Avdelningen för Byggnadsfysik
Examensarbete TVBH-5093
Lund 2016

# Improving indoor thermal comfort in residential buildings in Nepal using Energy Efficient Building Techniques

Isabell Borgkvist

LUND
UNIVERSITY

# Improving indoor thermal comfort in residential buildings in Nepal using Energy Efficient Building Techniques

Isabell Borgkvist

ISRN LUTVDG/TVBH-16/5093--SE(62)

Avdelningen för Byggnadsfysik
Institutionen för bygg- och miljöteknologi
Lunds tekniska högskola
Lunds universitet
Box 118
22100 LUND

# Abstract

Research within the field of energy efficient building techniques applied on Nepalese residential houses are a rare sight. Previous researchers have studied vernacular architecture in the country in aspects of climate-responsive design, but it is hard to find case studies on how material or architectural changes can improve the indoor climate in specific house types and climate zones in the country. This thesis aims to give examples of how passive energy efficient building techniques, such as use of insulation and passive solar heating, affect the indoor climate throughout the year in a one-storey Nepalese house.

Two locations on different altitudes are chosen to represent cold and warm temperate climate in the country. Eight interviews are performed with people living in similar houses in the chosen areas and one house of the interviewees is chosen for the indoor climate simulations. The indoor temperature and air quality is simulated for the warmest and coldest day of the year. Different constructional changes, like added insulation and changed orientation of the house, are made and the effects on the indoor climate are presented and analyzed.

The mean indoor operative temperature rose 5 °C in the chosen locations, Ghorepani and Dhulikhel, during the coldest winter day when insulation was added to the roof and outer walls and thermal bridges were improved. When adding two double glazed windows facing south the mean operative indoor temperature rose up to 10 °C the coldest winter day. Overall, the study shows that great improvements of the indoor thermal comfort in Nepalese houses can be achieved with the use of passive energy efficient building techniques.

# Acknowledgements

There are many people I would like to thank who contributed to make this thesis possible. First I want to express my gratitude to my supervisor Prof. Elisabeth Kjellsson who has given me valuable advice along the way and who encouraged me to take part in the collaboration between Lund University and the Katmandu University. I also particularly want to thank the Department of Mechanical Engineering at Kathmandu University and Dr. Hari Prasad Neopane and for his guidance and support during my time in Nepal.

Special thanks to Petter Wallentén who guided me in the indoor simulation work and to Akram Abdul Hamid for technical support. Thanks to my opponent Erik Larsen for interesting discussions during the oral examination.

Thanks to Bivek Baral for valuable input and help with weather data and Binaya Baidar for all the guidance and support during my first month in Nepal. Thanks to my dear friends at the KU Turbine Testing Lab; Atmaram Kayastha, Oblique Shrestha, Bidhan Rajkarnikar, Nirmal Acharya for all the good times and support during my time at KU.

I am very grateful to Binita Sedhai and her amazing family who treated me with care and generosity during my time in Nepal. Many thanks to Binita and Rakshya Thapa for all the good times and for their help in my fieldwork. Thanks to Maria Lagneby and BAS Nepal for your support and great hospitality.

Last I want to thank my family and friends for all the encouragement and support. Thanks to Mamma, Pappa, Mini, Emme, Ina, Emelie, Gäspan, Myran, Gärdet, Malmen, Stenen, Hannah, Viktor, Fansan and Högmodets Högborg (for the peace and quiet).

The financial support provided by the Swedish International Development Cooperation Agency (Sida) is gratefully acknowledged.

# Content

# 1 Introduction

This thesis is about studying the indoor thermal effects of applying energy efficient building techniques on a Nepalese one-storey house. There is little research on the area related to Nepal and the knowledge of energy efficient building technique are rare in the country. Previous studies have shown the indoor thermal benefits that come with climate responsive vernacular architecture, but there are few examples of indoor climate measurements or simulations. This introduction will present the background, objectives, research questions and limitations of the study.

## 1.1 Background

Nepal is facing a lot of development challenges (Nepal Environmental and Scientific Services, 2014). Nepal is one of the world's poorest countries, and it's estimated that 25 percent of the 27.8 million Nepalese people are falling below the international poverty line (US$ 1.25 per day). The country has increased the economic growth in the last decades mainly because of the expanding hydropower. But there is still much to be done to get the country out of poverty.

A major problem in Nepal is the power cuts (Nepal Environmental and Scientific Services, 2014). In dry season the regulated power cuts can be up to 18 hours a day and this causes great inconvenience. It's crucial for the development in the country to find smart and affordable solutions to this problem within the near future. In the entire country 70 % of the households have access to electricity indoors (CBS 2011). In the urban areas the amount is 96 % and 63 % in the rural areas. In the Kathmandu valley almost all have access to electricity in their houses, while only 21 % of the households in the rural- mid and far western hills areas have access.

The educational system has an essential role when it comes to sustainable development (EMF 2014). Many universities have focused on undergraduate education, with the outcome of a small amount of research in the higher education. The Higher Education Reform Project Nepal (2007-2014) is promoting research and innovation oriented curricula and many Universities are now working to develop their professional capacity for research and innovation.

This thesis is connected to a newly started cooperation between Lund University and Kathmandu University. The two universities are a part of the EU-project Erasmus+ Capacity Building of Higher Education, where Lund University is partnering Kathmandu University, with the goal on creating a Master's Program in Energy efficient building techniques.

## 1.2 Objectives

The objectives with this study is to give examples of how energy efficient building techniques, such as use of insulation and passive solar heating, can contribute to improve the indoor thermal comfort in Nepalese houses and the long-term sustainable development in Nepal.

**Main question**
In order to reach the objectives with the study, the main question is:
*How can small changes in construction, building design or choice of material, improve the indoor thermal comfort in Nepalese houses?*

**Sub-questions**
In order to answer the main question, following central sub-questions are:
*What building materials are commonly used in Nepal?*
*What are the typical house designs?*
*What's the climate like throughout the year in different regions?*
*Is the houses heated or cooled any time of the year?*
*Is any type of isolation used?*
*Is passive solar heating used in the regions?*

## 1.3 Limitations

No measurements of wind, temperature or relative humidity have been done in the specific buildings that are chosen for the simulations. The climate data used in the indoor climate simulations are created in Meteonorm. Since Nepal does not have many weather stations connected to Meteonorm the climate data used in the study is rather unreliable.

The study will not focus on moisture related problems that can come with more insulated constructions. If there will be condensation on surfaces it will be written in the report.

Indoor air pollution from open fire stoves will not be accounted for in the indoor simulations. This should be considered before implementing the suggested improvements in houses with open fire stoves. Regarding the ventilation and air quality, only the air change rate and carbon dioxide rate will be considered in the report.

# 2 Methodology

There are many different ways to perform scientific research, qualitative and quantitative methods are two different ways to collect information about a research area and both have advantages and disadvantages (Trost 2010). Qualitative methods have a more open structure and are often used to bring more understanding towards the studied area. Quantitative methods have a more statistic character and are used when analyses ought to be formal and generalized. This study has a case study structure containing a literature study, interviews and simulation work of a chosen building object. First some theory about the methods used will be presented and thereafter the structure of the thesis.

## 2.1 Case study

A case study is a way to study a phenomenon systematically and is suitable when an already existing phenomenon is to be examined further (Merriam 2010). To make sure that a case study is a suitable method for a study it is important to evaluate how the result might turn out and think of what questions should be answered. It is also important to constrain the area of the research in a suitable way to achieve the objectives of the study.

## 2.2 Interviews

Interviews are a good way of getting information about how people perceive or feel about different subjects (Lantz 1993). The interviews can be organized in different ways and be more or less open and standardized. The open interview have a high flexibility and detailed questions are not prepared in advance (Trost 2010). This technique is similar to a normal conversation and the interviewer only have certain areas in mind to direct the conversation for receiving the needed information.

The semi-structured interviews contain well prepared themes and questions but the order and formulation can be changed during the interview (Lantz 1993). This type, like the open interview, has a flexible character and the questions are not standardized.

The structured interview is highly standardized and usually contains a questionnaire (Trost 2010). The questions should be asked in the same order and same way so that the interviewees have a similar experience from the interviews. This makes the answers comparable and brings a higher reliability to the study.

The method used in the study is structured interviews with a questionnaire followed by a few open questions. The questionnaire is used to get the needed data for the indoor climate simulations and the open questions are asked to give the writer a broader understanding of the housing situation in the country.

## 2.3 Structure of the thesis

The study is made as a case study containing literature studies, interviews and simulations of a chosen building object. All the parts of the study are explained below in chronological order.

### Literature study

The first part of the study is the literature study. The aim of the literature study is to map out the different climate regions in Nepal and typical vernacular and modern architecture in the country. Common building materials and information regarding housing in Nepal are studied along with climate responsive building design strategies and passive energy efficient building techniques. These data and techniques are later used when working with the indoor climate simulations.

### Choice of location and building object

Nepal has five different climate zones, from sub-tropical climate in the southern regions to alpine and tundra climate in the high mountains (Shrestha 2007). Due to the time limit for the study only data from two climate types are used as weather data for the indoor climate simulations. The chosen locations represent warm and cold temperate climate and are chosen because they are quite easy to reach and have local weather stations.

### Creating climate files in Meteonorm

Hourly climate files are created in Meteonorm for the chosen locations. The monthly minimum and maximum temperatures are thereafter compared with climate data from the Department of Hydrology and Meteorology in Nepal. This is done to get an idea of the reliability of the Meteonorm files.

### Interviews

The interview questions are prepared based on the data needed for the indoor climate simulations. The interviews are performed as structured qualitative interviews and four interviews are performed in each chosen location. The people that are interviewed live in similar houses and the same questions regarding the house construction, indoor climate, energy consumption and number of occupants are asked to all the interviewees. The interview questions are found in chapter 6.2.

### Choice of building objects for simulation

When the interviews are completed, one of the houses of the interviewees are chosen and measured for the indoor climate simulations. The building material, thicknesses of building elements, room volumes and the placements of windows are mapped out and a model of the house is thereafter created in IDA ICE, which is the software used for the indoor climate simulations. IDA ICE is further described in chapter 5.1.

### Steady state energy calculation

To validate the building model a steady state energy calculation is made by hand and compared to the results in IDA ICE. This is done to ensure that the model is working correctly. The indoor temperature is fixed to 21 °C and the consumed energy to keep this temperature is calculated. To create the steady state condition in IDA ICE all the internal gains, furniture, air leakages, thermal bridges and direct solar radiation is taken away and ideal heaters are inserted in every zone to keep the indoor temperature constant. Synthetic winter weather for one of the locations is used for the calculation. If the result of the two energy calculations are reasonably close, the model are assumed to work correctly.

**Parameter study**

When the models are validated by the steady state calculations, a parameter study is made to contribute to the understanding of how the model are functioning. To understand how different parameters impact the model the steady state model is used as the base case and then one by one the parameters are added to the model. Example of added parameters are thermal bridges, different values of infiltration and internal gains. The synthetic winter weather is used for the first part of the parameter study and then the full year climate file is used.

**Indoor climate simulations**

When the parameter study is completed some constructional changes in the building model are made to improve the indoor thermal comfort. The changes are for example; adding insulation to the roof and walls, improving thermal bridges and changing the orientation of the house to increase passive solar heating. The indoor operative temperature and air quality in the dwelling zones are presented after each change, both for the coldest and warmest days of the year, to get an idea about the impact of the different changes.

**Simulations with an additional heating device**

Unfortunately the power of the firewood stove used in the study appeared to be whey too low. Therefore some additional simulations are made with a more powerful heating device to see how the indoor temperature is affected.

## 2.4 Reliability

There are great uncertainties within the climate files interpolated in Meteonorm. Since Meteonorm only have access to one weather station in Nepal the climate files are interpolated with data from the closest available weather stations, which sometimes are as far as 386 km away and on completely different altitude. To better understand the reliability of the climate data, the Meteonorm climate files are compared minimum and maximum monthly temperatures from the local weather station provided by the Department of Hydrology and Meteorology in Nepal. Unfortunately the complete set of data from the local weather stations needed for IDA ICE was not received, which lowers the reliability of the results in the study.

There are also uncertainties when preforming qualitative interviews. Since the interviews were performed in English with non-native English speakers there could easily be misunderstandings. During some of the interviews parts were translated by a fellow student from the Kathmandu University.  Since the questions were rather simple it was quite easy to understand when there were a misunderstanding. The questions where standardized and the received answers quite similar, which contributed to the reliability of the interviews.

Mistakes could have been made when measuring the houses chosen for the simulations. This could lead to a less correct building model, but the effect of this kind of mistake are assumed to be pretty low.

There are a lot of assumptions made when creating the simulation models in IDA ICE. Data regarding air leakages, emitted heat from cooking stoves and $U$-values of the building elements are not measured for the specific object but found in literature or assumed by the writer. Therefore the results should be taken as quite theoretical and further research regarding the materials, ventilation and indoor air pollution should be made to get more precise results.

# 3 Theory

This chapter will present some important theory for the study. First some facts about modelling and simulation of indoor climate in buildings will be presented, followed by energy efficient building techniques and climatic design. Data regarding climate and housing in Nepal will also be presented along with theory about heat transfer.

## 3.1 Modelling and simulation of indoor climate in buildings

There are many important parameters when it comes to indoor climate modelling. The modern simulation software are complex and include a huge amount of parameters. Some of the most important parameters are presented below along with the software that is used in the study.

**Local climate and surroundings**
The local climate and surroundings effect the energy balance of a house to a high extent (Abel & Elmroth 2013). The main factors are outdoor air temperature, humidity, wind speed and direction and solar and sky radiation. The closest surroundings, with shading trees and other houses, also affect the local climate conditions. It is important to include all these data when working with indoor climate simulations.

**The building envelope and ventilation**
The building envelope and ventilation are the most important parts of a house when it comes to indoor climate (Abel & Elmroth, 2013). The building envelope consists of all the building components that separate the indoors from the outdoors. Walls, windows, doors, roof and the floor on the ground level are all part of the building envelope. The building’s total transmission loss in a specific climate is a result of the quality of the building envelope. To maintain comfortable indoor conditions in low-energy buildings prevention of air leakages and the need of continuous insulation are of great importance.

**Internal gains and thermal mass**
The internal gains have an impact on the heat balance and are therefore included in the study. Internal gain is heat that is transferred to the indoor air from humans, electric devices, light, cooking devices and thermal mass (Abel & Elmroth 2013). The amount of heat that is transferred to the indoor air from humans depend on the activity level. The measurement used for this is called The Metabolic Equivalent of Task (met), which is defined as the ratio between a reference metabolic rate and the metabolic rate for a specific physical activity. One met is equivalent to 58.2 W/m$^2$ which is the amount of heat that a resting person is generating. A regular walk generates about 4.5 met.

Furniture and building elements can have high thermal mass which can have a great impact on the indoor temperature. Heat releases to the indoor air when the air temperature is lower than the temperature of the masses and if the masses are great they will minimize the temperature extremes in the building.

### Thermal comfort

Indoor thermal comfort can be measured in different ways (Abel & Elmroth 2013). One common way is to use the measurement operative temperature, which combines convective and radiant heat transfer to get a better criteria to describe comfort than the air temperature alone. The operative temperature is defined as the average air temperature and mean radiant temperatures from surrounding surfaces. This measurement is used in the study to describe the change in comfort rather than change in air temperature.

The amount of clothes that people wear also affect their experience of indoor thermal comfort (Abel & Elmroth 2013). The insulation capacity of clothes can be expressed in clo units. One clo is equivalent to 0.155 $m^2 \cdot K/W$ and heavy indoor clothing is set to a value of 1.5 clo. This unit is used when adding occupant data to the model.

### Indoor air quality

There are many different factors that affect the indoor air quality (Abel & Elmroth 2013). One way to measure the indoor air quality is measuring air age or air change per hour. Air age measures how long an average air molecule has spent in a building (EQUA 2013). If a zone is ventilated by outside air only, and is in steady state, the air age is equivalent to 1/air changes per hour (ACH). Air change per hour is defined as the volume of air that is added or removed from a space, like a room or a house, divided by the volume of the space. It is a measure of how often the air within a space is replaced.

The carbon dioxide rate is another measurement within the category of indoor air quality. It measures indoor air pollution generated by humans in the unit ppm, meaning Part per Million (Abel & Elmroth 2013). Human activity is often the largest contributor of particle pollutants and gas pollution, like carbon dioxide, unless there is an open fire place indoors. The carbon dioxide rate is easy to preform and is therefore a convenient way to measure the indoor air pollution generated by humans. The World Health Organization (WHO) has stated that the carbon dioxide rate should not be higher than 1000 ppm. This level is used as a reference level during the simulation when working with the natural ventilation through windows and openings.

### Meteonorm

Meteonorm is a global meteorological Database made by the Swiss company Meteotest (Meteotest 2016). It is used as a reference for solar energy applications, building design, heating and cooling systems. It is based on 8325 meteorological stations worldwide and five geostationary satellites. Meteonorm contains monthly climatological means for global radiation, ambient air temperature, humidity, precipitation, sunshine duration, wind direction and wind speed.

When the climate files are created in Meteonorm the locations are defined with coordinates for latitude and longitude, altitude, time zone and the surrounding situation. The meteonorm 7 climate data is used and the chosen temperature period is 2000-2009. Corrected global radiation data, excluding horizon effects are used and the chosen radiation period is 1991-2010. The IDA ICE format and hourly values are chosen for the climate files. The Meteonorm climate files are then compared with mean monthly minimum and maximum temperatures provided by the Department of Hydrology and Meteorology in Nepal.

**IDA**

The program IDA Indoor Climate Energy (ICE) is a simulation tool used to study the indoor climate and the energy consumption for a building (EQUA Simulation AB 2013). The indoor climate can be studied for one or several zones within the building and it's possible to model the building, it's systems and controllers. The program handles air handling systems, shade from the surroundings, weather data files and there are predefined components and parameter objects that can be loaded from a database 2D and 3D CAD files and models generated by, e.g. Revit, AutoCAD and MagiCAD can be imported to the program. In this study no air handling systems are used and the main focus is the indoor temperatures and air quality.

## 3.2 Energy efficient building techniques and climatic design

Passive techniques were ones the only way to cool buildings, while burning wood or coal was used for heating (Rosenlund 2001). The technical development have now made it possible to ignore the climate but there are still many good reasons to use passive techniques, both economically and from an environmental and sustainable point of view. Climatic design is therefore a key to achieve a comfortable and healthy indoor climate in a sustainable way. Nowadays “passive techniques” include even hybrid techniques such as low-energy systems that contain pumps and fans if the relation between energy input and output, Coefficient of Perforemance (COP), is high. The passive system often has multiple uses and ususally includes essential parts of the construction. Windows are an example of this; it can provide light and ventilation but also heat through solar gain.

The surroundings of a building also affect the indoor environment (Rosenlund 2001). The microclimate with its topography, vegetation, water and surrounding buildings are inputs needed for calculations concerning the indoor climate. Factors that should be taken into account are: sunlight and shadow, wind and wind shelter, temperature and humidity (Block & Bokalders 2009). In the climatic design process it is important to have a good working methodology to achieve a functional building and a good indoor climate (Rosenlund 2001). When the first data is collected and sketches are made, it is crucial to focus on the solar control, overall insulation properties and ventilation principles. After this, the individual building elements can be optimized.

To create an energy efficient building in cold climates, it's important to enclose a big volume with the smallest amount outer wall as possible (Block & Bokalders 2009). In theory the best shape is a sphere, but it's hard to utilize when it comes to buildings. Small individual houses could therefore have the shape of a cube or octagonal, both with hipped roofs, to get close to the optimized sphere form. In multi-storey buildings and apartment blocks outer walls and roof areas are effectively reduced. An apartment blockhouse can for example have only one outer wall.

To minimize energy losses it's possible to divide the house into zones where different temperatures are desired (Block & Bokalders 2009). In cold climates it's smart to place a pantry, wood shed or storage area along the northern façade and a glassed porch on the southern. This reduces the amount heat that needs to be added to the house for a comfortable indoor climate. In uninsulated houses, different rooms can be strategically placed to use the different temperatures that come with the different cardinal directions.

### Passive heating

In buildings you get free heat from people, household electricity and solar irradiation (Block & Bokalders 2009). It is good to have the rooms connected openly to spread this heat, an example of this is an internal stair case which lets the air flow between the floors. To distribute the heat over time, it is possible to take advantage of heavy materials and their ability to accumulate heat. The heat storage capacity of the material and its thermal conductivity, how fast the heat will penetrate the material, will affect the outcome. When it comes to daily storage within thermal mass, the heat will only penetrate a maximum of 10 cm of a massive material. Water can also be used as a heat accumulator that can be put in a tank. Nowadays there are also phase changing materials on the market that can be built into building elements who can store even more heat, for example Glaubersalt, but this is a very expensive alternative.

Utilizing passive solar energy can be done in four different ways (Block & Bokalders 2009):

1. Direct radiation, with windows facing south-east to south-west
2. Indirect radiation, through a glassed greenhouse or other facing the south. The heated glassed room is then connected to the main building with a door, window or a valve
3. Via a solar air collector
4. Through a heavy, black painted, wall construction that is glassed on the outside

When utilizing solar irradiation, by having windows or glassed parties facing the south, it can get to warm during the warmer season (Block & Bokalders 2009). It is therefore important to think about different shading possibilities like eaves, balconies, awnings, blinds, shutters or trees that has shading leaves during the warm season but loses them during winter when the solar irradiation is wanted. It is important to know the solar angels for the different seasons to be able to design fitting eaves and awnings.

### Passive cooling

In warm regions it is important to design the buildings so that uncomfortable temperatures are avoided as far as possible (Block & Bokalders 2009). The building should be cut off from direct sunlight as much as possible and the windows should be shaded. The shape of the building, the surface structure and colour affect the amount of heat that is absorbed by the building. A large façade facing south gets heated a lot compared to a dome that only has a small area facing the sun. A light surface does not get as warm as a dark one and an insulated wall prevents some of the heat from entering the house.

In a region where it is hot during the day and cold during the night, it is possible to use thermal mass through heavy building materials to get a more comfortable indoor climate (Block & Bokalders 2009). The heavy structure will then be cooled during night-time and the stored cold will help to cool the indoor climate during the warm day.

Another example on how to shade buildings effectively is to build dense, with small spaces between the houses so that they shade each other (Rosenlund 2001). Another is to have large overhanging eaves.

In some climates the only way to cool oneself is by air drafts (Block & Bokalders 2009). It is then important to design the houses so that they are easily ventilated, with open planning and windows that are easily opened.

Evaporation and dehumidification can also be used to cool buildings down (Block & Bokalders 2009). Depending on if the climate is dry or humid, either of them is more suitable. In a warm-humid climate dehumidification can be used passively with salt that absorbs moister and then dries in the sun.

Experiments in warm humid climates have shown that green vegetation on roofs and walls can decrease the temperature in the walls and roofs with 3 °C - 4 °C (Block & Bokalders 2009). It is also possible to take advantage of the large heat radiation against a clear night sky with a small rooftop basin that is covered during daytime. There are also steel sheets coated with a selective surface with the property to have a great reflection and emission of heat.

## 3.3 Climate and demography

Nepal has a great variety in climate because of it's diverse topography (CBS 2014a). The tropical southern parts of the country, called the Terai region, have warm and humid sub-tropical climate. The mid-land regions have temperate climate with generally pleasant temperatures except for the cold winter nights. The higher mountain regions in the north have alpine to arctic tundra climate with very low mean temperatures.

The seasons in Nepal are divided into two or four main parts. Shrestha 2007 defines the main seasons as winter and summer, with the subdivision of wet and dry period in summer. Winter lasts from October to March and summer from April to September. Other defines Nepal's main seasons as spring from March to May, summer from June to August, autumn from September to November and winter from December to February (CBS 2014a). Spring is a rather cloudy season with occasionally rains and has gradually rising temperatures until the monsoon arrives. During summer the monsoon sweeps up from Indian releases most of it's rains in the Terai region, mid-land region and the lower altitudes of the Himalayas. Autumn is known for it's pleasant temperatures and clear skies. Winter brings generally lower temperatures in the mid-land regions and higher altitudes, but the subtropical regions are rather warm year around.

The climatic zones shown in table 3.1 are based on data from Shrestha 2007.

*Table 3.1: Climatic zones in Nepal*

| Climatic zone | Altitude [m] | Mean temperature [°C] | |
|---|---|---|---|
| | | Winter | Summer |
| Sub-tropical | 0-1200 | 15 | >30 |
| Warm temperate | 1200-2100 | 10 | 24-30 |
| Cold temperate | 2100-3300 | <5 | 20 |
| Alpine | 3300-5000 | <0 | 10-15 |
| Tundra | Above 5000 | <0 | <0 |

The Terai region have the greatest population density of all the regions in the country (CBS 2014b). The main part of Nepal’s population live in the southern and mid-land regions that have sub-tropical, warm temperate and cold temperate climate.

### 3.3.1 Climate-responsive design strategies for Nepal

To get a greater understanding of the climatic conditions and climate-responsive building design applied in Nepal, this sub-chapter will present data from a study made by Bodach, Lang & Hamhaber 2014. This study is about vernacular architecture in different climate zones in Nepal in aspects of climate-responsive building design. The coldest climate zone, tundra climate, is not included in the study. The following theory will be based on this article.

**In sub-tropical climate**
Air movement is crucial for creating a comfortable indoor climate in sub-tropical areas (Bodach, Lang & Hamhaber 2014). Cross or stack ventilations or other provision for air movement is recommended in this areas. Rooms may advantageously be allocated single-banked, which means that the room have at least two outer walls which enables more posibillities for natural ventilation. The house should also be oriented with the long axis east-west to minimize passive solar gains in the warm season. Shading devices should be used for windows and other openings in summer and the amount of openings should be about 20 % - 40 % of the outer wall area. Well insulated light roofs are recommended. Light wall construction are recommended for the monsoon season, though high thermal mass with night ventilation could bring thermal comfort in the dry summer period. In winter the sun shading devises should be taken down if necessary, to get solar passive heating in winter. Rainwater drainage and other ways to protect the buildings for heavy rains should be used.

**In warm temperate climate**
Active solar heating or other heating facilities might be needed in December and January, but for the other cool months solar radiation and thermal mass could be efficient for having a comfortable indoor temperature in areas with warm temperate climate (Bodach, Lang & Hamhaber 2014). The longer façade should face south and have medium sized openings, this will generate the needed solar heat gains in winter. In summer these openings should be shaded to avoid overheating in summer. There are different opinions regarding the effects of high thermal mass in these areas. Some recommend heavy outer and inner walls and a light and well-insulated roof, while others implies that there is only positive effects of thermal mass in April and May, when the thermal mass balances the temperature swing. Air movement is needed in summer and allocated single-banked rooms and possibilities for natural ventilation should be counted for in the building design. Rainwater drainage and other protection from heavy rains should be used.

**In cool temperate climate**
The use of solar radiation is of great importance in cool temperate climate (Bodach, Lang & Hamhaber 2014). During the cooler half of the year active solar or other way of heating is needed. A more compact building design is recommended than in the warm temperate climate, so that less space needs to be heated. The nights will be especially cold, but passive solar heating combined with thermal mass could reduce the need for active heating. The ideal strategy for this would be to have heavy floors and walls with a time-lag longer than 8 hours that are passively heated by the sun during the day. Openings should be of medium

size and air movement is needed from June to September to avoid too high temperatures during the day. Rainwater drainage and other protection from heavy rains should be used in these areas.

**In alpine climate**
In the colder drier areas of Nepal the need for active heating should be from October to April (Bodach, Lang & Hamhaber 2014). A compact building layout is preferable and small openings, about 15 % - 25 % of outer walls, is recommended. The rooms should be double banked with possibilities to create air movement when needed in summer days. To balance the large temperature differences between day and night, internal and external walls should have high thermal mass that can absorb the solar passive heat gains. Heavy roofs with a time-lag of more than 8 hours are the best option in alpine climate. Protection from heavy rains is not needed here.

## 3.4 Households and housing

To better understand the housing situation in Nepal, and enable finding representative building objects, statistics regarding households and housing in Nepal are studied.

**Household members**
According to the Central Bureau of Statistics (CBS) 2011 the average number of members in a household in Nepal was 4.9 from 1996 to 2010. The lowest household size, of 4.1 persons, is found in the Kathmandu valley while the highest number of 5.7 persons is found in western rural Terai (CBS 2011). The amount of households with four people or less has increased and the amount of households with five persons or more has decreased during this period.

**Number of rooms and area of dwelling**
The average number of rooms is 4.6 nationally, in urban households the number is 5.0 and in rural households 4.5 (CBS 2011). The average available space within the house is 56.2 $m^2$, with a small variety between rural and urban areas. The variety lies between the richest and poorest quintile of the households, with 67.2 $m^2$ respectively 43.7 $m^2$.

**Locally available building materials**
The access to wood and other organic materials varies with the climate conditions (Bodach, Lang & Hamhaber 2014). The Terai region contains mostly coarse, gravel and fine sediments and the rich alluvial soil brings a fertile agricultural land and dense forest with Sal trees, a spiecies of tree also known as Shorea robusta. Mud, sand, wood, thatch and other organic material are available in the region.

The Hilly region stones like schist, phyllite, gneiss, granite, limestone and slate are available. There is a lot of timber from the Sal and hill forests and production of vegetation-based materials, like thatch, is possible due to the climate and fertile land. The larger valleys provide lacustrine soil, accumulated sediment in a drained lake, used for brickmaking. By the river bench sand and gravel can be found. Rocks, stones and mud are found in the Mountain region. Due to the harsh climate organic materials are hard to find in these areas.

### Materials used in outer walls

When you look at the entire country the most common material used in outer walls are mud-bonded bricks or mud-bonded stones (CBS 2011). Other common building materials are presented in table 3.2.

*Table 3.2: The distribution of materials used in outer walls*

| Material | Percentage [%] |
|---|---|
| Mud-bonded bricks/stones | 48 |
| Concrete or cement-bonded bricks/stones | 26 |
| Wood and tree braches | 24 |
| Other | 2 |

In the urban area the proportion of households using cement-bonded bricks/stones or concrete is 61 % compared to 17 % in rural areas (CBS 2011). The Kathmandu valley has the highest proportion. The materials used for the dwelling walls can be directly associated with the household consumption. The richer households tend to use concrete or cement in a much larger extent than poorer households.

### Materials used for roofing

The most common materials used for roofing are tile or slate, galvanized sheet, concrete and straw/thatch, with the following distribution shown in table 3.3 (CBS 2011):

*Table 3.3: The distribution of materials used for roofing*

| Material | Percentage [%] |
|---|---|
| Tile or slate | 30 |
| Galvanised sheet | 28 |
| Concrete | 20 |
| Straw/thatch | 18 |
| Other | 3 |

The eastern and the western region have the highest use of galvanized sheet (CBS 2011). Tile or slate are more common in the far western and the central area and the use of straw or thatch is the highest in the mid-western development region. In the Kathmandu valley and other urban areas the use of concrete roofs are very high.

### Materials used for foundation

The materials used for foundation are mainly mud-bonded bricks/stones, wooden pillars, cement-bonded bricks/stones and concrete pillars, with the following distribution shown in table 3.4 (CBS 2011):

*Table 3.4: The distribution of materials used as foundation*

| Material | Percentage [%] |
|---|---|
| Mud-bonded bricks/stones | 49 |
| Wooden pillars | 21 |
| Cement-bonded bricks/stones | 14 |
| Concrete pillars | 13 |
| Other | 3 |

In the mountain region the use of mud-bonded foundations are about 86 %, in the hills region 68 % and the Terai region 28 % (CBS 2011). In the Terai region wooden pillars are the most common foundation material with 38 %. In the rural areas the use of mud-bonded foundation is 54 % while concrete pillars are the most used material in urban areas. The majority of the households have mud-bonded foundations, apart from the richest households.

**Access to electricity**
In the entire country 70 % of the households have access to electricity indoors (CBS 2011). In the urban areas the amount is 96 % and 63 % in the rural areas. In the Kathmandu valley almost all have access to electricity in their houses, while only 21 % of the households in the rural- mid and far western hills have access.

**Main fuel used for cooking**
The primary fuel used for cooking in Nepal is firewood (CBS 2011). This fuel is used in 64 % of the households while LPG (gas) is used in 18 % and cow-dung or agricultural waste is used in 14 % of the households. In the urban areas the amount using LPG is a lot higher than the national average and in the urban areas of the Kathmandu Valley nearly 93 % use LPG. The poorer quintile of the population tend to use firewood, cow-dung or agricultural waste.

**Stoves used**
Different types of stoves affect the indoor pollution rate and the health of the household members to a large extent (CBS 2011). Half of the households in Nepal use mud-stoves for cooking, 22 % use open fireplaces and 21 % use gas stoves.

### 3.4.1 Insulation

To map out the use of insulation in Nepal for the Erasmus+ Capacity Building of Higher Education project, a pre-study was made by Teleman 2016. Several architects and engineers were interviewed on the subject. The work is not published but some of the results are presented below to give an idea of the use of insulation in the country.

There are many reasons for insulating houses and one is to minimize health problems related to cold climates (Teleman 2016). The indoor climate in Nepal is rather poor when it comes to thermal comfort. Buildings are generally not insulated and people accept a great variety in indoor temperature, some people use electrical heaters and air conditioners, but to a small extent. Insulation could be very useful in the cold mountain regions but also in the flatter areas. The warm-humid areas of Terai could use roof insulation to lower the indoor temperature during sunny days. Buildings that are built the traditional way are usually well adjusted to the climate. Many houses were built with thick mud walls, which insulate well compared to bricks and concrete. The biggest problems concerning indoor temperatures usually occur when modern architecture and materials are used in climates that they weren’t meant for.

In urban areas it is hard to get an optimum south-facing plot with ample sunlight and there the use of insulation might be more of interest than on the countryside (Teleman 2016). Insulation might be of greatest use in public buildings, where the rooms are bigger and the free heat from kitchens and animals are small. Finding proper insulation for RCC (Reinforced Concrete Construction) framed buildings with burnt bricks could also be relevant, since this is a very popular house construction in the country.

Generally people don’t know why they should use insulation in their homes (Teleman 2016). The first step could be to make the architects aware and that public buildings are designed in an energy efficient way. Then awareness will spread to the broader public in time.

## 3.5 Heat transfer

All building materials have thermal resistance and thermal capacity (Rosenlund 2001). Density ($\rho$, kg/m$^3$), specific heat ($c_p$, Wh/kgK) and conductivity ($\lambda$, W/mK) are the three factors that affect these properties. The density of the material is very important, the lighter the material is the more it insulates, while a heavier material store more heat. When it comes to specific heat, a low specific heat means low heat storing capacity. Conductivity is the property of how a material conducts heat. Insulating materials have a low conductivity which means they have a low rate of heat transfer.

The thermal properties have influence on the time lag and attenuation when it comes to the temperature in a building (Rosenlund 2001). The time lag is the time it takes for the maximum surface temperature to transport from the outside to the inside of the construction and the attenuation is the amplitude of the inside to outside temperature. These two have a great impact on the indoor temperature.

Thermal absorption and thermal emittance are important surface properties for building materials (Rosenlund 2001). Absorptance is the ability to absorb short-wave visible light, which is related to colour. It is normal for white surfaces to have an absorptance value around 20 % and for black paint a common value is 95 %. Emittance is the heat radiation which is related to the surface structure. A normal emittance value for building materials are 85 % - 95 %, but shiny metal planes have about 10 % - 30 %. A material with low thermal emittance will radiate less long-wave heat back to the atmosphere than a material with high thermal emittance. Determining the thermal emittance of building materials is very useful when it comes to heat and cooling energy cost reduction in buildings.

### $R$-value

The thermal resistance ($R$-value) is another important factor when it comes to calculating energy efficiency for a building. For steady-state conditions, the thermal resistance for a single material layer is the relation between thickness and conductivity ($d/\lambda$). The total thermal resistance of a building element is calculated as the sum of the R-values for each layer of the element including the film resistance of the air layers close to the surface of the element. The outer film resistance is 0.03 m$^2$K/W to 0.04 m$^2$K/W depending on the wind and the inner film resistance is 0.11 m$^2$K/W to 0.16 m$^2$K/W for non-reflective materials, depending on positions and heat flow directions.

### $U$-value

The thermal transmittance ($U$-value) is often used in heat flow calculations (Sandin 2011). The definition of $U$-value is the amount of heat passing through a unit area of the structure per time unit, when the difference in air temperature on each side of the structure is one Kelvin. The heat flow (q) of a building element is therefore:

$$q = U \cdot (T_i - T_o) \qquad \text{W/m}^2 \qquad (1)$$

The manually calculated heat transfer is made using the equation (Sandin 2011):

$$Q = U \cdot A \cdot (T_1 - T_2) \qquad \text{W/m}^2 \qquad (2)$$

### Thermal bridges

A thermal bridge is a part of a construction which has significantly higher heat transfer compared to the surrounding materials (Sandin 2011). This results in an overall reduction of the thermal insulation of the construction. This leads to greater heat losses and increases the risk for condensation on cold surfaces within the construction. Different types of constructions comes with different types of thermal bridges and some can increase the heat losses, through an outer wall for example, with up to 50 %. This leads to a greater indoor discomfort and a greater need for added heat. Uniform thermal resistance and continuous insulation on the entire building envelope minimizes the thermal bridges.

# 4 Empirical data and analysis

In this chapter the results from the study will be presented along with the analysis of the results. The climate data for Ghorepani and Dhulikhel and the results from the interviews will be presented first, followed by results and analyze of the simulation work.

To give the reader an idea of the different house types in Nepal some pictures of houses in the country will be presented. Figure 4.1 to 4.6 are pictures taken of houses in the central Terai region, the central hills and the western mountains. These pictures can give some idea of how the house types in the mentioned areas can look like.

Houses made of dried bricks are very common in Nepal, especially in the Terai and Hilly regions. Figure 4.1 below shows a traditional house in Dhulikhel in the central hills. The walls are made of dried bricks and mud, the foundation of stones and rammed earth, floors are made of tree piles or/and bamboo covered with mud. The roof is usually maid of tiles but steel sheets are also common these days. Many of these type of houses were destroyed or damage in the strong earthquakes 2015.

*Figure 4.1: A traditional house in Dhulikhel made of dried bricks*

Another house type that is quite common in the Terai region is houses with walls made of sticks and clay with tile, straw or steel roofs. The houses with straw roofs are known as traditional Taru houses, Taru is an ethnical group in Nepal (Bodach, Lang & Hamhaber 2014). The houses are usually places on wooden pillars or a plint of stone or soil to protect them from flooding in monsoon season. Small windows shaded with large roof overhangs, trees and shaded porches provide shade needed during the hot season. Figure 4.2 shows two houses of this kind in the rural areas outside Chitwan. The steel roof on one of the houses makes it very warm inside during daytime but cools the room effectively during nighttime when the skies are clear according to the people in the area. People choose steel roofs mainly because of the very low maintenance work compared to a thatch roof, even though the extremely high day temperatures are avoided with the well insulating thatch roof.

*Figure 4.2: A traditional Taru house in Chitwan made of sticks and clay*

In the mountain areas the houses are mainly made out of mud-bonded stones with tile roofs. The villages in cool temperate climate usually have a denser settlement pattern (Bodach, Lang & Hamhaber 2014). Figure 4.3 below is taken in the village of Ghorepani.

*Figure 4.3: Houses in the village of Ghorepani*

Reinforced concrete constructions (RCC) with burnt bricks are a very common modern way to build houses in Nepal. These houses can mainly be found along the roads throughout the country and in the cities. It is mostly rich people who can afford to build this kind of house, since bricks, reinforcement and concrete are rather expensive materials. If done correctly the house becomes earthquake resistance. Many nepalese people give earthquake resistance a high priority after the 2015 earthquakes.

The RRC are also seen as a status symbol and many people seem to want this type of house in Nepal at the time of writing. Figure 4.4 shows a RCC house in Dhulikhel with a quite characteristic look when it comes to shape and the unpainted side walls with no windows and decorated front façade. This kind of building is mostly found in sub-tropical climate and warm temperate climate. In sub-tropical climate the room height is normally a couple of decimetres higher. Figure 4.4 shows a three-storey burnt brick house in Dhulikhel.

*Figure 4.4: A reinforced brunt brick house in Dhulikhel*

Concrete hollow blocks are a quite common modern building material in some areas in the country. Figure 4.5 below show a one-storey reinforced concrete block house that is being built outside of Pokhara.

*Figure 4.5: A house of concrete blocks under construction outside Pokhara*

Another way of building reinforced earthquake resistant houses is to build in compressed stabilized earth bricks, a technique used by some NGOs in Nepal. This way of building houses is used in poor rural regions and the bricks are made of a mixture of soil, sand and 8 % to 10 % cement and are produced by the people in the communities with the help of a machine that runs without electricity. Figure 4.6 is a picture of a current project in Maji Gaun in Sindhupalchowk where the organization Build up Nepal is working with villagers whose houses were destroyed in the earthquakes 2015.

*Figur 4.6: A house of compressed earth blocks under construction in Maji Gaun*

## 4.1 Climatic conditions

Many of the Nepalese districts contain climatic conditions from sub-tropical to alpine climate within the district. The elevation has a huge impact on the local climate, therefore the examples will only be representative for the chosen locations and not for the whole district.

Two locations are chosen to represent warm temperate and cold temperate climate and are marked out in the figure 4.7 below. The locations are Dhulikhel with the elevation of 1550 m and Ghorepani with the elevation of 2600 m.

*Figur 4.7: The chosen locations Ghorepani and Dhulikhel and their positions on the Nepalese map*

The weather data for these two locations are interpolated in Meteonorm and then compared with data from weather stations provided by the Department of Meteorology and Hydrology in Nepal. Monthly mean temperatures are calculated, using daily minimum and maximum temperatures for each month from the local weather station. These data are listed along with the monthly minimum and maximum temperatures from Meteonorm in table 4.2 and 4.4.

Due to a misunderstanding no climate data, except for precipitation, was available for Ghorepani. The data was therefore compared with weather data from Gurja Khani, a village at a level of 2530 m about 50 km west of Ghorepani.

### 4.1.1 Ghorepani

The climatic data for Ghorepani is presented in figure 4.8, 4.9 and table 4.1. The outside temperature varies from -12 °C to 25 °C and is shown in figure 4.8, where the dark green line show the daily maximum temperature and the lower line in lighter green shows the daily minimum temperature. The yearly precipitation is 367 mm, which is very low for

Nepal. Most of the rain falls from June to September and the monthly precipitation is shown in figure 4.9 where the red dots shows the amount of days with precipitation and the blue field shows the precipitation in mm.

Table 4.1 shows mean monthly and yearly values for temperature, relative humidity, wind speed, wind direction and precipitation. The average relative humidity is 67 % as it's highest in August, the mean wind speed is 2.1 m/s and is at the highest average speed in April and the lowest in August. The average wind direction is 271 °N and is quite similar throughout the year.

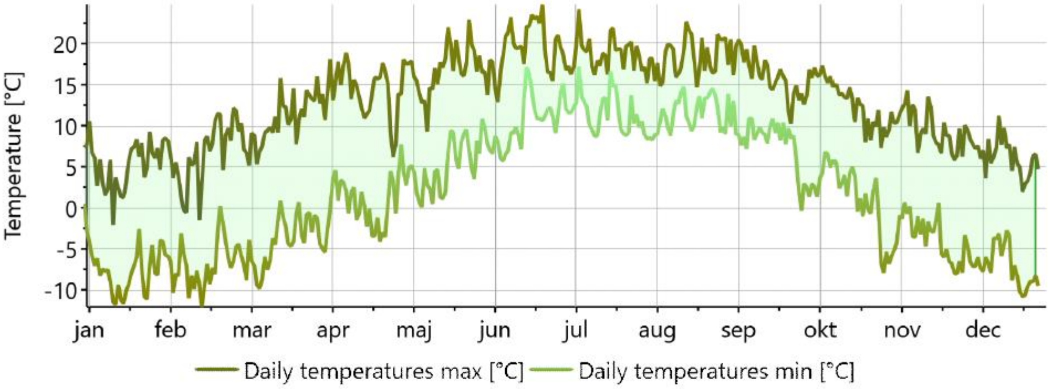

*Figure 4.8: Daily temperature for Ghorepani (2600 m) in the western hills. Figure created in Meteonorm.*

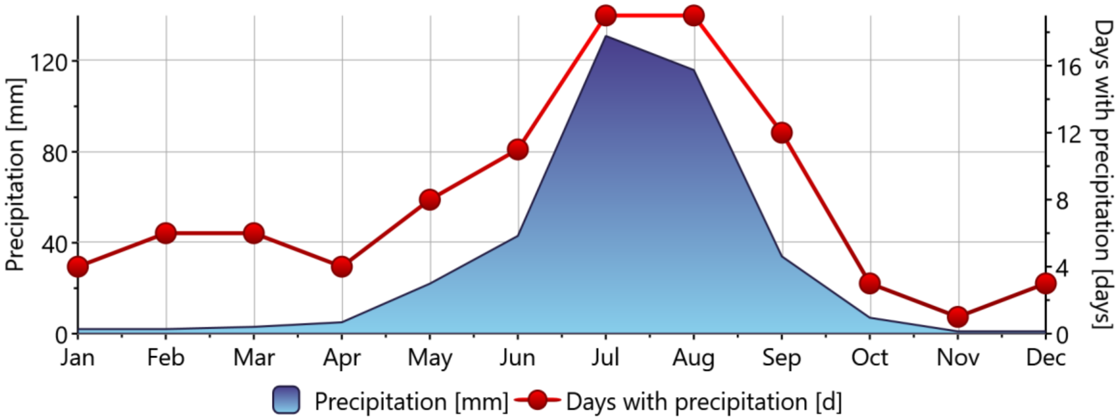

*Figure 4.9: Monthly precipitation for Ghorepani (2600m) in the western hills. Figure created in Meteonorm*

*Tabell 4.1: Mean monthly and yearly data for Ghorepani from Meteonorm*

| Month | Mean monthly temperature [°C] | Relative humidity [%] | Wind speed [m/s] | Wind direction [°N] | Precipitation [mm] |
|---|---|---|---|---|---|
| January | -3.6 | 32 | 2.4 | 273 | 2 |
| February | -2.2 | 30 | 2.9 | 273 | 2 |
| March | 1.3 | 34 | 2.9 | 273 | 3 |
| April | 5.5 | 36 | 3.1 | 273 | 5 |
| May | 9.6 | 43 | 2.6 | 273 | 22 |
| June | 13.9 | 51 | 1.9 | 273 | 43 |
| July | 14.4 | 61 | 1.7 | 257 | 131 |
| August | 13.5 | 67 | 1.4 | 257 | 116 |
| September | 11.9 | 59 | 1.5 | 273 | 34 |
| October | 6.1 | 41 | 1.7 | 273 | 7 |
| November | 0.6 | 37 | 1.6 | 273 | 1 |
| December | -2.6 | 31 | 1.6 | 273 | 1 |
| | | | | | |
| Year: | 5.7 | 44 | 2.1 | 271 | 367 |

When the precipitation for Ghorepani interpolated in Meteonorm is compared with local weather data from Gurja Khani the values from Meteonorm are about 50 % lower during the rainy season. This could be reasonable local differences but could also be a reason to assume that the amount of rain during rainy season could be larger than predicted in Meteonorm. The Meteonorm values are future values based on ten years of data from 1996 to 2005. The local data is from the year 2014 only.

The trends for the Ghorepani climate in general indicate a cold climate with low winter temperatures, low relative humidity and a low amount of rain. The wind speed is crucial for the natural ventilation of houses and if the daily variation is close to the average values in the table, the air change can be at a satisfying level.

The monthly minimum and maximum temperatures from Meteonorm are listed in table 4.2 with mean monthly values from 2014 from the local weather station in Gurja Khani. The monthly minimum and maximum temperatures from the 2014 climate file are calculated with the assumption that they are the mean of the daily extreme minimum and maximum temperatures. The monthly values from Meteonorm are rough estimations made from figure 4.8.

*Tabell 4.2: Monthly minimum and maximum temperatures for Ghorepani from Meteonorm and data from a local weather station in Gurja Khani*

| | 2014 Department of Meteorolog, Gurja Khani | | Meteonorm, Ghorepani | |
|---|---|---|---|---|
| Month | Minimum temperature (°C) | Maximum temperature (°C) | Minimum temperature (°C) | Maximum temperature (°C) |
| January | -1.1 | 16.5 | -7.5 | 5.5 |
| February | -3.6 | 16.4 | -7.0 | 7.0 |
| March | -3.7 | 16.1 | -4.0 | 12.0 |
| April | 2.3 | 20.9 | 2.0 | 15.5 |
| May | 9.0 | 23.9 | 6.0 | 16.5 |
| June | 9.5 | 24.3 | 11.0 | 20.0 |
| July | data missing | data missing | - | - |
| August | 11.4 | 23.4 | 13.0 | 18.0 |
| September | 8.5 | 23.2 | 6.5 | 16.0 |
| October | 5.8 | 21.3 | 1.0 | 12.5 |
| November | 1.1 | 17.9 | -4.0 | 9.0 |
| December | -0.9 | 19.0 | -7.0 | 6.0 |
| | | | | |
| Year: | 3.5 | 20.3 | 0.9 | 12.5 |

The Meteonorm climate file for Ghorepani shows generally lower temperatures than the 2014 data from the weather station in Gurja Khani. The largest difference is among the winter maximum temperatures. Here the Meteonorm climate file has a maximum temperature of 5.5 °C for January while the local station in Gurja Khani shows 16.5 °C. This difference is very high and might show that the Meteonorm file shows too low winter temperatures. Over all the lower temperatures can be reasonable due to the yearly variations but the temperatures for Ghorepani could also be assumed to be a low.

The data for Ghorepani from Meteonorm is the data that will be used for the simulations. The indoor temperatures that will come out from the simulations are assumed to be lower than the actual case. But the focus will be to find solutions for improved thermal comfort and the trends would be similar even if the temperatures are slightly lower.

### 4.1.2 Dhulikhel

The climatic data for Dhulikhel is presented in figure 4.10, 4.11 and table 4.3. The outside temperature varies from -5 °C to 35 °C. The monthly average relative humidity is 77 % as it’s highest in July and August. The mean wind speed is 0.9 m/s and is at the highest average speed in May and the lowest in November. The average wind direction is 270 °N and has the same direction throughout the year. The yearly precipitation is 965 mm and most of the rain falls from June to September.

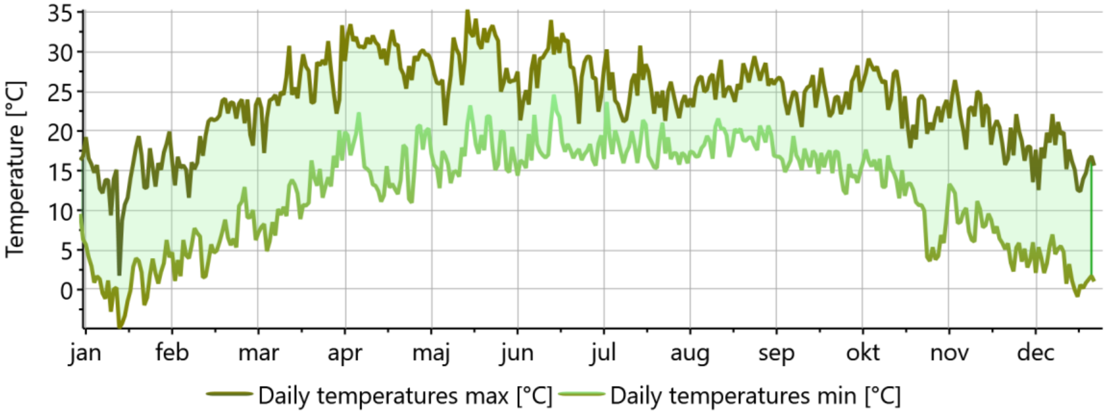

*Figure 4.10: Daily temperature for Dhulikhel (1550 m) in the central hills. Figure created in Meteonorm.*

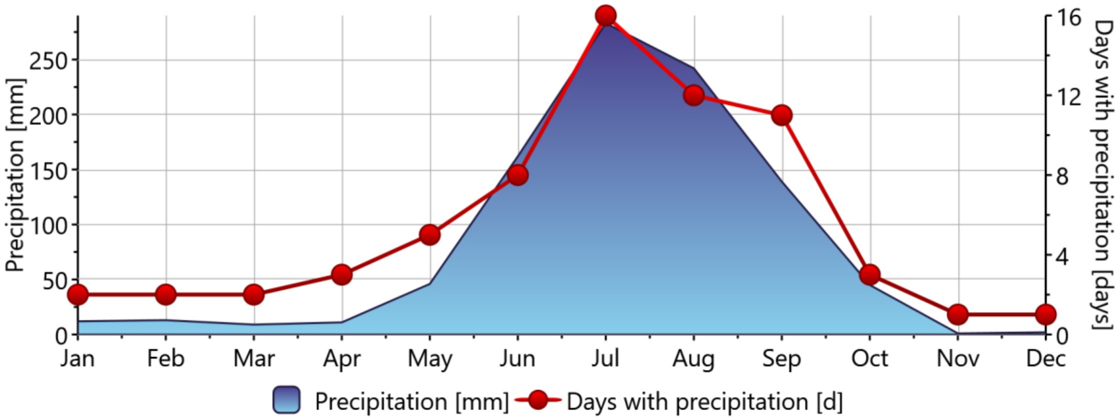

*Figure 4.11: Monthly precipitation for Dhulikhel (1550 m) in the central hills. Figure created in Meteonorm*

When the precipitation is compared with local weather data from the Kathmandu Airport (1337 m) 22 km from Dhulikhel, year 1981-2010 from the Department of Meteorology, the values from Meteonorm seems very low. For Kathmandu the average yearly precipitation is 1908 mm while only 965 mm for Dhulikhel. The monthly trends are similar but the amount of rain is about the double from May to September.

The mean monthly data for the Dhulikhel climate are shown in table 4.3 below. The trends indicate a warm temperate climate with a rainy season from June to September. The wind speed is at its highest during summer which correspond to the greatest need for ventilation. The mean wind direction is West throught the year.

*Table 4.3: Mean monthly and yearly data for Dhulikhel from Meteonorm*

| Month | Temperature [°C] | Relative humidity [%] | Wind speed [m/s] | Wind direction [°N] | Precipitation [mm] |
|---|---|---|---|---|---|
| January | 7.6 | 67 | 0.6 | 270 | 12 |
| February | 12.1 | 58 | 1.0 | 270 | 13 |
| March | 17.5 | 45 | 1.1 | 270 | 9 |
| April | 22.6 | 38 | 1.3 | 270 | 11 |
| May | 23.6 | 51 | 1.4 | 270 | 46 |
| June | 23.2 | 64 | 1.2 | 270 | 162 |
| July | 21.9 | 77 | 1.1 | 270 | 283 |
| August | 21.9 | 77 | 1.0 | 270 | 242 |
| September | 21.3 | 76 | 0.9 | 270 | 139 |
| October | 19.0 | 69 | 0.4 | 270 | 45 |
| November | 14.5 | 64 | 0.3 | 270 | 1 |
| December | 9.7 | 65 | 0.4 | 270 | 2 |
| | | | | | |
| Year: | 17.9 | 63 | 0.9 | 270 | 965 |

The monthly minimum and maximum temperatures from Meteonorm are compared with monthly mean values from the Kathmandu Airport in table 4.4. The temperatures for Dhulikhel are slightly lower than the temperatures at the Kathmandu Airport. This makes sense since the elevation of Dhulikhel is about 200 meters above the weather station at Kathmandu Airport. The two different data sources have the similar patterns when it comes to the yearly trends but the Meteonorm climate file have slightly larger differences among the maximum temperatures. The reason for this is unknown to the writer but the Meteonorm file has the temperature calculation for 2016 based on the year 2000-2009 while the used climate data from Kathmandu Airport is the mean of the temperatures from 1981-2010.

*Table 4.4: Monthly minimum and maximum temperatures for Dhulikhel from Meteonorm compared with local weather data from the Department of Meteorology*

| | 2014 Department of Meteorology, Dhulikhel | | Meteonorm, Dhulikhel | |
|---|---|---|---|---|
| Month | Minimum temperature (°C) | Maximum temperature (°C) | Minimum temperature (°C) | Maximum temperature (°C) |
| January | 2.4 | 19.1 | 0.0 | 15.5 |
| February | 4.5 | 21.4 | 6.0 | 19.5 |
| March | 8.2 | 25.3 | 11.5 | 26.0 |
| April | 11.7 | 28.2 | 15.5 | 30.0 |
| May | 15.7 | 28.7 | 17.0 | 29.0 |
| June | 19.1 | 29.1 | 17.5 | 27.0 |
| July | 20.2 | 28.4 | 18.0 | 25.0 |
| August | 20.0 | 28.7 | 18.5 | 27.5 |
| September | 18.5 | 28.1 | 16.0 | 24.5 |
| October | 13.4 | 26.8 | 12.5 | 23.5 |
| November | 7.8 | 23.6 | 6.5 | 20.0 |
| December | 3.7 | 20.2 | 3.5 | 18.0 |
| | | | | |
| Year: | 12.1 | 25.6 | 12.0 | 24.0 |

## 4.2 Interviews

The interviews are performed as structured qualitative interviews and focus on the house construction, occupant patterns and energy use. Eight persons from different households in the rural area of Ghorepani and Dhulikhel are asked the same questions formed to present the needed data for the simulation work in IDA ICE. The questionnaire and summarized answers are shown below.

### 4.2.1 Questionnaire

**The house**

- *What materials is this house made of?*
    - *Roof*
    - *Walls*
    - *Foundation*
    - *Floors*
- *How many floors and rooms are there in this house?*
- *Where is the kitchen situated?*

**Household members**

- *How many people live in this house?*
- *At what time during the day are people home?*
    - *In which rooms are they staying during daytime?*

**Indoor climate**

- *What's the indoor climate like throughout the year?*
    - *Temperature*
    - *Humidity*

**Energy consumption used for cooking, heating and cooling**

- *What energy source do you use for cooking?*
- *At what times during the day do you cook/is the fire lit?*

*How many hours?*
*Breakfast*
*Lunch*
*Afternoon*
*Dinner*

- *What energy source is used for heating the house/hot water?*
- *Which months do you use heating?*
    - *In which rooms?*
    - *At what time of the day?*
    - *For how many hours?*
    - *What power/effect? (electrical heater)*

- *How is the house cooled in summer?*
    - *Is any device is used (like fan, air conditioner, etc)?*
    - *Which months do you use this device?*
    - *In which rooms?*
    - *At what time of the day?*
    - *For how many hours?*
    - *What power/effect?*

**The environment**

- *How does the wind blow during different seasons?*
    - *Speed*
    - *Direction*
- *How does the wind blow during different times of the day?*
- *How is your house shaded during the hot season?*

### 4.2.2 Summarized answers

**Ghorepani**

The interviewees in the rural area of Ghorepani live is one-storey houses made of 300-400 mm mud-bonded stone walls with 15 mm - 20 mm tile roofs. The foundations are made of stones and rammed earth and the floor is made of soil. The kitchen is sometimes situated in the main living area where the family also sleeps and sometimes in a separated room. The number of occupants in the different households are 3, 4, 5 and 5. They usually eat at home three times a day but spent most of the daytime outdoors. Bedtime is usually from 9 pm to 6 am but varies with the light possibilities and power cuts.

The indoor climate is described as cold in winter and comfortable in summer. Nobody have nothing to say about the humidity nor problems with rain. All use firewood for cooking and cook three to four times a day 6-8am, 10.30am-12.30pm and 4pm-7pm, including some tea in the afternoon.

The interviewees heat their house to a small extent. They sometimes sleep close to the fire and keep it going during cold winter nights but otherwise they don’t heat or cool their houses. None of the interviewees have anything to say about the wind speed but two say the wind usually comes from the west. The houses are not shaded by any objects at the time of the interviews.

**Dhulikhel**

In Dhulikhel the interviewees live in reinforced concrete framed houses. The walls are made of cement-bonded burnt bricks (110 mm) with thin layers of concrete render and the floors and roof are made of concrete. The houses have two or three floors, several bedrooms and a kitchen. Some houses have a business area in the floor connected to the road.

The number of occupants is 3, 3, 5 and 5 in the households. Some of the family members are away for work and eat two times a day in the house, while the rest eat three times. The ones who have a business in the house spend most of the daytime there while some spend a lot of time outdoors. Bedtime is usually from 9 pm to 6 am but varies with the light possibilities and power cuts.

The interviewees describe the climate as comfortable throughout the year in most cases. One said it is a bit cold in winter and sometimes hot in summer. It rains a lot during rainy season and could be quite humid indoors during that time. The households mainly used gas for cooking but the Indian gas blockade forced some to go back to use firewood the last few months. The blockade started the 23th of September 2015 and lasted more than four months (INSEC & DFHRI 2015).

The interviewees say they cook three to four times a day 6.30-7.30am, 10.30am-12.00pm and 5pm-7pm, including tea in the afternoon. Compared to the interviewees in Ghorepani the people in Dhulikhel generally use less time for cooking, which might have to do with the usage of gas instead of firewood.

The interviewees heat and cool their house to a very small extent. They don’t use anything for heating in winter and in summer some use table fans for cooling during hot days. Regarding the wind speed one interviewee say the wind usually comes from the west, the rest don’t know. The houses are sometimes a bit shaded by surrounding houses but all of them are quite exposed to direct sunlight.

## 4.3 Chosen building object

A simple one storey stone house is chosen for the indoor simulations. The house is found in the rural areas of Ghorepani and is shown in figure 4.12.

*Figure 4.12: The house chosen for the indoor climate simulations situated in the rural areas of Ghorepani*

The house is a mud-bonded stone house with tile roof. It is partly built on a foundation of stones to reach the ground level at the back of the house. It has got one outer door made of wood and has two openings with wooden shutters that are oriented to east and west. The front of the house is facing west. A family of five is living in the house that is divided into three rooms. The large main room is facing north and is used for sleeping, living and cooking. The other rooms, the entrance and storage room are mainly used for passing and storage. A firewood stove is used for cooking and figure 4.13 below shows the floor plan and the placement of the stove.

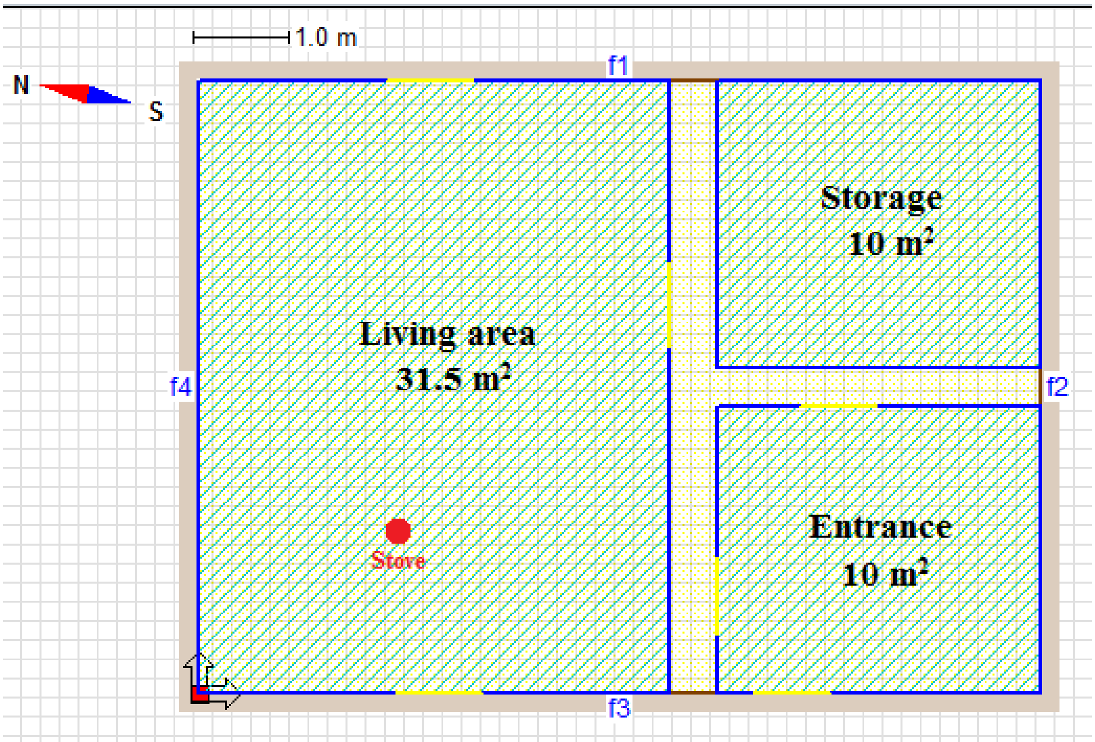

*Figure 4.13: Floor plan for the mud-bonded stone house in Ghorepani.*

## 4.4 Creating the building model

The building is completely made out of mud-bonded stones, including the walls, foundation and roof. Soil or clay does sometimes cover the walls and internal floor of these kinds of houses, but the example will only have layers of soil on the ground floor to start with. The window openings have no glass but wooden shutters and the air leakage is added separately as openings above and below all the windows and external doors. The thicknesses of different building elements and $U$-values are shown in table 4.5.

*Table 4.5: Building defaults for the Ghorepani stone house*

| Elements of construction | Material | Thickness [m] | U-value [W/m$^2$K] |
|---|---|---|---|
| External walls | Stone | 0.4 | 3.30 |
| Internal walls | Stone | 0.4 | 3.30 |
| Roof | Slate | 0.015 | 5.71 |
| Ground floor and foundation | Stones and soil | 0.9 | 1.86 |
| Windows | Wooden shutters | 0.025 | 2.87 |
| Door construction | Wooden door | 0.035 | 2.38 |

The $\lambda$-values for the different materials in the building envelope used in the model is standard values found in IDA ICE. This is because of the difficulty in finding material properties of local building materials in Nepal.

There is nothing shading the site, like trees or other houses. The house is oriented 258 °N, with the short storage façade facing south. The thermal bridges are set as "Very Poor" in IDA ICE and the values can be seen in appendix 1.

The ground model ISO-13370 is used in IDA ICE for calculating the heat resistance for the ground. The infiltration flow is wind driven and set to 5 air changes per hour at the pressure coefficient of 50 Pa and is distributed proportional to the external surface area. The infiltration of air into the house occurs mainly through bad alignments around windows and doors and an extra 0.005 $m^2$ infiltration at pressure level 4 Pa is added to all windows and outer door. The wind profile Suburban (ASHRAE 1993) is chosen, with the coefficient 0.67 and exponent 0.25.

The "Living area" is where the family spend their indoor time. They are five persons at the most and they are assumed to be in the room sleeping from 9pm to 6 pm and eating 7.30am-8.30am, 12.30pm-1.30pm and 6pm-9pm. One person is cooking from 6am-8am, 10.30am-12.30pm and 4pm-9pm.

The kitchen is provided with a firewood stove that is assumed to emit 500 kJ/h, which is 139 W (Fuller, Zahnd, Thakuri, 2007). The firewood stove is assumed to be burning from 06.00-08.00, 10.30-12.30, 16.00-19.00 every day and 19.00-06.00 from October to last of March. The lights are assumed to be on 06.00-08.00, 10.30-12.30, 16.00-21.00, but this is rather optimistic since there are regular power cuts. The windows are assumed to be closed to start with to simplify the simulation work. Defaults for the different zones can be seen in annex 2 and 3.

## 4.5 Steady state calculations

Steady state heat transfer calculations are made to validate the model. A static heat transfer through the building envelope is calculated by hand and compared with the result from an energy simulation in IDA ICE. An almost steady state condition is created in IDA ICE by taking away all the internal gains, furniture, air leakages, thermal bridges, direct solar radiation and inserting ideal heaters in every zone to keep the indoor temperature constant. Then the Synthetic winter weather is used to create the steady state condition, the mean temperature the 15th of January is automatically chosen in IDA ICE and the simulation period is 24 h.

The manually calculated heat transfer is made using the $U$-values and areas from the IDA ICE model. The indoor temperature is set to 21 °C and outdoor temperature is set to 0 °C, which is the mean temperature of the 15th of January according to the Meteonorm. No thermal bridges are included in the calculations. The result form the calculation is shown in table 4.6.

*Table 4.6: Manually calculated steady state heat transfer through the building envelope*

| Construction element | $U$-value [$W/m^2K$] | Area [$m^2$] | Indoor temperature [°C] | Outside temperature [°C] | Heat transfer [W] |
|---|---|---|---|---|---|
| Walls | 3.297 | 57.84 | 21 | 0 | 4004 |
| Roof | 5.714 | 56.32 | 21 | 0 | 6758 |
| Windows and doors | 2.381 | 3.16 | 21 | 0 | 158 |
| Floor | 1.863 | 50.4 | 21 | 9 | 1127 |
| | | | | **Sum [kW]:** | **12.047** |

The manually calculated heat transfer is 12.0 kW. This correspond to the calculated heat demand in IDA ICE, which also is calculated to 12.0 kW. The results are shown in table 4.7.

*Table 4.7: Result of steady state energy calculations*

| Manuel calculation [W] | IDA ICE [W] | Difference [%] |
|---|---|---|
| 12047 | 12020 | 0.2 |

The results indicates that the simplified steady state IDA ICE model is working correctly.

## 4.6 Parameter study

To understand how different parameters impact the model a parameter study is made. The steady state level is used as the base case and the energy demand for keeping the indoor temperature at a level of 21 °C is listed to indicate the impact of the different parameters. One by one parameters like thermal bridges, infiltration, internal gains are added along with the generated energy demand. Table 4.8 shows the result from the parameter study with the synthetic winter weather for Ghorepani.

*Table 4.8: Parameter study with synthetic winter weather data*

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Synthetic winter weather | X | X | X | X | X | X | X |
| Fixed indoor temperature at 21°C | X | X | X | X | X | X | X |
| “Very poor” thermal bridges | | | X | X | X | X | X |
| Internal gains (4 occupants, lights and 139 W heat for 11 h) | | | | | | X | X |
| Wind driven infiltration 5 ACH at 50 Pa | | | | X | | X | X |
| Fixed infiltration 0.5 ACH | | | | | X | | |
| Leak areas around windows and outer door | | X | X | X | X | X | X |
| 100 mm flax insulation added to the roof | | | | | | | X |
| Energy demand 24 h winter day | | | | | | | |
| [kWh] | 234 | 246 | 269 | 270 | 274 | 268 | 195 |
| [kWh/m$^2$] | 4.5 | 4.8 | 5.2 | 5.2 | 5.3 | 5.2 | 3.8 |

The simulation of the base case with the fixed indoor temperature at 21 °C generates an energy demand of 4.5 kWh/m$^2$. This is very high but reasonable when considering the winter temperature and the $U$-values of the building envelope. In reality the demand would probably be a lot higher since the natural ventilation of the house is low when all the windows are closed at all times.

When 0.005 m$^2$ air leakages are added below and above all the windows and outer door the energy demand rises a bit. The ventilation is probably still below acceptable levels but these levels must be analyzed after the occupants are added. In the third simulation “Very Poor” thermal bridges are added to the model. These have quite an impact on the energy demand and will be taken into account in the later indoor simulations. When the wind driven infiltration is added in the fourth simulation, the energy demand doesn’t change at all. This indicates that the wind in the synthetic winter weather data has low speed and a very small impact on the model even though the infiltration rate is high. The infiltration rate at 5 ACH at 50 Pa is ten times higher than for a passive house in Sweden and states that the building envelope in the model has a lot of air leakages.

The fixed infiltration at 0.5 ACH is an ideal state and shows that the energy demand would rise from 5.2 kWh/m$^2$ to 5.3 kWh/m$^2$ with this fixed level. The value 0.5 ACH is still a quite low ventilation rate and indicates that the energy demand would be even higher if an adequate ventilation was added to the model.

In the sixth simulation the wind driven infiltration is used again and the internal gains are added. The internal gains don’t reduce the energy demand at all when the house is uninsulated. This seems a bit strange since five persons sleep in a quite small room, further simulations with the full year climate file will be made to look into this a bit more.

In the seventh simulation 100 mm flax insulation is added to the inside of the roof. This radically lowers the energy demand from 5.2 kWh/m$^2$ to 3.8 kWh/m$^2$, with the assumption that all the doors and windows are closed at all times. This would not be the case in reality especially since an open mud stove is used for cooking. When working with the full year simulations in the next chapter aspects of indoor air quality will be considered. The simulations will not include pollution from the stove though, which is a limitation important to remember.

To get an idea of how the different internal gains affect the energy demand the full year climate file is used and then the energy from the stove, occupants and light are added separately. Table 4.9 shows the result from these simulations.

*Table 4.9: Parameter study with the full year climate file*

| | 1 | 2 | 3 |
|---|---|---|---|
| Meteonorm climate file | X | X | X |
| Fixed indoor temperature at 21°C | X | X | X |
| “Very poor” thermal bridges | X | X | X |
| Internal gains | | | |
| Occupants | | X | X |
| Light | | X | X |
| Stove | | | X |
| Wind driven infiltration 5 ACH at 50 Pa | X | X | X |
| Leak areas around windows and outer door | X | X | X |
| Yearly energy demand | | | |
| kWh | 60666 | 60391 | 60224 |
| kWh/m$^2$ | 1172 | 1167 | 1163 |

When the full year Ghorepani climate file is used the energy demand for the house is 1172 kWh/m$^2$ when no internal gains are considered. When the occupants and lights are added the energy demand reduces to 1167 kWh/m$^2$. The firewood stove reduces the total energy demand to 1163 kWh/m$^2$, which is remarkably low. This indicates that the chosen effect for the firewood stove is low, this will not be changed in the further simulations though. All in all the internal gains have a positive impact on the indoor temperature, this will increase in winter if the house is more insulated.

## 4.7 Indoor climate simulations

To get a reasonable indoor air quality the windows must be open during some parts of the day. When the base case with closed windows and doors is used in the parameter study simulations, the carbon dioxide level is at 6000 ppm per m$^3$ which is extremely high and not acceptable. To get an average carbon dioxide level below 1000 ppm per m$^3$ different schedules of open windows are tested. When the western window is open 25 % at all times and the eastern window is open 25 % while cooking and during night time the average carbon dioxide level is 796 ppm per $m^3$ and the daily variation is low. These window settings will be used in all further simulations if nothing else is written.

As long as the people used open firewood stoves these levels of ventilation won't be nearly enough. Simulating indoor pollution from fire is not part of this study but should be accounted for when considering to increase air tightness and insulation levels.

### Description of the different simulations

The first simulation is the base case with windows open as described above. Thereafter insulation will be added on different surfaces and windows will be moved to increase the passive solar heating. The following simulations will be performed:

1. Base case
2. 50 mm clay is added on the all the wall surfaces
3. A well ventilated attic is added
4. 100 mm insulation is added on the top floor
5. 50 mm insulation is added on the inside of the walls around the "Living area"
6. The wall insulation is moved to the outside of the walls
7. The values of the thermal bridges are changed from "Very Poor" to "Typical"
8. The orientation of the house and the placement and type of the windows are changed to increase the passive solar heating

The results will be presented by the following parameters explained in table 4.10.

*Table 4.10: Description of parameters that will be presented as simulations results*

| Parameter | Description |
|---|---|
| Mean, minimum and maximum operative temperature | The mean, minimum and maximum value of the operative temperature at the position of an inserted occupant in the zone, placed 1.5 m from two outer walls and 0.6 m from the floor. |
| Mean and maximum $CO_2$ | Mean and maximum values of the concentration of $CO_2$ in the zone. |
| Mean and maximum air age | Maximum of 1/(fresh air changes per hour). The age of the air is equal to the mean time the air is inside the building (includes the air exchange between zones). |
| Maximum relative humidity | Maximum value of the relative humidity of the air in the zone. |

### Numerical validity

The simulation data have the following tolerances and accuracy:

| | |
|---|---|
| Tolerance | 0.02 |
| Maximal time step | 1.5 h |
| Tolerance for periodicity | 0.001 |

The tolerance determines how accurately equations are to be solved. The given numbers tells the degree of accuracy reached in the calculated variables. Relaxing the tolerance normally results in a faster simulation, but if the tolerance is too relaxed the solver will have trouble finding a solution, which causes poorer stability in the simulations.

When changing the tolerance to 0.002 and the maximum time step to 1.0 hour nothing in the results are changed. Therefore the values above are considered to have enough accuracy for further simulations.

### Simulation with the full year climate file for Ghorepani

The first simulation of the indoor temperature in the "Living area" zone, with the full year climate file, are shown in the figure 4.14 below. The daily variety of the operative indoor temperature is high and the temperature falls below zero in winter and has a minimum operative temperature of -5.0 °C and a maximum operative temperature of 32.4 °C.

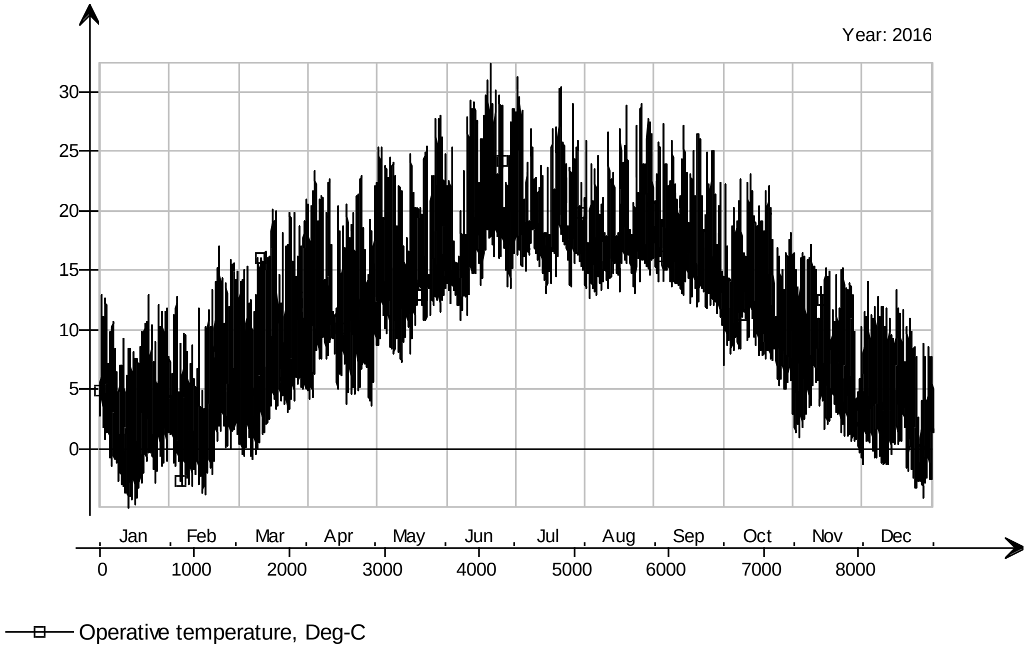

*Figure 4.14: Daily operative temperature for the "Living area" in the year of 2016*

The monthly mean indoor air quality is shown in table 4.11. The mean air age is 0.7 h and the mean carbon dioxide level is 796 ppm per $m^3$. From this point of view the values look good but it's important to not only look at mean levels but also to check the variation during the day. Therefore the coldest winter day and the warmest summer day will be chosen for further simulations to state the daily extremes.

*Table 4.11: Indoor air quality for ground level simulation*

| Month | Variables | | |
|---|---|---|---|
| | Air age [h] | CO2, [ppm] | Relative humidity [%] |
| January | 0.7 | 743.5 | 41.9 |
| February | 0.7 | 757.7 | 41.8 |
| March | 0.7 | 752.0 | 38.8 |
| April | 0.7 | 776.9 | 39.3 |
| May | 0.8 | 809.9 | 43.0 |
| June | 0.8 | 840.0 | 48.8 |
| July | 0.9 | 873.8 | 55.5 |
| August | 0.9 | 880.3 | 61.6 |
| September | 0.8 | 825.3 | 52.8 |
| October | 0.7 | 775.6 | 40.3 |
| November | 0.7 | 759.4 | 41.4 |
| December | 0.7 | 756.1 | 42.0 |
| mean | 0.7 | 796.0 | 45.6 |
| min | 0.7 | 743.5 | 38.8 |
| max | 0.9 | 880.3 | 61.6 |

The coldest indoor temperature is found on the 13th of January and the daily temperature is shown in figure 4.15, with the minimum operative temperature -4.9 °C and maximum 8.2 °C.

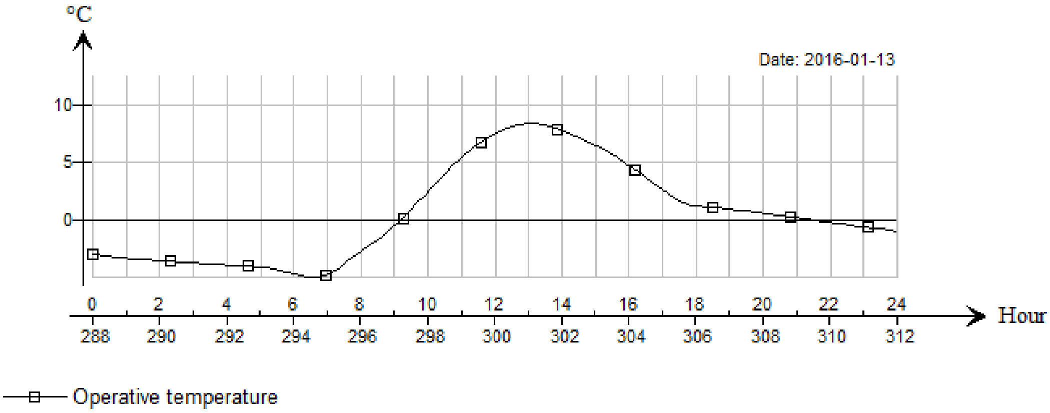

*Figure 4.15: Hourly operative temperatures the 13th of January 2016*

The indoor air quality for the 13th of January is shown in figure 4.16. The brown line with the circles shows the air age, the blue line with the triangles show the carbon dioxide rate and the turquoise line with crosses show the relative humidity. The carbon dioxide runs between 500 and 1600 ppm per $m^3$, the air age is 0.7 to 1.2 h and the relative humidity is 12 to 93 %.

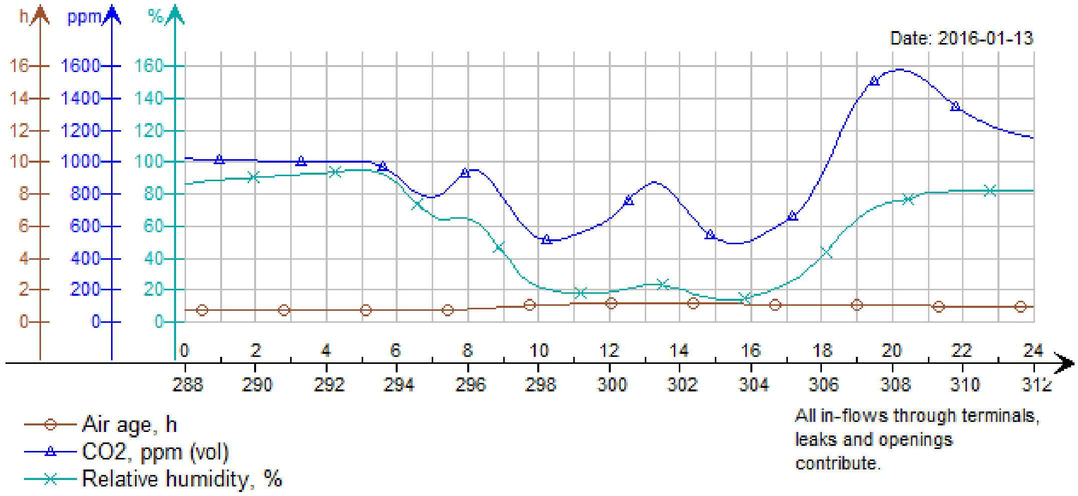

*Figure 4.16: Hourly values for air age, carbon dioxide levels and relative humidity the 13th of January 2016*

The warmest summer day is the 20th of June and the daily indoor temperature is shown in figure 4.17, with the minimum operative temperature 17.3 °C and maximum 32.0 °C.

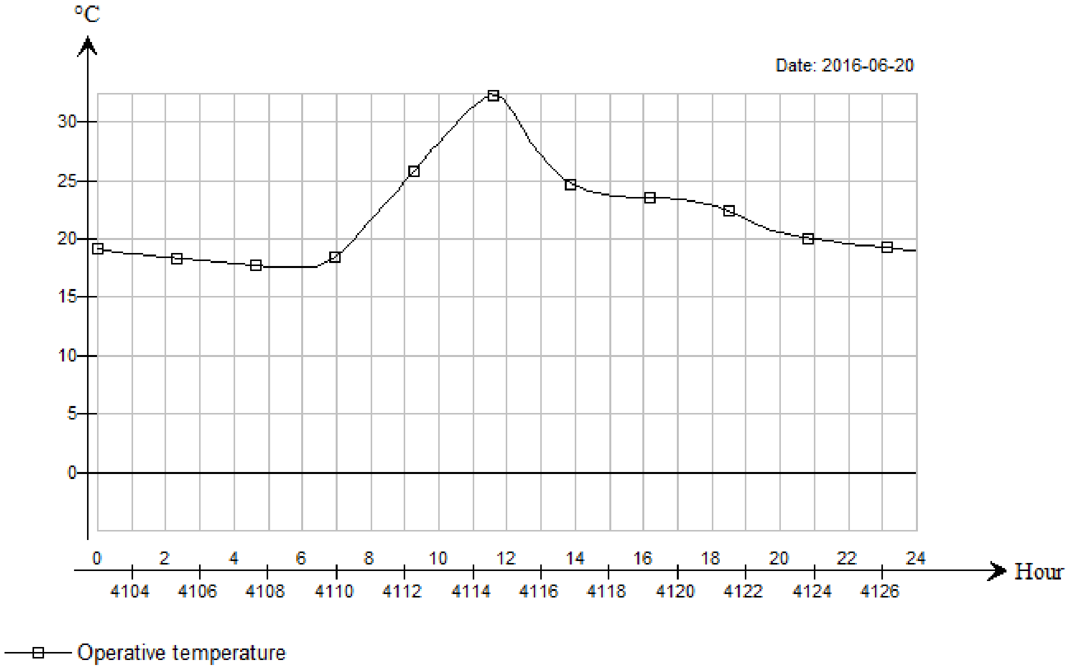

*Figure 4.17: Hourly values of operative temperature the 13th of January 2016*

The indoor air quality for the 20th of June is shown in figure 4.18. The mean carbon dioxide is 832 ppm per $m^3$ and the highest level is about 1300 ppm per $m^3$ and occurs around 8pm when the family is having dinner. The mean air age is 0.7 and the highest relative humidity is 72 %.

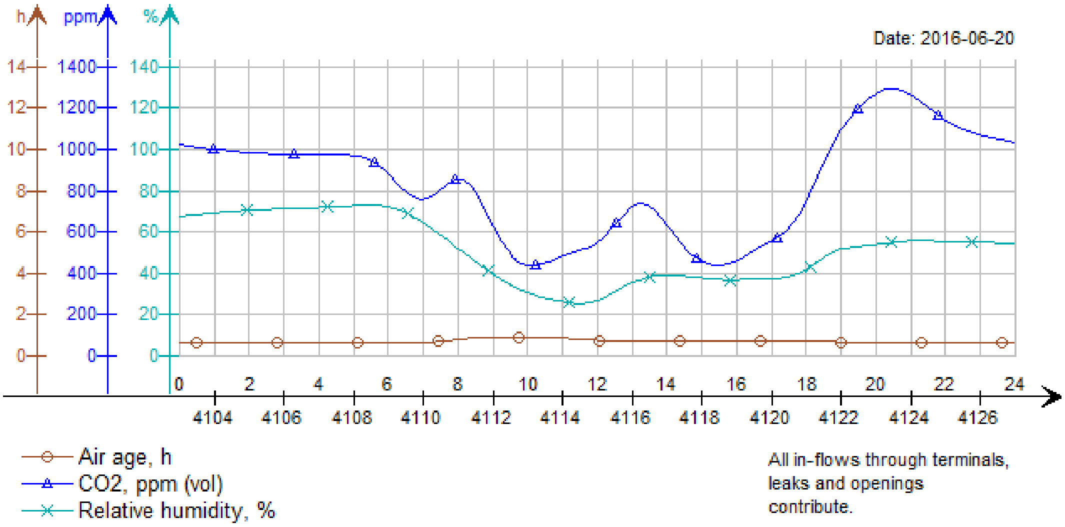

*Figure 4.18: Hourly values for air age, carbon dioxide levels and relative humidity the 20th of June 2016*

There is condensation on surfaces at some point in all the simulations even when the moisture from cooking is excluded. The results from all the simulations with the Ghorepani climate file are shown in table 4.12 and 4.13.

*Table 4.12: Mean indoor temperatures and indoor air quality for the different simulations the 13th of January in Ghorepani*

| | Operative temperature (°C) | | | $CO_2$ (ppm) | | Air age (h) | | Relative humidity (%) |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | Mean | Mean max | Mean | Mean max | Mean max |
| Base case | 0.8 | -4.3 | 8.1 | 719 | 976 | 0.6 | 1.2 | 72 |
| 50 mm clay on all wall surfaces | 0.9 | -3.3 | 9.5 | 713 | 977 | 0.6 | 1.1 | 71 |
| Well ventilated attic added | 0.9 | -1.5 | 3.0 | 768 | 1311 | 0.7 | 2.1 | 59 |
| 100 mm top floor insulation | 1.6 | 0.2 | 2.8 | 759 | 1275 | 0.6 | 2.1 | 57 |
| 50 mm wall insulation on the inside | 3.7 | 1.4 | 5.1 | 664 | 937 | 0.5 | 1.2 | 33 |
| 50 mm wall insulation on the outside | 4.5 | 2.7 | 5.6 | 652 | 908 | 0.5 | 1.1 | 31 |
| Improved thermal bridges | 5.8 | 4.1 | 6.9 | 635 | 857 | 0.4 | 0.9 | 27 |
| Changed orientation and windows | 11.1 | 8.9 | 13.1 | 866 | 1150 | 0.8 | 1.1 | 31 |

The base case has a very low mean indoor temperature on the 13th of January, the coldest winter day. If the dwellers spend time indoors they will probably have the fire going all day when the temperature falls as low as this. But the fire schedule will be kept as it is for the further simulations. Many Nepalese houses of this type have a layer of clay on the wall surfaces. When the clay is added on both sides of the walls this increases the thermal mass, which leads to a slightly higher temperatures.

Many houses in Nepal have well ventilated attics to improve the indoor thermal comfort. An attic with a floor made of wood and soil is added to the house. This is an effective way to lower the daily temperature variation and avoid the extreme maximum temperatures in summer. When the attic is added the daily varieties in the indoor temperatures radically reduces, the mean temperature is almost the same as before but the minimum and maximum temperatures are less extreme. In daytime this leads to a colder indoor climate while it gets warmer during the night. This might not be a good thing during the entire year but the change in construction will be kept for further simulations. The mean maximum carbon dioxide rate is a lot higher when the attic is added, this is because the thermally driven ventilation reduces compared to previous cases. This means that the indoor temperature would be a bit lower if the same ventilation rates as before were generated.

In the fourth simulation 100 mm flax insulation is added on top of the top floor. The $U$-value of the top floor changes from 2.22 W/m$^2$K to 0.32 W/m$^2$K. The added roof insulation leads to a lowered daily variety of the indoor temperature throughout the year even though the ventilation rate rises a bit. The average monthly minimum operative temperature rises to 6.0 °C and the maximum to 18.9 °C.

The insulation used has the following properties (Isolina, 2015):

| | | |
|---|---|---|
| Heat conductivity: | 0.038 | W/(m K) |
| Density: | 26.1233 | kg/m3 |
| Specific heat: | 1600 | J/(kg K) |

In the fifth simulation 50 mm flax insulation is added to the walls surrounding the “Living area”. When the insulation is placed on the outside of the walls the use of the walls’ thermal mass makes the indoor temperatures rise compared to when it is placed on the inside. The wall insulation also rises the ventilation rates, this is because the temperature difference between the indoors and the outdoors are larger which rises the thermally driven ventilation. The outside wall insulation is kept for the further simulations.

If the insulation is placed on the outside of the walls and the top floor is insulated, the thermal bridges will probably be improved. Therefore the values for the thermal bridges are changed from “Very poor” to “Typical” and this also rises the mean indoor temperatures slightly. At the same time the ventilation rate rises and this probably happens because the thermally driven ventilation increases when the thermal bridges improves.

In the last simulation for the 13th of January the orientation of the house and the placement of the windows are changed to increase the passive solar heating. The longest outer wall of the “Living area” is now facing south and the windows are also moved to the south facing wall and are changed from windows with wooden shutters to double-glazed windows with a $U$-value of 3.04 W/m$^2$K . The windows are placed 170 mm from the outside surface of the wall to avoid direct radiation from the high summer sun. The schedule of the opening of the windows are also changed to fit the new orientation and needed ventilation. Three small ventilation doors are added on the Western and Eastern wall to enable a good natural ventilation through the room. All in all these changes and the earlier added insulation etcetera have risen the mean indoor temperature from 0.8 °C to 11.1 °C and the minimum temperature from -4.3 °C to 8.9 °C. In the last simulation the ventilation rate is a bit lower than in the previous simulations and this also contributes to a higher indoor temperature.

The results for the warmest summer day, the 20th of June, is shown in table 4.13 below.

*Table 4.13: Mean temperatures and indoor air quality for the different simulations on the 20th of June in Ghorepani*

| | Operative temperature °C | | | $CO_2$ (ppm per $m^3$) | | Air age (h) | | Relative humidity (%) |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | Mean | Mean max | Mean | Mean max | Mean max |
| Base case | 22.0 | 17.6 | 32.0 | 859 | 1175 | 0.8 | 1.5 | 74 |
| 50 mm clay on all wall surfaces | 22.1 | 17.3 | 33.1 | 867 | 1204 | 0.9 | 1.4 | 75 |
| Well ventilated attic added | 20.6 | 18.5 | 22.9 | 961 | 1379 | 1.2 | 3.3 | 66 |
| 100 mm roof insulation | 18.9 | 18.1 | 19.5 | 1009 | 1267 | 1.2 | 2.8 | 67 |
| 50 mm wall insulation on the inside | 18.3 | 17.2 | 19.5 | 1047 | 1348 | 1.2 | 2.8 | 72 |
| 50 mm wall insulation moved to the outside of the wall | 17.8 | 16.9 | 18.7 | 1058 | 1466 | 1.2 | 2.4 | 73 |
| Improved thermal bridges | 18.0 | 17.3 | 18.8 | 1023 | 1394 | 1.1 | 2.3 | 71 |
| Changed orientation and windows | 18.7 | 17.4 | 20.0 | 842 | 1203 | 0.9 | 2.0 | 68 |

The base case brings a quite high maximum temperature at 32 °C when the ventilation rate is at acceptable levels. The extreme temperatures increases a bit when clay is added to the walls in the second simulation, otherwise this change doesn’t affect much. In the third simulation the well ventilated attic is added and the maximum temperature is lowered to 23 °C. This is a very positive outcome and a well ventilated attic is highly recommended for minimizing the overheating in summer. The mean maximum carbon dioxide rate is significantly higher when the attic is added, this is because the thermally driven ventilation is reduced compared to previous cases. This means that the indoor temperature would be a bit higher if the same ventilation rates as before were generated.

In the fourth simulation 100 mm flax insulation is added on top of the top floor. This lowers the mean temperature considerably while the ventilation rate slightly increases. After that, 50 mm flax insulation is added to the walls surrounding the “Living area”. When the insulation is placed on the outside of the walls the use of the walls thermal mass make the indoor temperatures lower than if it is placed on the inside. The ventilation should be increased a bit to get a lower carbon dioxide level and also rise the indoor temperatures a bit. This could be done by opening the windows and doors more.

In the last simulation for the 20th of June the orientation of the house and the placement of the windows are changed as described on page 45. The glazed windows are placed 170 mm from the outside of the wall to minimize the direct radiation from high summer. The mean temperature is in this case 18.7 °C and the mean carbon dioxide level is 842 ppm per $m^3$. This shows that the changes that were made to improve the thermal comfort in winter also works well during warm summer days.

**Simulations with the Dhulikhel climate file**

Since the climate file for Ghorepani is very uncertain the house and its indoor climate is also simulated with a climate file from Dhulikhel. This is to get results from a location with a lower altitude to enrich the analysis of the model and see how it works in different climates.

There will be no heating during night time in winter in this case, since the results from the interviews from this area shows that none of the interviewees use anything for heating their houses. The 400 mm stone walls will be changed to 110 mm brick walls with concrete pillars since this is a very common wall construction in the area according to the interviewees. The coldest winter day 2016 in Dhulikhel is the 16th of January according to Meteonorm and the warmest summer day is the 22 of June. Not all the simulations that was made for Ghorepani will be done for Dhulikhel. The simulations made will be the following:

1. Base case
2. A well ventilated attic is added
3. 100 mm insulation is added on the top floor
4. 50 mm insulation is added on the outside of the walls around the ”Living area”
5. The values of the thermal bridges are changed from “Very Poor” to “Typical”
6. The orientation of the house and the placement and type of windows are changed to increase the passive solar heating

Except for what is mentioned above the same data used in the previous simulations for Ghorepani will be used in the Dhulikhel simulations.

There is condensation on surfaces at some point in all the simulations even when the moisture from cooking is excluded. The results from the simulations with the Dhulikhel climate file are shown in table 4.14 and 4.15.

*Table 4.14: Mean indoor temperatures and indoor air quality for the different simulations the coldest winter day, 16th of January in Dhulikhel*

| | Operative temperature (°C) | | | $CO_2$ (ppm per $m^3$) | | Air age (h) | | Relative humidity (%) |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | Mean | Mean max | Mean | Mean max | Mean max |
| Base case | 7.9 | 1.8 | 16.0 | 712 | 921 | 0.7 | 1.4 | 82 |
| Well ventilated attic added | 8.3 | 5.7 | 11.0 | 730 | 1173 | 0.6 | 1.5 | 60 |
| 100 mm top floor insulation | 8.8 | 6.1 | 11.3 | 701 | 1034 | 0.6 | 1.2 | 57 |
| 50 mm wall insulation on the outside | 10.8 | 9.1 | 11.9 | 658 | 902 | 0.5 | 0.9 | 48 |
| Improved thermal bridges | 11.9 | 10.4 | 13.0 | 639 | 851 | 0.5 | 0.8 | 44 |
| Changed orientation and windows | 18.1 | 16.4 | 19.8 | 849 | 1112 | 0.9 | 1.1 | 37 |

The base case has a mean indoor temperature of 7.9 °C on the 16th of January, the coldest winter day. The minimum temperature is low but the ventilation rates are good. When the attic is added it is mainly the minimum temperature that rises significantly. Since there is nothing heating the indoor air except for the occupants and cooking stove the improvements of the building envelope doesn’t rise the indoor temperature very much. When the insulation is added to the roof and walls, and the thermal bridges are improved, the mean indoor temperature have gone from 8.3 °C, with the ventilated attic, to 11.9 °C. It is first when the passive solar heating, through the south facing windows, brings the needed heat source that the indoor temperatures really rises to more comfortable levels at 18 °C.

The ventilation rates are a bit high regarding the cold winter temperatures before the changes are made for the last simulation. This means that the simulated indoor temperatures could be a bit higher and still have an acceptable ventilation rates. The natural ventilation is a very sensitive and difficult type of ventilation to control, it highly depends on the wind speed, wind direction and thermal conditions. All in all the changes made to improve the building envelope and increasing the passive solar heating are very positive regarding the indoor thermal comfort in winter.

The results for the warmest summer day are shown in table 4.15 below.

*Table 4.15: Mean temperatures and indoor air quality for the different simulations on the warmest summer day, 22th of June in Dhulikhel*

| | Operative temperature | | | $CO_2$ (ppm per $m^3$) | | Air age (h) | | Relative humidity (%) |
|---|---|---|---|---|---|---|---|---|
| | Mean | Min | Max | Mean | Mean max | Mean | Mean max | Mean max |
| Base case | 31.0 | 22.4 | 41.0 | 564 | 760 | 0.5 | 1.1 | 75 |
| Well ventilated attic added | 28.1 | 24.4 | 32.2 | 596 | 1100 | 0.7 | 3.3 | 69 |
| 100 mm top floor insulation | 27.3 | 23.8 | 31.2 | 691 | 1273 | 0.9 | 4.3 | 71 |
| 50 mm wall insulation on the outside | 26.6 | 24.4 | 28.6 | 686 | 1305 | 0.7 | 3.4 | 69 |
| Improved thermal bridges | 26.7 | 24.6 | 28.5 | 674 | 1279 | 0.6 | 3.0 | 67 |
| Changed orientation and windows | 26.5 | 24.3 | 28.4 | 558 | 884 | 0.4 | 1.8 | 68 |

The base case brings very high indoor temperatures with a maximum at 41 °C. When the well ventilated attic is added the windows are open more to reach acceptable ventilation levels. The mean change is that the maximum temperature is radically lowered to 32 °C. When the insulation is added to the roof and the walls around the “Living area”, and the thermal bridges are improved, the maximum temperature is lowered to 28.5 °C. The change of orientation and type and placement of windows is manly to increase the indoor temperature in winter. It is still important to know what the changes does to the indoor climate in summer and for example determine that the direct radiation from the summer sun is not entering too much through the inserted glazed windows. The results of the last simulation shows that these changes doesn’t affect the indoor climate in a negative way.

The higher ventilation rate in the last simulation is an outcome of added ventilation possibilities through two 0.12 $m^2$ wooden shuttered doors added on the Western and Eastern façade. It’s determined that the changes made to the building envelope to increase the indoor temperature in winter also have positive impact on the indoor climate in summer.

The mean changes in indoor operative temperature are listed in table 4.16 and table 4.17, so that the results from Ghorepani and Dhulikel can be compared easily.

*Table 4.16: Mean changes in indoor operative temperatures for the different construction changes the coldest winter day in Ghorepani respective Dhulikhel*

| Indoor thermal changes between the Base case and the following: | | Change in operative temperature (°C) | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Ventilated attic | Ghorepani | 0.1 | 2.8 | -5.1 |
| | Dhulikhel | 0.4 | 3.9 | -5.0 |
| Ventilated attic, insulation in roof and outer walls and improved thermal bridges | Ghorepani | 5.0 | 8.4 | -1.2 |
| | Dhulikhel | 4.0 | 8.6 | -3.0 |
| Ventilated attic, insulation in roof and outer walls, improved thermal bridges and changed orientation and windows | Ghorepani | 10.3 | 13.2 | 5.0 |
| | Dhulikhel | 10.2 | 14.6 | 3.8 |

The changes in indoor operative temperature for Ghorepani and Dhulikhel the coldest winter day follow the same trends. When the ventilated attic is added the maximum temperature is lowered a lot and the minimum temperature is rising. When the insulation is added and the thermal bridges are improved the main change is the radical rising of the minimum temperature, which also make the mean daily temperature rise a lot. It is clear that the true positive effects from the insulated building envelope comes when a heat source, like passive solar heating, is added.

The results for the summer temperatures are listed in table 4.17 below.

*Table 4.17: Mean changes in indoor operative temperatures for the different construction changes the warmest summer day in Ghorepani and Dhulikhel*

| Indoor thermal changes between the Base case and the following: | | Change in operative temperature (°C) | | |
|---|---|---|---|---|
| | | Mean | Min | Max |
| Ventilated attic | Ghorepani | -1.4 | 0.9 | -9.1 |
| | Dhulikhel | -2.9 | 2.0 | -8.8 |
| Ventilated attic, insulation and improved thermal bridges | Ghorepani | -4.0 | 0.3 | -13.2 |
| | Dhulikhel | -4.3 | 2.2 | -12.5 |
| Ventilated attic, insulation, improved thermal bridges and changed orientation and windows | Ghorepani | -3.3 | 0.2 | -12.0 |
| | Dhulikhel | -4.5 | 1.9 | -12.6 |

The changes in indoor operative temperature for Ghorepani and Dhulikhel also follow the same trends on the warmest summer day. When the ventilated attic is added the maximum temperature is lowered a lot and the minimum temperature is rising a little. The same happens, but to a larger extent, when the insulation is added and the thermal bridges are improved. This make the mean temperatures lower and it doesn't change much when the orientation and windows are changed.

All in all the trends for the changes in the indoor operative temperature are very similar for Ghorepani and Dhulikhel. This indicates that the results could be applicable on this specific house construction and other one-story houses of the same size, with building envelopes with low thermal resistance and similar internal gains, on altitudes between 1500 m to 2600 m. The local wind profile will impact on the results a lot since they are very dependent in the ventilation rates. In the case of the passive solar heating the glazed widows need to be facing south and can't be shaded by any object.

To see how the indoor temperature is affected when a more powerful stove is running in the Living area a 2000 W "Ideal heater" is inserted in the room for the last analysis. An "Ideal heater" is a room unit in IDA ICE that is used when no detailed information about the actual heating device is available. The "Ideal heater" has no given physical location and has fixed performance parameters and no flue gas emissions. The power is set to 2000 W and the efficiency to 1.0. The results from these simulations are shown in table 4.18.

*Table 4.18: Operative temperatures in the Living area when a 2000 W ideal heater is running 24 hours a day the coldest winter day, the 13<sup>th</sup> of January, in Ghorepani.*

| | Mean operative temperature (°C) | | | | | |
|---|---|---|---|---|---|---|
| | From table 4.12 | | | With an 2000 W ideal heater running 24 h a day | | |
| | Mean | Min | Max | Mean | Min | Max |
| Ventilated attic | 0.9 | -1.5 | 3.0 | 5.1 | 2.1 | 8.0 |
| Ventilated attic, insulation in roof and outer walls and improved thermal bridges | 5.8 | 4.1 | 6.9 | 10.2 | 7.2 | 12.9 |
| Ventilated attic, insulation in roof and outer walls, improved thermal bridges and changed orientation and windows | 11.1 | 8.9 | 13.1 | 21.1 | 20.1 | 21.5 |

The temperatures rises considerably when the 2000 W ideal heater is inserted. In the last simulation the mean operative temperature rises from 11.1 °C to 21.1 °C in the coldest winter day in Ghorepani.

# 5 Conclusion

*How can small changes in construction, building design or choice of material, improve the indoor thermal comfort in Nepalese houses?*

The building tradition in Nepal is very diverse, both when it comes to use of material and building design. Local available material along with ethnicity and cultural identity are the most important factors that have formed variety in the country's building stock. According to the Central Bureau of Statistics 2011 the most common building materials used for foundation and walls was mud-bonded bricks and stones, for roofing tile or slate is the most common material followed by galvanised sheet and concrete. These materials have low thermal resistance which make it hard to get comfortable indoor temperatures in winter in the studied areas.

The latest housing statistics from Nepal says the average number of members in a household in Nepal is 4.9 and the average available space within the house is 56 m$^2$, with a small variety between rural and urban areas. The main fuel used for cooking in the country is firewood, which covers about 64 % of the households while LPG is used by 18 % of the population. These facts along with data of common building materials contributed to the choice of building object for the indoor simulations. The closely studied object is a one-storey mud-bonded stone house outside the village of Ghorepani. There are five persons living in the house and they spend most of their indoor time in the "Living area" which is a room of 31.5 m$^2$ where they cook, eat and sleep. The total available space within the house is 54 m$^2$ where the two smaller rooms are used only as entrance and storage. The kitchen is placed in the "Living area" and contains a mud stove that is used for cooking three times a day and also for heating during night time in winter. Firewood is the main fuel used for cooking and heating.

Ghorepani is situated in the Myagdi District in the north-central Nepal at the elevation 2600 m. The climate is considered as cold temperate climate and the weather data used is interpolated in Meteonorm. Four interviews were performed in the Ghorepani area to determine the used building materials, number of rooms, placement and use of kitchen, energy consumption used for heating and other data that was needed for the indoor climate simulations. The chosen house was then measured and a model was created and validated in IDA ICE. The indoor climate simulations and changes in construction was made to improve the thermal comfort without decreasing the ventilation rates.

The results indicate that the use of passive solar heating and insulation in roof and walls can increase the mean temperature the coldest winter day from 0.8 °C to 11.1 °C. The coldest winter day was defined as the day with the lowest indoor temperature in the base case. This means that the coldest day after the constructional changes could be a different one, since direct solar radiation affect the results significantly when it comes to the last simulation when the orientation and windows are changed.

In summer a well ventilated attic is all that is needed to get a comfortable indoor temperatures. The added insulation unnecessarily lowers the indoor temperature a bit but the most important thing is that the added double-glazed windows doesn't increase the passive solar heating too much in summer.

In the case of Dhulikhel the same building design is used but the material in the outer walls is changed to burnt bricks and the floors are concrete, since these a very common building materials in the area. This house design is not representative for the area but is used to get an idea of the effects of the construction changes in a different climate on a lower elevation. The schedule of the opening of windows is changed to reach acceptable ventilation rates and there is no heating during night time in winter, otherwise the same data is used as in the simulations for Ghorepani. The coldest winter day in Dhulikhel brings a mean indoor temperature of 7.9 °C. A well ventilated attic rises the minimum temperatures a few degrees while the maximum temperature is lowered. The added roof and wall insulation, changed orientation, changed placement and type of windows increase the mean temperature the coldest winter day from 7.9 °C to 18.1 °C. In summer a well ventilated attic is all that is needed to avoid extreme overheating temperatures. The insulation slightly reduces the extreme temperatures and the changed orientation and windows doesn’t increase the passive solar heating too much in summer.

All in all the different construction changes affect the indoor operative temperatures in very similar ways for Ghorepani and Dhulikhel. This indicates that the results could be applicable on this specific house type and also other one-story houses of the same size, with building envelopes with low thermal resistance and similar internal gains, on altitudes between 1500 m to 2600 m. The local wind profile will impact on the results a lot since they are very dependent in the ventilation rates. The passive solar heating is dependent on that the glazed windows are facing south and that they are not shaded by any object.

A heating device, like a smokeless stove, could rise the indoor temperature significantly, as shown in table 4.18. When an ideal heater of 2000 W is inserted in the well-insulated “Living area”, with double-glazed windows facing south, the mean operative temperature rises from 11.1 °C to 21.1 °C.

# 6 Discussion

The results show that the indoor thermal comfort, in both warm temperate and cold temperate climate in Nepal, can be improved a lot in winter by using passive energy efficient building techniques. The materials used in Nepalese houses often have low thermal resistance and this leads to cold indoor temperatures during winter. Some of the traditional houses in the studied regions with thick walls of raw bricks and well-ventilated attics probably have the highest thermal comfort in the studied regions, but the thermal comfort in winter could still be improved a lot if passive solar heating was used along with an even more thermal resistant building envelope.

The aim of the work is to contribute to the knowledge within the field of energy efficient building techniques in Nepal and also to give examples on what effects these techniques can have on the indoor temperature in the studied regions in the country. Today the people in Nepal accept a great variety of indoor temperature, but in the future the Nepalese people might want to increase their indoor comfort and then energy efficient building techniques can be used to improve the indoor climate, reduce the need of added heat or cold which would lead to a more effective use of natural resources.

Regarding the building materials used in the country the statistics listed in the study are from the period of 1996-2010. This probably means that the amount of houses with walls made of concrete-bonded bricks and stones and concrete roofs are higher than it was when the data was collected. The use of these materials and reinforcement will probably increase even more in the future since many Nepalese want earthquake resistance houses, if they can afford it. The Nepal National Building Conde from 1994 presents standards for seismic design of buildings in the country (DUDBC 2007).

The typical house designs varies a lot depending on region and the ethnicity of the people living there. In the region of Ghorepani the houses are one- to three-storey houses made of primarily stones or mud-bonded stones. Some of the houses have shaded porches and ventilated attics but the simpler houses doesn’t. Even though the walls are thick, the low thermal resistance of the materials in the building envelope make the heating of the houses very energy consuming. This is the case for most of the houses in the studied regions.

The climatic regions in Nepal vary from sub-tropical to tundra climate. Due to the time limits only two locations, representing warm temperate and cold temperate climate, were chosen for further research. The climate data for the cold temperate climate in Ghorepani, with its cold winters and cool summers, are considered to show low temperatures when it is compared with data from a local weather station in the village of Gurja Khani, which is on the same altitude but 50 km to the west. But since the local weather data was from 2014, it can be misleading to due to yearly variations. The precise values in the Meteonorm climate file has to be seen as very uncertain, which affects the reliability of the results regarding the air temperatures. The climate data for Dhulikhel seems to be more certain according to the comparison with climate data from Kathmandu, which is based on 20 years of weather statistics. This means that the simulated indoor temperatures for Dhulikhel should be seen as realistic.

The building object used in the simulations was chosen because it is a common house type in the Annapurna mountain region and the available space inside the house and the used building materials are commonly used in the country according to statistics. The simple building design of a one-story house with few rooms made it easy to model and also simplified the simulation work.

The next phase of the study was the interview process. Most of the interviews were performed with help from a person that spoke both English and Nepali, the official language in Nepal. The answers from the interviews were very similar and this can indicate that the person helping with the interviews might have affected the responses. It can also be quite difficult to answer questions regarding how many hours you cook daily, since that might be something you haven’t paid attention to, etcetera. The assumptions regarding internal gains based on the interviews can therefore be seen as a bit uncertain. But since the impact on the simulation results from the internal gains are rather low, it doesn’t matter too when it comes to the results.

A parameter study was performed after the simulation model was created. The results from this was mainly used for understanding the model. The thermal resistance of the building envelope was very low and this led to a very high energy demand for keeping the indoor temperature at a fixed level. The case with a fixed indoor temperature is not a relevant case for Nepal but was used to give a greater understanding of the building model, for those who are used to work with indoor climate simulations and energy demand of buildings. The most interesting result was that the energy demand was radically lowered when roof insulation was added. The effect of the insulation would not be that high in reality since the needed ventilation would be a lot higher. Another interesting observation was that the heat from the fire stove had almost no effect on the heat demand. This is because the assumed effect used for the fire stove is whey too low. A better reference regarding the effect of the stove would contribute to a more realistic heating situation in the simulations.

The simulation results from the coldest winter day in Ghorepani shows very low mean indoor temperatures. The improvements of the building envelope are added step by step to enable to see the effect of each change. This is a bit deceiving since the different building elements in the building envelope is working as a system, because of the indoor temperature increase. When the roof is insulated, more heat is transferred through the walls than when the roof wasn’t insulated. When the wall insulation is added in the fourth simulation it is easy to believe that the wall insulation is more effective than the roof insulation, but the rising of the indoor temperature would probably not occur at all if the roof insulation wasn’t already there. The same works for the thermal bridges, which are generally improved if the insulation is placed on the outside of the walls. This should be considered when evaluating the results for the different changes.

The low indoor winter temperatures are not surprising since the heat source in the house provides a very low amount of heat. It’s clear that a heat source is needed to get the most out of an insulated house. The passive solar heating, shown in the last simulation, shows the importance of this. It is still not enough to reach what generally is seen as comfortable indoor temperature levels, but still it makes a great difference for the thermal comfort in Ghorepani in winter.

Regarding the indoor climate on the warmest summer day in Ghorepani the mean indoor temperatures are higher in the uninsulated construction. This is because the higher temperatures from the attic doesn't enter the "Living area" when the top floor is insulated. The most comfortable temperature levels occur therefore when the well ventilated attic is added and nothing else. The slightly negative effects of insulation, which in summer brings too low indoor temperatures to the house in Ghorepani, don't outtake the positive effects the insulation and passive solar heating bring during winter. And since the temperatures from Meteonorm might be to be too low, this might mean that the summer indoor temperatures in the region would be higher in reality. This could mean that slightly lowered indoor temperatures during summer could be a positive thing.

When comparing the results from Ghorepani with the results from Dhulikhel the trends of the effects from the construction changes are very similar. This indicates that the results could be applicable on other one-storey houses of the same size in similar climates as the studied zones. The local wind profile will still have a great impact on the results since the ventilation rates depend a lot on this. Therefore the results from these kinds of construction changes will vary with the local climate even for locations in the same regions. Overall the results in the study should be seen as bit uncertain since they depend a lot on the ventilation rates, which in reality are very difficult to control when it comes to natural ventilation.

The ventilation rates used in the study are only suitable for rooms with no open fire. In warm temperate climate most people don't heat their houses at all and generally people heat and cool their buildings to a very small extent in the studied regions and this is probably the case for the entire county. On higher altitudes firewood is sometimes used for heating, but in this case a lot of ventilation is needed to get rid of all the fire related air pollution. With such high ventilation rates the positive effects from insulation is lost. The use of passive solar heating is very energy efficient solution for heating a house, it is dependent on direct sunlight though which makes it hard to apply in crowded cities and for example on north-facing slopes.

A heating device, like a smokeless stove, is a great complement or alternative to the passive solar heating. To make the mean indoor temperatures rise to the comfortable level of 20 °C an additional 2000 W heater is needed the coldest winter day in Ghorepani, for the insulated house with double-glazed windows facing south. Since most people in Nepal use firewood for cooking, a smokeless stove could be a suitable and affordable solution for such a heating device.

Even though the diversity in building design is great in Nepal the results from this study state examples of how insulation and passive solar heating can improve indoor thermal comfort in simple houses in the country. Most of the buildings in Nepal have very low thermal resistance and this leads to low indoor temperatures in winter in many regions. Today the people in Nepal accept a great variety of indoor temperature, but in the future the Nepalese people might want to increase their indoor comfort and then energy efficient building techniques can be used to improve the indoor climate, reduce the need of added heat or cold which will lead to a more effective use of natural resources. Generally the interviewees didn't not know at what levels the indoor temperature usually was in a year. In Ghorepani people said it was cold in winter but pleasant otherwise. In Dhulikhel people seemed quite satisfied with the indoor climate throughout the year. This could indicate that the interest for investing in a more insulated house might be very low.

Since the techniques for building energy efficient buildings with comfortable indoor climate throughout the year is rather unknown to the people in the country, this probably have a negative effect on the demand for improved thermal comfort. To educate the people about the possibilities with these techniques and create an interest for the field, it could be a good idea to first implement the techniques in public buildings. In this case it would be preferable to have mechanical ventilation with heat recovery, which would enable a more efficient energy use to achieve a stable and comfortable indoor climate.

The following part will contain comments of the used method.

The case study was a good method for performing this kind of research. The literature study, with its broad perspective on energy efficient building techniques, climate and building tradition in Nepal, contributed to an important orientation within the fields in the first part of the process. The method of using interpolated climate data from Meteonorm have affected the results a lot. The main uncertainties in the study are the local climate data like temperature, wind speed, wind direction, direct and diffuse solar radiation and relative humidity. It would have been preferable to use data from local weather stations, but due to misunderstandings between the writer and the Department of Meteorology in Nepal this was not possible.

The results from the interviews are also a bit uncertain, which is unavoidable. The fact that a person was translating make the results even more unsure. The effect of this is rather small when it comes to the simulation results, since the internal gains has a quite small impact on the indoor temperature.

Since the ventilation rates for the different simulations was rather similar the effects of the construction changes could be fairly compared between Ghorepani and Dhulikhel. A small amount of heat from the fire in winter during night time is added in the case of Ghorepani and not for Dhulikhel. This difference is considered to have such a small impact on the indoor air temperature and are therefore overlooked.

To end this chapter the final conclusion will be repeated; the results show that a more stable indoor thermal comfort can be achieved in the studied regions with the use of insulation. The positive effects of the higher indoor temperatures in winter outtake the possible negative effects of lower temperatures in summer in both regions. The thermal comfort reach much greater levels when a heat source, like passive solar heating, is used in the house.

Another optional heat source could be a smokeless stove, which might be more relevant alternative for the poorer rural areas of Nepal.

### Further studies

Insulation could be of great use in Nepal. The reason for using flax insulation instead of locally available building material for insulation is because the thermal resistance is so much higher than any local material found in the studied regions. The 50 mm flax insulation used in the simulations would correspond to 750 mm of dry clay or 1 m of concrete hollow bricks. Regarding roofing, straw or thatch have quite high thermal resistance but these materials are hard to find properties for and are therefore not used in the study. The reason for using flax insulation is to give an example of an organic product that can be used as insulation. In the Teleman 2016 pre-study there was interest of organic alternatives that could be locally grown and produced in Nepal. This is also of interest for the Erasmus+ project and since flax is already growing in Nepal it could be interesting to study the possibilities for local production. Studies on what type of insulation that could be produced in the country would be very interesting. A case study on similar construction changes used in this study on a modern reinforced concrete building, with a cost and benefit analysis, would also contribute a lot to the understanding of applicability of insulation and passive solar heating in Nepal. Another interesting area would be to work with energy efficiency and indoor climate in public buildings.

Research on the possibilities of using solar water heating for heating houses would also be an interesting area. Many modern houses in Nepal have flat concrete roofs and some of the richer households have solar panels. The heated water is usually only used for hot showers and very seldom for room radiators. Investigating the possibilities for using this energy for indoor heating along with more thermal resistant building envelopes could be interesting.

# References

Abel, E. & Elmroth, A. (2013). *Byggnaden som system*. Lund: Studentlitteratur.

Adamson, B. & Åberg, O. (1993) *Design for Climatization; Houses in Warm-humid Areas*. Diss. Lunds universitetet. Lund: Univ.

Block, M. & Bokalders, V. (2009) *Byggekologi: Kunskaper för ett hållbart byggande.* Stockholm: Svensk Byggtjänst

Bodach, S. & Hamhaber, J. & Lang, W. (2014) *Climate responsive building strategies of vernicular architecture in Nepal*. Elsevier, 23 juli 2014

Central Bureau of Statistics (CBS) (2011) *Nepal Living Standard Survey.* Thapathali, Kathmandu: Central Bureau of Statistics.

Central Bureau of Statistics (CBS) (2014a). http://cbs.gov.np/atlas/general.html?page= geography_of_nepal [2016-03-20]

Central Bureau of Statistics (CBS) (2014b). http://cbs.gov.np/atlas/maps.html?chapter=2&

map=2.1 [2016-03-20]

Central Intelligence Agency (CIA) (2015). https://www.cia.gov/library/publications/the-world-factbook/geos/np.html [2015-09-04]

Konsumentverket (2013). *Marknadskontroll av leksaker med magneter och andra magnetvaror*
(Rapport 2013:5). Karlstad: Konsumentverket.

Department of Urban Development and Building Construction (DUDBC) (2007). *Seismic design of buildings in Nepal.* Kathmandu: Department of Urban Development and Building Construction

EMF (2014). *Environmental Management Framework for Higher Education Reform Project Nepal.* Project Components, ss. 1-3. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2014/09/17/000442464_20140917120220/Rendered/PDF/E46410SAR0EMF000Box385324B00PUBLIC0.pdf [2015-09-20]

Enginering Toolbox (2016). *Specific heat capacity. http://www.engineeringtoolbox.com/specific-heat-capacity-d_391.html* [2016-05-19]

Enginering Toolbox (2016). *Thermal conductivity.*

http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html [2016-05-19]

EQUA Simulation AB (2013). *IDA Indoor Climate [User Manual]*. http://www.equa.se/deliv/ICE45eng.pdf?lic=ICE40:4812%20 [2016-02-08]

Fuller, R.J. & Zahnd, A. & Thakuri S. (2007) *Improving comfort levels in traditional high altitude Nepali house*. Elsevier, Building and Environment 44, 15 April 2008, ss. 485.

INSEC & DFHRI (2015). *Unilateral Coercive Blockade Imposed by Indian on Nepal. http://www.inseconline.org/pics/1446549391.pdf* [2016-09-03]

Isolina (2016). Linisoleringsbroshyr. http://www.isolina.com/se/IsolinaBroschyrSWE.pdf [2016-04-05]

Lantz, Annika. (1993). *Intervjumetodik*. Lund: Studentlitteratur

Merriam, Sharan. (2010). *Fallstudien som forskningsmetodik*. First edition. Lund: Studentlitteratur.

Meteotest (2016). *Features*. http://www.meteonorm.com/en/features [2016-02-08]

Nepal Environmental and Scientific Services (NESS) (2014). Grid solar and energy efficiency project. *Indigenous People and Vulnerable Community Planning Framework,* ss. 1. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2014/06/23/000442464_20140623123152/Rendered/PDF/IPP7270P14634400Box385251B00PUBLIC0.pdf [2015-09-20]

Nevander L E och Elmarsson B, 1994. *Fukthandbok. Praktik och teori*. Svensk Byggtjänst, Stockholm.

Rosenlund, Hans. (2001) *Climatic Design of Buildings using Passive Techniques*. Diss. Lunds universitetet. Lund: Univ.

Sandin, Kenneth. (2011). *Praktisk byggnadsfysik*. Lund: Studentlitteratur.

Shrestha, Vinod Prasad. (2007). *A Concise Geography of Nepal*. Kathmandu: Mandala Publications.

Trost, Jan. (2010). *Kvalitativa intervjuer*. Fourth edition. Lund Studentlitteratur AB.

Wfeist (2016). *Building envelope*. http://www.passipedia.org/planning/thermal_protection [2015-09-17]

Teleman, Y. (2016). In-house document. *Pre-study for a new master program at Kathmandu University, with focus on insulation*. [Unpubliced prestudy]. Lund: Lunds tekniska högskola, avd. Energi- och Byggnadsdesign.

# Appendix

## Appendix 1

*Specifics for thermal bridges*

| Elements of construction joints | Unit | |
|---|---|---|
| External wall/internal slab | W/K/(m joint) | 0.4 |
| External wall/internal wall | W/K/(m joint) | 0.4 |
| External wall/external wall | W/K/(m joint) | 0.8 |
| External windows perimeter | W/K/(m perim) | 0.4 |
| External doors perimeter | W/K/(m perim) | 0.4 |
| Roof/external wall | W/K/(m joint) | 0.8 |
| External slab/external walls | W/K/(m joint) | 0.8 |
| Balcony floor/external walls | W/K/(m joint) | 1.2 |
| External slab/internal walls | W/K/(m joint) | 0.4 |
| Roof/internal walls | W/K/(m joint) | 0.4 |

# Appendix 2

*Zone defaults for "Entrance and storage"*

| Entrance and storage room Zone defaults | Description | Specifics | Value | Unit |
|---|---|---|---|---|
| General | | | | |
| Room units | No heating, no cooling | | | |
| Room height | | | 1.9 | m |
| Furniture | | Covered part of the floor | 50 | % |
| | | Weight per area with furniture | 25 | kg/$m^2$ |
| Air | No central AHU | | | |
| Advanced | | | | |
| Elements of construction | Same as "Building default" | | | |
| Room units | | Room unit power | 0 | W/$m^2$ |
| Internal gains | | | | |
| Occupants | Never present | Number of occupants | 0 | No./$m^2$ |
| Equipment | None | | | |
| Light | On 06.00-08.00, 19.00-21.00 | | 1 | Quantity |

## Appendix 3

*Table xx: Zone defaults for "Living area"*

| Kitchen template Zone defaults | Description | Specifics | Value | Unit |
|---|---|---|---|---|
| **General** | | | | |
| Room units | No heating, no cooling | | | |
| Room height | | | 1.9 | m |
| Furniture | | Covered part of the floor | 20 | % |
| | | Weight per area with furniture | 15 | $kg/m^2$ |
| Air | No central AHU | | | |
| **Advanced** | | | | |
| Elements of construction | Same as "Building default" | | | |
| Room units | Firewood stove, burning from 06.00-08.00, 10.30-12.30, 16.00-19.00 every day and 19.00-06.00 from October to last of March. | Unit power | 139 | W |
| **Internal gains** | | | | |
| Occupants | People are expected to be in the room 18.00-08.00 | Number of occupants | 5 | |
| | | Activity level | | met |
| | | Sleeping | 0.7 | |
| | | Cooking | 1.8 | |
| | | Eating | 1.0 | |
| | | Clothing | 1.1 | clo |
| Light | On 06.00-08.00, 10.30-12.30, 16.00-21.00 | | 1 | Quantity |