	-8	-8	-7	-9	-11	-12	-93	kWh
Losses summer ventilation	1191	717	446	442	490	741	827	838	741	925	1124	1281	9674	kWh
Sum spec. heat losses	12.2	7.6	4.8	4.6	5.0	7.6	8.6	8.5	7.6	9.4	11.4	13.0	100.5	kWh/m²
Solar load North	20	20	23	26	38	36	33	27	23	22	20	20	309	kWh
Solar load East	8	8	10	9	9	7	7	7	7	7	7	7	91	kWh
Solar load South	137	116	90	52	49	47	48	50	63	83	101	127	962	kWh
Solar load West	15	16	18	16	16	13	12	12	13	12	12	13	168	kWh
Solar load Horiz.	0	0	0	0	0	0	0	0	0	0	0	0	0	kWh
Solar load Opaque	581	614	741	746	787	662	615	585	578	526	484	520	7440	kWh
Internal heat gains	646	583	646	625	646	625	646	646	625	646	625	646	7602	kWh
Sum spec. loads solar + inter	3.4	3.3	3.7	3.6	3.7	3.4	3.3	3.2	3.2	3.1	3.0	3.2	40.1	kWh/m²
Utilisation factor losses	28%	43%	75%	76%	74%	44%	35%	38%	42%	33%	27%	25%	40%	
Useful cooling energy deman	0	0	27	28	23	0	124	0	0	0	0	0	202	kWh
Spec. cooling demand	0.0	0.0	0.1	0.1	0.1	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.5	kWh/m²
Specif. dehumidification dem	0.0	0.0	0.0	1.8	3.8	4.6	4.6	3.8	2.9	2.9	0.5	0.0	24.7	kWh/m²
Sensible fraction	100%	100%	100%	4%	1%	0%	6%	0%	0%	0%	0%	100%	2%	



PHPP, Cooling