Climate responsive building design in warm and humid climates

Analysis of passive design and the impact on indoor thermal comfort in Dar es Salaam, Tanzania.

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Abstract

This study assess climate consideration in building designs and aims to explore the extent of passive house performances in warm and humid climates. Previous studies have shown significant correlation between climate conscious building designs and meaningful improvements in indoor climate. The study uses a number of indices that are used to summarize indoor climatic parameters that describes human thermal comfort. Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) comfort model in conjunction with Gagge's Standard Effective Temperature (SET) are used as a reference for the indoor thermal comfort.

According to the Intergovernmental Panel on Climate Change, (IPCC), the building sector was in the year 2010 responsible for 24% of the global greenhouse gas emissions. As the developing countries of the world keep industrializing and evolving economically, the global energy use will fatefully increase. A big part of the increased energy usage will undoubtedly come from all the new houses that are going to be built as well as the increasing usage of air conditioning units and other electrical home appliances. The rate of urbanization is growing rapidly, particularly in developing countries as increasing number of people move to urban areas in search for opportunities. Today, one out of four people live in urban areas and this number is expected to increase. Due to the shortage of affordable housing, lack of opportunities and the high cost of living in major urban areas has resulted in the rise of informal settlements, so called slums. For instance, two third of close to five million inhabitants of Dar es Salaam live in informal settlements according to the 2013 government census. Generally, building designs in developing countries follow international trends or the architecture of temperate countries neglecting the prevailing local climate conditions. This results in buildings that are designed for a wrong climate at a wrong place. In order to fix the indoor climate requires the use of mechanical ventilation which further increases the cost for housing, energy use and maintenance. This remains huge challenge in developing countries such as Tanzania where resources are limited.

Comparative housing studies were carried out on traditional, contemporary and modern housings in terms of building design, orientations and construction materials. Parametric model simulations were generated and used to determine the influence of various design features on indoor climates in terms of the human thermal comfort and cooling energy demand whenever necessary. According to the simulations, buildings in warm and humid climates have the potentials of obtaining and maintaining the human requirements for adequate indoor thermal comfort given the buildings are properly designed according to prevailing climatic conditions. From the analysis of the parametric model simulations, the study concludes that design parameters have significant influence on the indoor thermal comfort and potential to reduce the need for mechanical ventilation. The use of various design parameters in buildings in warm and humid climate is highly recommended as a means to regulate the indoor thermal comfort, lower the building costs and eliminate or significantly reduce the need for mechanical ventilation systems.

Keywords: affordable housing, building designs, climate considerations, thermal comfort, developing countries, Dar es Salaam

Sammanfattning

Denna studie utforskar klimatanpassad byggnadsdesign och syftar till att utforska effektens omfattning av passiva designtekniker i varmt och fuktigt klimat. Tidigare studier har visat ett tydligt samband mellan klimatanpassade byggnadsdesigner och förbättrat inomhusklimat. Studien använder ett antal index som används för att sammanfatta de inomhusklimatiska parametrarna som beskriver människans termiska komfort. Fangers Predicted Mean Vote (PMV) (and Predicted Percentage of Dissatisfied (PPD) komfortmodell i kombination med Gagges Standard Effective Temperature (SET) används som referens för inomhus termisk komfort.

Enligt FN:s klimatpanel (Intergovernmental Panel on Climate Change, IPCC) var byggsektorn 2010 ansvarig för 24% av de globala utsläppen av växthusgaser. När världens utvecklingsländer fortsätter att industrialiseras och utvecklas ekonomiskt, ökar den globala energianvändningen ödesdigert. En stor del av den ökade energianvändningen kommer utan tvekan komma från alla de nya hus som kommer att byggas, liksom den ökande användningen av luftkonditioneringsaggregat och andra elektriska hushållsapparater. Urbaniseringsgraden växer snabbt, särskilt i utvecklingsländer, eftersom allt fler flyttar till stadsområden på jakt efter möjligheter. Idag bor en av fyra personer i stadsområden och detta antal förväntas öka. På grund av bristen på bostäder till rimliga priser har brist på möjligheter och de höga levnadskostnaderna i större stadsområden resulterat i uppkomsten av informella bosättningar, så kallade slumområden. Till exempel, idag bor två tredjedelar av nära fem miljoner invånare i Dar es Salaam i informella bosättningar enligt 2013 års folkräkning. Generellt, byggnadsdesign i utvecklingsländer följer internationella trender eller arkitekturen i tempererade länder som försummar helt de rådande lokala klimatförhållandena. Detta resulterar i byggnader som är konstruerade för fel klimat på fel plats. För att kunna lösa inomhusklimatet krävs användning av mekanisk ventilation som ytterligare ökar kostnaden för bostäder, energianvändning och underhåll. Detta är stor utmaning i utvecklingsländer som Tanzania där resurserna är begränsade.

Jämförande bostadsstudier utfördes på traditionella, nutida och moderna hus med avseende på byggdesign, orientering och byggmaterial. Parametriska modellsimuleringar har använts för att studera den påverkan som olika designval har på inomhusklimatet när det gäller mänsklig termisk komfort och behov av tillförd kylenergi vid behov. Enligt simuleringarna har byggnader i varma och fuktiga klimat möjligheter att uppfylla och behålla de mänskliga kraven på tillräcklig termisk inomhuskomfort om byggnaderna är väl utformade enligt rådande klimatförhållanden. Från analysen av parametriska modellsimuleringar drar studien slutsatsen att designparametrar har betydande påverkan på den termiska inomhuskomforten och potentialen att minska behovet av mekanisk ventilation. Användning av olika designparametrar i byggnader i varmt och fuktigt klimat rekommenderas starkt som ett sätt att reglera den termiska komforten inomhus och sänka byggnadskostnaderna och eliminera eller minska behovet av mekaniska ventilationssystem.

Nyckelord: prisvärda bostäder, byggnadsdesign, klimatanpassning, termiska komfort, utvecklingsländer, Dar es Salaam

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List of abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
NHBRA	National Housing and Building Research Agency, Dar es Salaam, Tanzania
UNDP	United Nation Development Programme
GDP	Gross Domestic Product
HDI	Human Development Index
SIDA	Swedish International Development Cooperation Agency
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SET	Standard Effective Temperature
MET	Metabolic rate
HVAC	Heating, Ventilation and Air Conditioning
IPCC	The Intergovernmental Panel on Climate Change
Clo	Clothing Insulation value
DBT	Dry Bulb Temperature
WBT	Wet Bulb Temperature
DPT	Dew Pont Temperature
MRT	Median Radiant Temperature
DARCH	Dar es Salaam Centre for Architectural Heritage
A/C	Air-Conditioning (unit)
BBCC	Building Bio-Climatic Chart

1 Introduction

1.1 Background

The building sector was in the year 2010 responsible for 24% of the global greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) has in their fourth assessment report stated that catastrophic consequences on the world's ecosystems and water resources can incur if the global temperature rise, relative to the pre-industrial era, isn't kept below 2 °C (Butera 2014). As the developing countries of the world keep industrializing and evolving economically, the global energy use will fatefully increase. A big part of the increased energy usage will undoubtedly come from all the new houses that are going to be built as well as the increasing usage of air conditioning units and other electrical home appliances.(Butera 2014)

Cities are becoming homes to an increasing number of people and the rate of urbanization is increasing globally, particularly in developing countries. Tanzania like many other developing countries has seen significant increase in its urban population, an increase of 10% by the last ten years. The largest city in Tanzania, Dar es Salaam is home to some 4.4 million inhabitants(National Bureau of Statistics 2013) in which an estimated 75% live in slum areas(UN-HABITAT 2010). Today, one out of four people lives in urban areas and this number is expected to increase. Due to the shortage of affordable housing, lack of opportunities and the high cost of living in urban areas has created the rise of informal settlements, so called slums. The informal settlements are often set up without permission from the municipality, thus have no proper planning, climate assessments and lacks the basic infrastructure such as sewage, waste management and access to water.

The shortages and urgent need for housing often leads to buildings that are set up quickly to alleviate the situation however, this is done so without proper environmental and climatic assessments. Very often building designs in developing countries follow international trends or the architecture of temperate countries, and architectures rely on engineers to "fix" the indoor climate. This can be done using mechanical ventilation and cooling systems, but at high annual costs for energy and maintenance. This is a huge challenge in Tanzania where less than 20% of the population have access to electricity (Msyani 2013).

The results of the study are applicable not only in Tanzania, but also in other developing countries with similar climates. It is worth mentioning nonetheless that the simulations, weather data and other retrieved information in the rapport may be limited to the geographical location of Dar es Salaam, Tanzania. The information gathered, and the results of this rapport are hoped to contribute to the bulk of information on efficiency of climate building design in warm and humid climates.

1.2 Aim of the study

Through building designs and material analysis, the study aims to explore the extent of passive house performances in warm and humid climates with the focus on improving the indoor climate and thermal comfort of buildings. In addition to the building designs, the study is also examining with the aim of understanding the planning and the development process of affordable housing in Dar es Salaam, Tanzania. Consideration will be given to the local circumstances such as the climate conditions, available building materials, building techniques, living costs, traditions, and lifestyle.

The term “affordable housing” is ambiguous at best and its definitions is determined differently based on regions and countries. Nonetheless, the general accepted term is “housing which is deemed affordable to those with median household income as determined by the national or local governments”. That is a house that is reasonably adequate in standard and location for lower or middle-income households and does not cost so much that a household is unlikely to be able to meet the other basic needs on sustainable basis.

1.3 Research objectives

The primary objective for the study is to determine which design features that contributes to better thermal comfort through passive means. These should lead to less variations in operative temperatures of the buildings throughout the day and night, all year around.

The expected result of the study is to highlight the most important design features and combination thereof which affects indoor climate and contribute to better thermal comfort in a naturally climatized house. In a long-term perspective, the acquired knowledge can contribute to improve planning and development for low-cost energy efficient housing which will lead to better infrastructure, lower energy use and improved indoor climate.

1.4 Research questions

1. To what extent and in what ways do various construction techniques, material and design choices influences thermal comfort in warm and humid climates?
2. In what ways can geometry and orientation of buildings be combined to minimize solar heat gain in warm and humid climate?
3. What effect do shading techniques such as roof overhangs/eaves and windows shading devices have on the indoor temperature?
4. Do the use of higher window proportions in naturally climatized house enables better cross-ventilation and lowering of indoor temperature?
5. What effect do the use of night (flushing) ventilation have on indoor temperatures in relations to buildings thermal mass?
6. What effects do optimizing various design parameters on existing buildings in warm and humid climates have in terms of thermal comfort and cost saving and energy use?

1.5 Scope of the study

There are many ways to improve the indoor climate through various passive methods. To limit the scope of the study, the primary focus is on lowering the indoor operative temperature, in other words the indoor thermal comfort as well as the variations of the same by any of the means below.

- Orientation regarding solar radiation and wind
- Colour of external surfaces
- Shading techniques
- Natural ventilation and passive cooling
- Shape and geometry of building
- Properties of construction materials

Only two common materials for the walls and roof are chosen and compared to each other regarding cost and cost/performance-effectiveness. Internal loads, i.e. heat produced by humans and electrical equipment inside the building, is not considered.

1.6 Methods

The study of this thesis is carried out as a minor field study within the fields of sustainable development in built environment. The study is done in close collaboration with several organizations based in Dar es Salaam, Tanzania, beginning with *Ardhi University*, *School of Architecture and Design*. In addition to the university, other collaborations include local governmental organizations such as the *National Housing and Building Research Agency* which is tasked with researching on building designs and construction materials to promote the use of locally sourced low-cost sustainable building materials. The structure of the thesis reflects the order of our studies.

1.6.1 Literature review, climate data analysis and interviews

The literature and climatic data used ranges from general to specific which are directly related to the subject of the study and are used to varying degrees. Issues from the geographical locations, tropical weather and its impact on building designs and materials are discussed and analyzed. Indoor thermal comfort and related issues from international standards and previous studies on warm and humid tropical climates are presented and discussed in detail.

The first phase has involved studying the history and the development of the building designs in Tanzania to get familiar with the development of both the building techniques and construction materials. This began with field trips to the cities of Dar es Salaam and Zanzibar to study the design and the structures in and around the old cities. This is combined with an architectural tour of city of Dar es Salaam organized by Dar es Salaam Centre for Architectural Heritage, DARCH to gain an understanding of the historical development of the city. The emphasis has been given the changes that has taken place in areas of housing design and the use of building materials, and what factors that has contributed to these changes. This includes the process of gathering the necessary data and facts in the field with the support from the field supervisor. During this phase, data and facts are obtained from various sources that are deemed highly reliable on the topic of this thesis. Apart from literature such as books and articles on building technology and design in tropical climates, other sources include interviews conducted with professionals in the field about the accessibility, quality, and cost of building materials. The first phase concludes with choosing a single family detached house as a study object for the thesis.

Climate measurements that are used in the report were carried out in two different locations in Dar es Salaam. One measurements were taken at the reference house, both indoor and outdoor and the other measurements such as the wind roses, annual temperature and radiations at a roof of a 12 m high building in the city centre of Dar es Salaam. With regards to indoor measurements taken from the reference house was done using handheld laser thermometer. In combination of stationary thermometer, air and surface temperatures were taken inside the house. Indoor air and surface temperatures were used to obtain the operative temperature of the house. These measurements are presented in tables and figure in details throughout the report.

1.6.2 Comparison study of housing types

The second phase has involved the studying and analyzing of the study object both in theory and practice regarding design choice, properties of the building materials and the orientation of the building regarding solar radiation and prevailing wind directions. The study is looking at the housing development and building techniques in Dar es Salaam, Tanzania and examine how different building designs have changed and what contribution it has on the thermal indoor temperature and human comfort.

There are two main different housing types that are referred to throughout this study. These are;

Naturally climatized house: is a building which does not make any use of mechanical ventilations for either cooling or heating. They are naturally ventilated with operable windows and ceiling fans.

Actively climatized house: is a building which partly or wholly rely on mechanical ventilations for either cooling or heating.

A point to note: the house in which this study was partly conducted is actively climatized house having air conditions system installed. However, when this study was carried out the house was in a naturally climatized period due to lower than normal temperature brought about by the rainy seasons.

1.6.3 Model simulations

In the third phase, model simulations of fictive reference designs are carried out using assorted design aspects to produce an optimal design model regarding thermal comfort. The various aspects taken into consideration during the simulation of the model include:

1. Design and geometry of the model.
2. Orientation regarding the sun and wind.
3. Colour choice for external surfaces.
4. Properties of construction materials, e.g. thermal inertia, time-lag, absorptivity, and emissivity.
5. Shading devices for windows and walls.
6. Natural ventilation and passive cooling means.

The software used for the model simulations is called DEROB-LTH, a dynamic and detailed energy simulation tool originally developed at Austin School of Architecture, University of Texas and further developed at the Faculty of Engineering, Lund University. It has accurate models to calculate the influence of solar insolation and shading devices on the energy balance in the building. Other instrument and software used during the course of the study includes small portable weather station for measurements of in and outdoor temperatures, humidity, pressure, windspeed and precipitation in addition to a combined Thermo and Hygrometer Data Logger.

1.6.4 Analysis and discussions

Analysis of the model simulations is offering hindsight on the significance of climate consideration in building designs and the influence this has on the improvement of indoor climate and thermal comfort in warm and humid climates. Findings of the model simulations are compared with the previous research on the subject and see how well it correlates. Lastly, the study is providing suggestions based on the parametric model simulations regarding the optimal design model and combination thereof of different design features that contributes to best indoor climate in warm and humid climates. The result of the building designs and the different construction techniques carried out in this study and analysis of the study object as well as the simulation model are applicable not only in Tanzania but similarly to buildings that are found in warm and humid climates elsewhere.

2 Tanzania

2.1 Background

Tanzania is a country situated in Eastern Africa that borders with Burundi, Kenya, Malawi, Mozambique, Rwanda, Uganda, Zambia, Democratic Republic of the Congo, and the Indian Ocean. With a total area of 947,303 km² and a population of about 55 million people, it is the largest and most populous country in East Africa. The capital city is Dodoma whereas the largest city is Dar es Salaam which was the country's former capital city and remains the commercial hub of the country and to large degree functions as de facto capital. Dar es Salaam accounts for about 10% of the country's population with current estimates puts close to 5 million. The country is made up of the mainland Tanganyika and Zanzibar archipelago which forms the United Republic of Tanzania after it gained its independence from United Kingdom in the 1960s(World factbook 2018).

Due to recent economic development and the relative peace in the country, an influx of people from rural parts of the country to urban areas seeking opportunities can be seen. This has led to an increase of the urban population and the shortages of housing in major urban areas of the country as a result. In terms of development according to the United Nation, Tanzania is still classified as developing country with low Human Development Index. Human Development Index is composite statistical method that looks at life expectancy, education, gross domestic product or GDP per capita which puts the country at the 151st position on the list of countries by development index (UNDP 2016). Currently Tanzania has one of the fastest growing economies in sub-Saharan Africa with an annual growth of around 6-7% based on its vast natural resources and tourism. Agriculture remains the backbone of the country's economy which accounts for slightly one quarter of gross domestic product however employs about 65% of the labor force(National Bureau of Statistics 2017). The country has several major tourist attractions both in northern regions which contains the major national parks and games reserves such as the world-renowned Serengeti National Park and Ngorongoro Conservation Area as well as Mount Kilimanjaro, the highest point in Africa. The East coast and the Zanzibar archipelago is also major tourist attractions. Tourism in the country accounts for about 18% of Tanzania's gross domestic product and employs about 11% of country's labor force. Approximately 38% of the country's land is set aside in protected areas for conservation which is home to national parks, games reserves and other conservations areas and marine parks(Tanzania Tourism Board 2017).

The country's population are unevenly distributed and concentrates mainly on northern regions and eastern coast of the country whereas other parts of the country remain sparsely populated. Much of the population is young, under the age of 15 which constitutes about 45% of the total population. The country is multicultural which consist of over 100 different ethnic groups with sizable populations of Arabs, Asians and Europeans. Due to its diverse multicultural communities, more than 100 different languages are spoken in the country by the different groups making the most linguistically diverse country in East Africa. There is no de jure official languages in the country however Swahili and English are widely spoken and are language of instruction in most institutions and business sector.

2.2 Geography

The country is situated at the East coast of Africa, close to the equator just 6°00′S 35°00′E and thus has warm and humid equatorial climate conditions with regional variations due to its topography. North of the country forms the highlands with slightly cooler temperatures ranging between 10 and 20 °C whereas the lowlands and the coastal areas have much higher temperature variations of around high 20 and 30 °C during the dry seasons. The country experiences main rainy seasons between the end of March and late May with a fall in temperature and may cause some flooding problems. Minor rainfalls can also be seen between October and December.

Figure 1 Tanzania in Africa and map showing position of Dar es Salaam (Google Maps).

2.2.1 Dar es Salaam

2.2.1.1 Urbanization and housing deficiency

Being the largest city and an important economic hub for the country, Dar es Salaam has seen the largest increase of its population accounting for 10% of country's population. The large influx of people to the city has led to acute shortage of affordable housing. This in turn has created the development of informal settlement in the city which now account for about 75% of the population in Dar es Salaam, living in slums with no proper housing and infrastructure. A survey made by the National Bureau of Statistics 2011/12 shows that the total housing demand within the country then was 3,000,000 dwelling units(J. M. Twwimanye, Hadija 2015), with an estimated annual growth of 300,000 units(Kwanama 2015). With an urban growth rate between 3 and 5%, Dar es Salaam is one of the ten fastest growing large cities in the world. Accompanied with the fact that about 80% of the population in Tanzania cannot afford a house with decent living standard, the need for low cost houses with optimal climate responsive building designs is immense.(Kwanama 2015)

2.2.1.2 Historical influences of the city and its architectural building design

The present-day Dar es Salaam was established in the 1860s by Sultan Majid bin Said of Zanzibar. Arab traders from the Persian Gulf most notably from Oman established trading routes and settled down around the east coast of Africa. The Arab influence of the coastal towns and Zanzibar archipelago can still be traced through its architecture and buildings types which is characterized using coral stones and mangrove woods as the principle building materials. This is demonstrated clearly in Stone town, the old city in Zanzibar and Asian zone of the old neighborhood of Dar es Salaam. The country later under the influences of European countries led by Germany and later by Britain. Germany laid the foundation for the planning of the city during the colonial period with characteristics of German and European architecture. As the consequences of the different influences, the city has three distinctive zones based on the history, architecture and building materials which gives glimpses of the early divisions of the city center clearly demarcating the African, Asian, and European zones. According to the Dar es Salaam Centre for Architectural Heritage (DARCH), remnants of those earlier divisions of the city is still evident.

2.3 Climate characteristics

This study refers to a warm-humid climate. (Koenigsberger et al 1973) after (Atkinson 1953) defines this climatic type as warm-humid equatorial climate, found near the equator. According to Köppen climate classification, the climate of Tanzania is classified as tropical climate with characteristics of warm and humid. The climate characteristics of a given region is determined by the pattern of several elements and their combination. The principle natural elements that defines climatic characteristics when human comfort and building design is considered are solar radiation, air temperature, humidity, wind and precipitation (Gut, Ackerknecht 1993, Givoni 1997).

Figure 2 World climate classification after Köppen. Source (Köppen 2018)

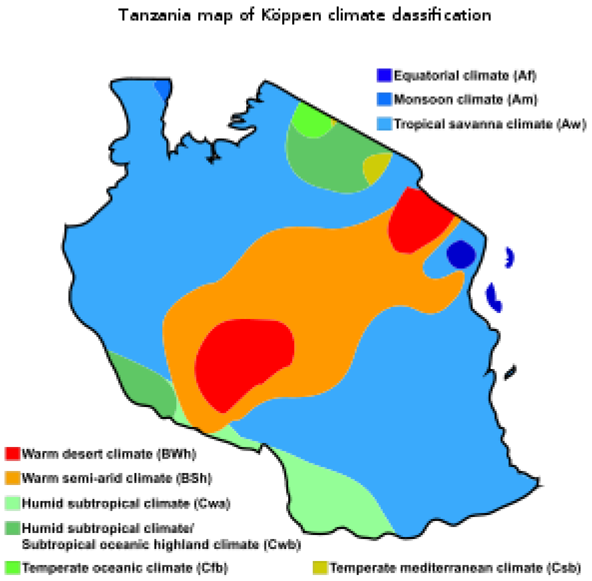


Figure 3 Map of Tanzania showing Köppen-Geiger climate classification. Source (Köppen 2018)

2.3.1 Climate of Dar es Salaam

Dar es salaam lies within the warm and humid equatorial climate zone due to its proximity to the equator and shares similar climate to cities such as Ho Chi Minh City (Saigon), Bangkok, Singapore, Jakarta, Madras, Mombasa, Lagos and Manaus. It has tropical wet and dry climate according to Köppen climate classifications. This zone includes the coastal areas, islands, and extends to strip of land from 20 to 100 km wide along the coast. Most of the zone is less than 300 m above sea level. It is never excessively hot, but has high humidity, which causes discomfort. The zone is characterized by permanent high humidity, generally high temperatures, small daily temperature swing, moderate breezes, and high values of solar radiation, except on cloudy days. Along the coast and up to 2-8 km inland, depending on the terrain the prevailing north-east and south-east monsoon winds are modified by sea-land breezes during the day and, to a much lesser extent, by land-sea breezes at night. February is the warmest month of the year. The temperature in February averages 27.9 °C. July is the coldest month, with temperatures averaging 23.8 °C. There is a difference of 228 mm of precipitation between the driest and wettest months. Throughout the year, temperatures vary by 4.1 °C. The average annual temperature in Dar es Salaam is about 25.9 °C with average annual precipitation of between 900-1,250 mm.

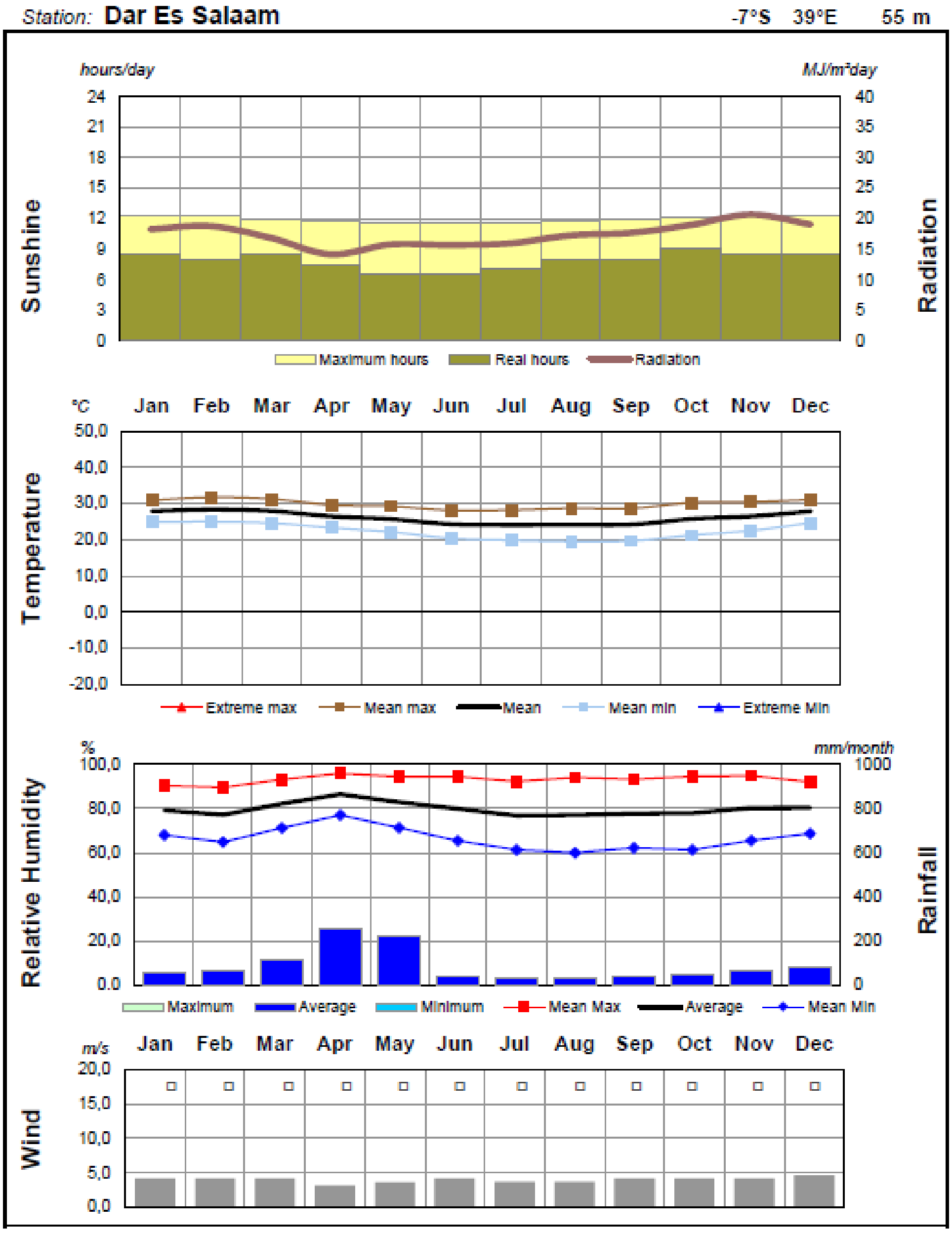


Figure 4 Annual climate data for Dar es Salaam (Johansson 1990).

During the hottest months, the Physiologically Equivalent Temperature (PET) reaches values between 35 and 40°C in afternoons in February. The prevailing wind direction during the hottest months (February-March) is from Northeast. The dominating wind direction for most months (May-October) is however from south-southwest. The wind roses based on measurements at the roof of a 12 m high building in the city centre of Dar es Salaam is shown below.

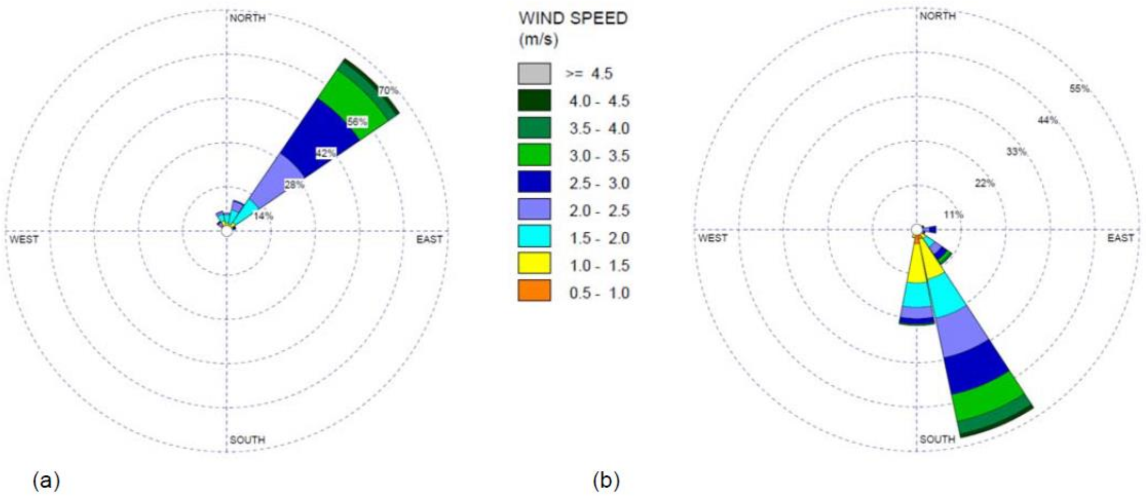
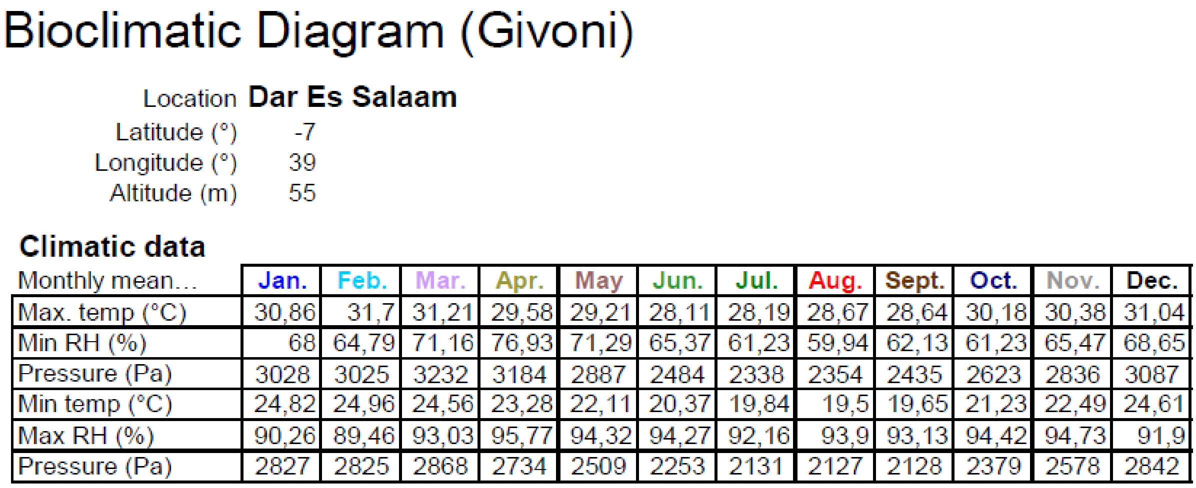


Figure 5 Calculated Wind roses for Dar es Salaam based on measurements. (a) February 2015, (b) July 2014 (Johansson 2015)

The building bio-climatic chart developed by Givoni (1976) enables architectures to determine the appropriate strategies to be adopted in the building design in order to achieve indoor thermal comfort. Due to the different climatic conditions in each climatic zone different studies are made. Climatic data, bioclimatic chart analysis. In a process known as bioclimatic architecture, an architect uses the bioclimatic chart to design buildings that include the most efficient passive cooling and heating strategies based on the climate and location of a building site. Graphically, the BBCC is drawn on a conventional psychrometric chart, like the ASHRAE chart. The BBCC suggests boundaries of the climatic conditions within which various building design strategies, as well as passive and low-energy cooling systems, can provide indoor comfort in hot climates without air conditions. The cooling option include:

a) Daytime ventilations
b) High mass, with or without and nocturnal ventilation
c) Direct evaporative cooling
d) Indirect evaporative cooling by roof ponds



Bioclimatic Diagram (Givoni)

Location **Dar Es Salaam**
Latitude (°) -7
Longitude (°) 39
Altitude (m) 55

Climatic data

Monthly mean…	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Max. temp (°C)	30,86	31,7	31,21	29,58	29,21	28,11	28,19	28,67	28,64	30,18	30,38	31,04
Min RH (%)	68	64,79	71,16	76,93	71,29	65,37	61,23	59,94	62,13	61,23	65,47	68,65
Pressure (Pa)	3028	3025	3232	3184	2887	2484	2338	2354	2435	2623	2836	3087
Min temp (°C)	24,82	24,96	24,56	23,28	22,11	20,37	19,84	19,5	19,65	21,23	22,49	24,61
Max RH (%)	90,26	89,46	93,03	95,77	94,32	94,27	92,16	93,9	93,13	94,42	94,73	91,9
Pressure (Pa)	2827	2825	2868	2734	2509	2253	2131	2127	2128	2379	2578	2842

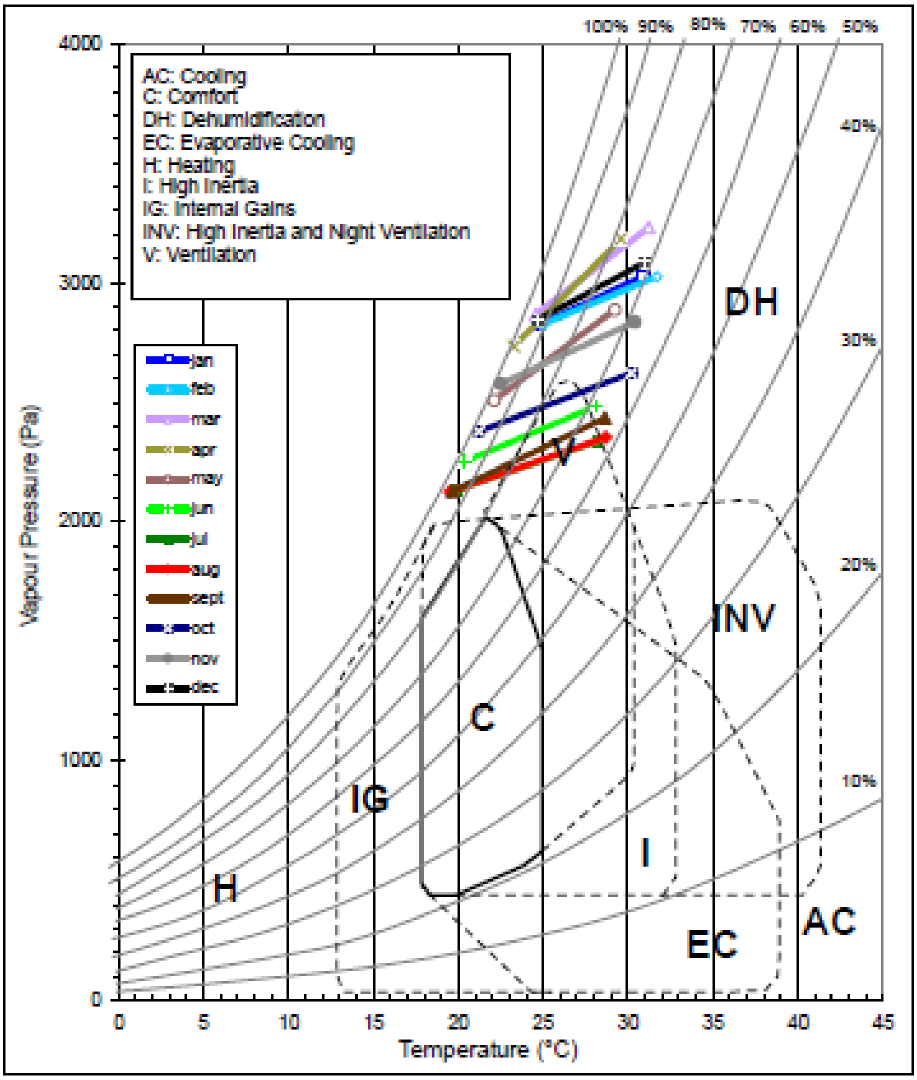


Figure 6 Bio-climatic chart (Givoni 1976)

2.3.1.1 *Air temperature*

Air temperature is one of the most important climate elements and which have significant impact when it comes to human comfort as well as planning of building design. The air temperature is determined by many factors, including incoming solar radiation, humidity, and topography of the immediate environment. The air temperature determines the convective heat exchange between the skin and ambient air (Givoni 1997). Air temperature is measured with a dry bulb thermometer, (DBT) protected from solar and heat radiation. This data is generally available in meteorological records as monthly means, maximum and minimum values (both normal and extreme). The wet bulb temperature (WBT) is the temperature at which vapor saturation occurs (Rosenlund 2000).

2.3.1.2 *Humidity*

Humidity describes the amount of water vapor present in the air. It often indicates the likelihood of rainfalls or fog and is measured in either absolute, relative or specific humidity. The most commonly used is relative humidity, (RH %) expressed as percentage which measure the current absolute humidity in relation of the maximum humidity for a given temperature.

$$\frac{humidity\ at\ saturation\ point\ (\frac{g}{m^3})}{effective\ humidity\ (\frac{g}{m^3})} \times 100 = \cdots \% \qquad \text{Equation 1}$$

The relative humidity varies with the temperature. In the morning, when the temperature is comparatively low and relative humidity high, up to 95%, but in the afternoon when the temperature rises, the relative humidity is normally lower, around 60%. An exception in the rainy seasons, when the temperature and relative humidity do not vary much throughout the day (Adamson, Aberg 1993). Humidity is very important element of the weather because the impact of humidity on human thermal balance and on comfort is complex. The role of the humidity is in its effect on the environment potential for evaporation and the way by which the body adapts to changes in the evaporative potential. Under humid conditions, the *rate* at which perspiration evaporates on the skin is lower than it would be under arid conditions. At higher humidity levels its effect om human comfort and physiology is indirect, though its effect on evaporative capacity of the air. A higher humidity reduces the evaporative cooling from a given surface area of the skin, but the body can counter this reduction by spreading the sweat over skin and thus increasing the fraction of the skin surface from which evaporation takes place(Givoni 1997).

The humidity level affects the amount and the rate a person perspires and therefore influences how temperatures are felt. High humidity reduces the comfortable maximum temperature, low humidity allows a tolerance for higher temperature. However, at the lower limit of the comfort level humidity has little influence(Gut, Ackerknecht 1993).

2.3.1.3 Precipitation

A major factor of the climatic characteristics is water. It occurs as rain, hail, snow, clouds and vapor. Annual precipitation differs considerably in different regions and have significant impact on human comfort and settlements whether in building design, agriculture or other human activities. In warm-humid regions in which Tanzania falls under, the types and quantity of seasonal distribution of precipitation is manifold. These differences in precipitation patterns are reflected in construction details and is illustrated by typical building types for different regions(Gut, Ackerknecht 1993).

2.3.1.4 Solar radiation and wind conditions

Solar radiation is the main source of earth’s energy and thus determines the earth’s temperature and wind conditions. The temperature at a given latitude depends on the angle of incidence of solar rays to the ground: it is highest at the equator and lowest at the poles. The higher the angle of incidence and thus the lower the latitude the more energy reaches the ground and the higher the air temperature. Regional winds derive from the difference in air temperature and thus pressure between northern and equatorial latitudes (Butera 2014). Due to its proximity to the equator, the country receives large amount of solar radiation, amongst the highest in the world throughout the year. The amount of solar radiation in different parts of the earth’s surface is determined by the geometry and the rotation of the sun and the distance from the equator. The angular rotation of the earth around the sun near the equator does not deviate significantly, thus the temperature variation around the equator throughout the year remain very much constant.

This is evident in Dar es Salaam with annual temperature variations between maximum and minimum temperature of just about 4 °C as shown in Figure 4.

Seasonal climate change is the result of the different ways in which the sun’s rays hit the various regions of the earth during the year. This is due to the inclination of the plane of the equator, thus to the inclination of earth’s axis. The tilt of earth’s axis with respect to the plane of the orbit is constant but the angle formed between the line joining the center of the earth with the center of the sun and the equatorial plane changes day by day. This angle is called the solar declination δ, is equal to zero at the spring and autumn equinoxes and is +23.45° at the summer solstice and -23.45° at the winter solstice as shown in Figure 7. The angle of solar declination varies continuously, very slowly, and for our purposes it can be assumed that its value is approximately constant in a single day; it can be calculated using the formula:

$$\delta = 23{,}45 sin\left[\frac{360}{365}(N+284)\right] \qquad \textit{Equation 2}$$

Where N is the progressive number of the day of the year (N = 1 for 1st Jan., N = 365 for December 31st; for example: March 21st corresponds to (N = 31 + 28 + 21 = 80).

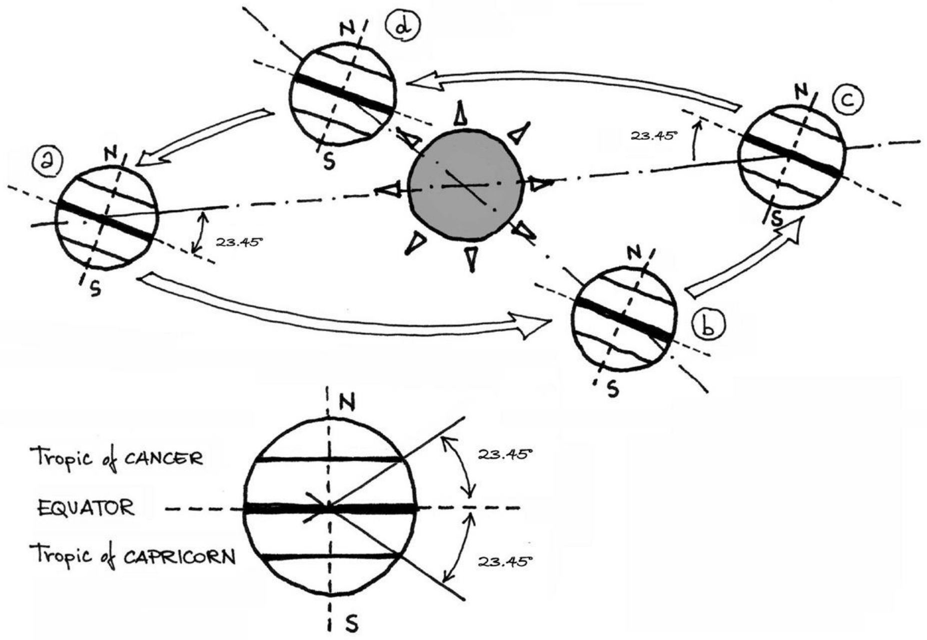


Figure 7 Solar declination angle. (A) Summer solstice; (B) Autumn equinox; (C) Winter solstice; (D) Spring equinox.

Coastal areas are subject to various factors that can affect solar radiation. The development of sea breezes sometimes leads to the formation of clouds which move inland with increasing speed and density during the day, and so the local solar radiation pattern is also affected. Another factor to be considered is that the atmosphere of the coastal zones is characterized by greater turbidity than that of the inner zones, due to the presence of aerosols and saltiness; this factor can contribute significantly to a change the in the ratio between the values of direct and global radiation.

The pattern of radiation closely follows the monsoon system, the radiation is at its lowest at the end of march and beginning of April when the rain-laden cloud cover is heaviest. During the cool season in June to august, the cloud cover is less, from mid-august to November the radiation increases, with annual peak in November and slight decrease in radiation during the short rain seasons in November and December (Bodoegaard 1981).

2.4 Housing development and building techniques in Tanzania

2.4.1 Construction materials in use

In a survey made by the National Bureau of Statistics, information about various household characteristics was collected, including construction materials used(National Bureau of Statistics 2015). The materials used in the different structural parts of the house differ largely by area throughout Tanzania. In Dar es Salaam, concrete hollow blocks are predominantly used for the floors and walls, and metal sheets for the roof. In rural areas however, earth floors, walls made with stones, mud or mud bricks (raw or burnt), are mainly used. Grass, leaves and bamboo are common materials for the roofing in the rural areas, although metal sheets are still found more often. The use of concrete for floors and walls, and various types of metal sheets for the roof, is growing year by year as the availability and affordability increases.(National Bureau of Statistics 2015) Concrete and metal sheets are to be considered as modern building materials in Tanzania but are not necessarily the best regarding indoor comfort and environmental friendliness.

Although concrete and metal sheets are modern materials in the sense that they are used most commonly in urban areas, a new generation of cheap and locally sourced building material is currently in development. Therefore, concrete and metal sheets is hereafter, for the sake of this report, named contemporary building materials.

2.4.2 Contemporary building design and construction materials

2.4.2.1 Walls

The contemporary building material used for the outer walls are concrete hollow blocks made of a mix between sand and cement. In Table 1, the typical dimensions and approximative cost is presented.

Table 1 Typical dimensions and cost of sand-cement (concrete) blocks.

Dimensions (LxHxW) [mm]	**Cost/unit**	**Cost/m^2 wall**
450x100x230	1,200 TSH (~0.5 USD)	28,000 TSH (~12 USD)
450x125x230	1,600 TSH (~0.7 USD)	
450x150x230	2,000 TSH (~0.9 USD)	

These building blocks are the ones being widely used as of today, at least in the urban areas of Tanzania as mentioned earlier. However, the blocks are not affordable enough for most of the population, nor are they environmentally sustainable for several reasons. The blocks are industrially produced and need to be transported out to the building site, thus contributing carbon dioxide emission to the atmosphere. The cement content is relatively high requiring both large scale cement production which is energy intensive which leads to high cement price.

The high cement content also makes the blocks unnecessarily strong structurally for simple residential buildings.(Munyaga 2018) Another negative impact on the environment is the extraction of sand, which is a valuable natural resource that is on its path to depletion, causing significant impact on the environment(UNEP 2014).

2.4.2.2 Roof

The contemporary building material used for the roof are various types of metal sheets, such as corrugated iron and aluminum sheets. The cost for these metal sheets depends on the choice of material and quality. The sheets commonly used for residential buildings has an approximate effective cost/m^2 roof of 8,000-12,000 TSH (~3-6 USD).(J. Twwimanye 2018)

The use of metal sheets for roofing has both advantages and disadvantages. The advantages are that they are lightweight, easy to install and relatively cheap. The disadvantages are that they corrode easily, provide minimum thermal resistance and are very noisy when it’s raining.(Svard 1980) Due to corrosion, the sheets used for roofing require careful maintenance such as paintings in order to extend the performance and life span of roofing sheets. Quite often, the roofing sheets need to be replaced a few times during course of buildings life span.

2.4.3 Modern building design and construction materials

The National Housing and Building Research Agency has during recent years done some successful research on locally sourced building materials, making it more affordable and environmentally sustainable. Soil-cement bricks and roofing tiles are the main construction materials on which research has been made. The results from the research have been finalized. The agency has initiated a phase where the materials are made available to the public market.(Munyaga 2018)

The initiative by the NHBRA is aimed at making the building materials more accessible by using easily available low-cost materials and the use of innovative solutions that require less capital. The agency designs the materials as well as the equipment that is used to produce the materials, the operation of the equipment’s requires no technical knowhow and as a consequence low or median income households are able to build adequate affordable housing at reasonable price that’s within their reach. So far, not many houses have been built using the new building materials.

2.4.3.1 Walls

Soil-Cement Interlocking Blocks is the name of the building bricks for walls that NHBRA has adopted and worked on. As the name implies, the bricks are made of a mix between locally sourced soil and cement, unlike sand and cement for the contemporary concrete hollow blocks. The bricks are available in numerous sizes, but there is a main dimension which is used for building structural walls. In Table 2, the main dimension and approximative cost is presented.(J. Twwimanye 2018)

Table 2 Typical dimension and cost of soil-cement interlocking blocks.

Dimensions (LxHxW) [mm]	**Cost/unit**	**Cost/m^2 wall**
300x100x150	500 TSH (~0.2 USD)	17,000 TSH (~7 USD)

The bricks are interlocking, meaning they are shaped in a way that they can safely be stacked upon each other, creating a robust structure without the use of any mortar (Figure 8).

Figure 8 Soil-cement interlocking blocks stacked upon each other.

The side facing inwards is plastered using traditional techniques, mainly for esthetics and wind proofing and to improve stability and strength. The side facing outwards does not need any special treatment other than the joints being filled with mortar. If a higher level of esthetics is desired, the face can be polished as shown in Figure 9. The face polish also acts as water proofing to some extent.

Figure 9 Finished wall with filled joints and polished face

The blocks are produced in a manually operated machine that shapes and compresses the block simultaneously. The manually operated machine shown in Figure 10 produces one block at a time, although manually operated machines for two blocks and automated machines are currently in development. According to the agency, once the products are designed and the equipment's required to produce the materials are completed, they trained people in the industry about the production and the use of the machineries so that they can produce and make the products available to the masses throughout the country. In the rural areas, the use of burnt clay for home buildings is extensive with the main sources of energy used for burning the clay resulting massive deforestation in what government has pointed out as source of environmental concern. By making these low-cost solutions available to the masses, the government hope to reduce the use of burnt clay and save the environment while at the same time addressing the challenges of affordable housing in the country.

Figure 10 Manually operated machine for single block production

These newly developed modern building blocks are both economically and environmentally superior to the traditional concrete blocks already available.

The modern building blocks themselves are nearly half the price of the conventional concrete blocks (per square meter wall). The fact that they don’t require any mortar lowers the total cost even more. Furthermore, the side facing outwards doesn’t require any plaster, reducing the cost even further.

The use of soil as the main ingredient makes the blocks more environmentally sustainable since the sand reserves can be left untouched. Moreover, the soil can often be extracted on the building site, where the blocks are also being produced, minimizing transports. The cement content is usually between 10-13% contrary to the higher percentage 12-17% in contemporary concrete blocks, lowering the production energy usage as a result.

One disadvantage with the blocks is their tendency to deteriorate structurally. As shown in Figure 11, a ten-year-old house where the lowest row of blocks suffers from this problem. According to John Twwimanye, an engineer at the NHBRA, salt is being carried with the winds from evaporation taking place in the Indian Ocean in combination with the very humid climate conditions of Dar es Salaam, causing a chemical reaction in the blocks and loss of strength. A potential solution, suggested by John, is to plaster the lower part of the wall, thus protecting it from rainwater spattering from the ground.(J. Twwimanye 2018)

Figure 11 Moisture induced erosion problem

2.4.3.2 Roof

Sisal Reinforced Soil-Cement Roofing Tiles is the name of the roofing tiles that NHBRA has adopted and worked on. Like the wall blocks, the roofing tiles are made of a mix between locally sourced soil and cement. To make the tiles more rigid and shapeable, fibers from the local Sisal plant are mixed in the mixture. The approximate cost/m^2 roof is 6,500 TSH (~3 USD). As shown in Figure 12 the tiles come in different colours and are installed overlapping each other.

Figure 12 Miniature building model

The tiles are produced in a machine like the one in Figure 13 (A). A plastic sheet is placed at the bottom plate, the rim is locked down and the mixture is poured on. The machine itself is mounted on a wooden table, equipped with a vibrator to make it easier for the mixture to compact and create a smooth surface and sharp edges Figure 13 (B). The rim is then removed, the plastic sheet is transferred onto a mold that is then set aside for the tile to cure Figure 13 (C). When the tile has cured enough to be removed from the mold, it is placed in a water bath to continue the curing process Figure 13 (D). The tiles do not necessarily have to cure in a water bath. A humid environment, under a plastic sheet with regular watering, should be sufficient.(J. Twwimanye 2018)

These newly developed modern roofing tiles are both economically and environmentally superior to the traditional metal sheets already available. The cost is at least the same as the traditional metal sheets. A metal sheet of decent quality however, is double the price of the modern roofing tiles. The environmental benefits are the same as with the soil-cement blocks (see 2.4.3.1). Their thermal resistance is also considerably higher, which theoretically should limit the amount of solar heat energy being transferred through to the inside living environment. They are not as noisy in heavy rain either.

Figure 13 Process of roofing tile production, tile plate form (A), vibrator mix (B), tile moulder (C) and drying and curing (D)

3 Climate and building design

3.1 Climate analysis and building design

There are significant correlations between climate and buildings designs and this has been recognized by earlier Greeks and Roman architects. First records of earlier Roman architect's Vitruvius wrote that it obvious that designs for homes ought to conform to the diversities of climate (Flavin 1980).

Climate conditions remains an integral part and significant factor for consideration when planning building designs and the choice of building materials. The golden rule which is fundamental and applies in all climate conditions is the provision of adequate shelter and the protection of the inhabitants from the adverse outdoor climatic conditions. In cold climates where the outside temperature plunges below zero, the emphasizes is placed in maintaining acceptable level of indoor temperature. This is done through designing well-insulated buildings such that buildings become as air tight as possible to prevent heat escaping from indoor to outdoor of the buildings.

Whereas in cold climates, it serves the building to be as air tight as possible, in warm and humid climates the opposite is true unless the building is heavily dependent on mechanical ventilation, e.g. air conditioning.

3.2 Thermal comfort in warm-humid climates

The indoor climate inside buildings is different from the surrounding outdoor climate. Indoors, people are protected from the physical outdoor weather elements such as the solar radiation and wind gusts which are often harsh and hostile. The outdoor temperatures are usually higher compared to indoors. The actual relationship between the indoor and outdoor climates depends to a great extent on the architectural and structural designs of the buildings and thus the indoor climate can be controlled by building designs to accommodate human comfort needs. The thermal comfort is defined as the range of climate conditions considered acceptable inside buildings. It implies an absence of any sensation of thermal discomfort, be it too cold or too hot. In dealing with heat discomfort, there are two distinct and independent sources of discomfort: the thermal sensation of heat and discomfort resulting from skin wetness, sensible perspirations (Givoni 1997).

When designing buildings, the physiological functions of the human body are to be considered. The physiological factors are of primary importance with regards to comfort. The internal temperature of the human body must always be kept within the narrow limits at around 37°C. Any fluctuations from this value is a sign of illness, and a rise of 5°C or a drop of 2°C from this value can lead to death (Gut, Ackerknecht 1993).

The human body has the ability to balance its temperature by various means. The thermal balance is determined, on the one hand, by the internal heat load and on the other hand by, the energy flow, the thermal exchange between the body and the environment. Thermal exchange between the body and the environment occurs in four different ways, through conduction, convection, radiation, and evaporation by perspiration and respiration.

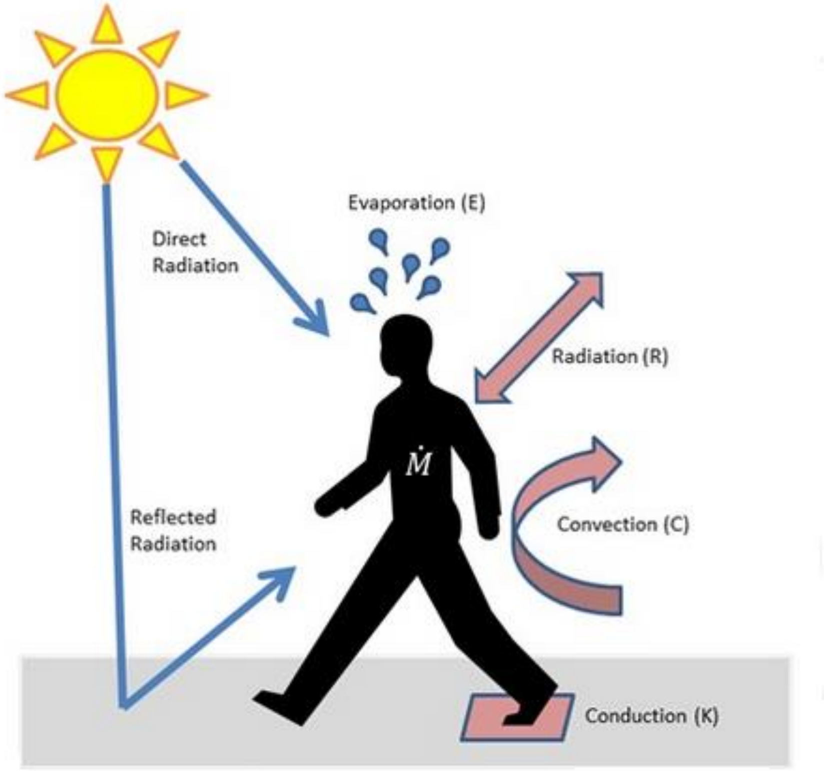


Figure 14 Four modes of thermal exchange of the human body, conduction, convection, radiation and evaporation.

3.2.1 Conduction

The heat exchange process through conduction depends on the thermal conductivity of the materials in immediate contact with the skin. Clothing plays an important role in maintaining and adapting to the prevailing climate whether been cold or warm climates. Light and thin clothes are preferred in warm and humid climates to allow the heat produced by the body through metabolic activities to escape. Having light coloured thin clothes with minimal clothing insulation values allows the better ventilation options. This is the reason it feels better having less clothes on the beach in hot summer days. Similarly, the same way it feels better having heavy clothes in cold climates such as during winter because having more layers of clothes greats better insulation from the cold outside, in addition to the layers of air created by the different layers reduces the heat exchange hence air is poor conductor of heat.

3.2.2 Convection

Convection occurs through fluid motions, in most cases air and depends primarily on the temperature difference between the skin and the air and the movement of air. Convection can be of two types, caused by two forces, by temperature differences, natural and forced air motion generated by wind or fans. When air moves along the skin on warm day, it has cooling effect because the moving air lowers the perceived temperature. This is the same process behind the use of fans or opening windows in homes during the hot summer day in order allow wind into the building for cooling and hygienic ventilation purposes.

3.2.3 Radiation

Radiation takes place between the human body and the surrounding surfaces such as walls and windows, and in open air, the sky and sun by electromagnetic waves across space. Radiation occurs between different body objects with different temperatures that are very close to one another. This exchange of heat happens through the air. This is experienced inside buildings when standing close to windows in cold or hot sunny days or any other area or component of an object which higher thermal conductivity has - commonly known as a thermal bridge - than the surrounding materials, creating a path of least resistance for heat transfer.

3.2.4 Evaporation

in evaporation, the sole compensatory mechanism is loss by evaporation in the form of perspiration, together with, to a certain extent, respiration. During evaporations water absorbs heat, and as humans normally lose about one liter of water a day in perspiration, a fair amount of heat is taken from the body. The lower the vapor pressure, dry air and the greater the air movement, the greater the evaporation potentials. This explains why the extreme temperatures in humid climates are less bearable compared to the same temperatures in dry climates (Gut, Ackerknecht 1993).

3.3 Climate and comfort

Comfort is subjective experience, and few people agree about optimal comfort. To handle comfort, it was deemed necessary to define some kind of index, or comfort zones where the majority of people will experience well-being. This is usually done by votes of a population in an experimental situation. Different researchers developed a number of scales to determined what can be considered optimal thermal comfort as explained in the followings (Rosenlund 2000). People who live in different climate regions adapt to the prevailing climate conditions everything from home buildings and clothes and because how different people perceive the climate of particular region is different. If you ask someone who is from tropical climates about the weather in temperate regions, he or she would most likely perceive the temperature somewhat cold whereas someone who is from the region would perceive it entire differently. People who experience cold winters have adopted to climate and dress accordingly and therefore can tolerate cold weather in similar way someone in warm and humid climates would tolerate much higher temperature than person from temperate regions. This is the reason the comfortability is defined by how the majority of population perceive given temperature condition rather than individual perceptions.

In order to determined what can be considered thermal comfort, there are few parameters that are needed to be established, in other words measured and known. These parameters include the type of clothing, level of activity or the metabolic rate, air temperature, mean radiant temperature, humidity, and air speed.

The internal heat load, the amount of heat a person produces, depends on metabolic activity, the value varies greatly based on the form of activity. The rate at which produced heat is lost to the immediate environment depends on the prevailing climate conditions, but also significantly the type of cloths a person is wearing and its insulation value.

Table 3 Clothing's insulation value in clo (Dahlblom 2010).

Clothing	**Insulation value clo**
Naked	0
Tropical clothing	0,3
Light summer clothing	0,5
Light working clothing	0,7
Normal indoor clothing	1,0
Three-piece clothing	1,5
Polar clothing	4,0
Sleeping back	10,0

Metabolic activity determines the level of energy production as form of heat in the human body. An adult person in sedentary activity produces around 60 W/m^2 and can rises up to 450 W/m^2 with physical activity.

Table 4 Heat generation of an adult person at different activities based on body surface 1.8 m^2.

Activities	**Metabolic rate**	
	Met	W
Sleep	0,8	85
Rest, sitting	1,0	105
School/office work	1,2	125
Medium activity	1,6	160
House work	1,8	180
Walking 5 km/h	3,2	320
Physical activity	3,6	360
Going down stairs	4,7	470
Running 10 km/h	7,4	740

At normal room temperature with sedentary work, the human body releases 40% of the heat through convection, 40% through radiation, 15% through evaporation, 5% through conductions.

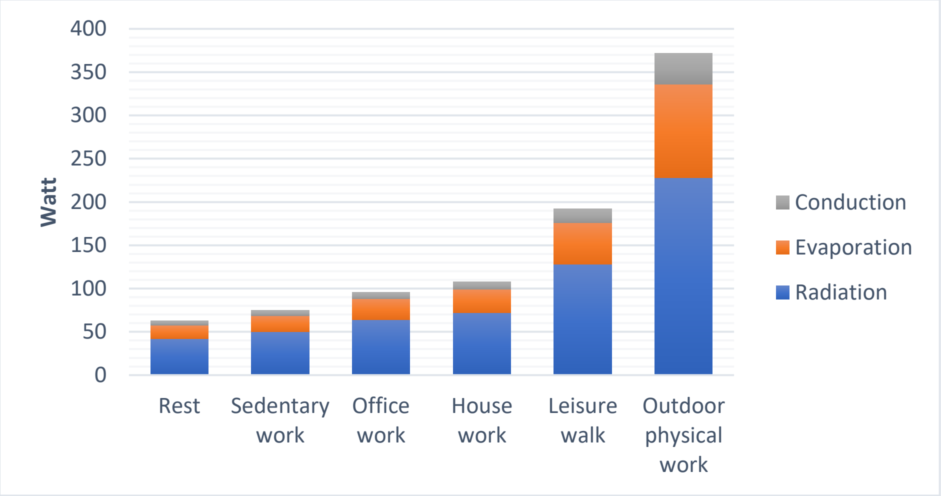


Figure 15 Thermal exchange through convection and radiations is relatively constant independent of work performed compared to evaporation (Dahlblom 2010).

The optimal thermal conditions can be defined as the situation in which the least extra effort is required to maintain the human body's thermal balance. The greater the effort that is required, the less the comfortable the climate is felt to be. The maximum comfort conditions can usually not be achieved. However, it is the aim of the designer to build a house that provide an indoor climate close to optimum, within a certain range in which thermal comfort is still experienced. The range at which thermal comfort is experienced is called comfort zone. It differs somewhat with individuals and it depends also on clothing worn, the physical activity, age and health conditions. Although ethnic difference is not of important, the geographical locations plays a role because of the habits and of the acclimatization capacity of individuals (Gut, Ackerknecht 1993).

Gagge's DISC index expresses degree of discomfort rather than comfort. the most common definition of the comfort zones is DISC ±0.5 which means that 80% of the population is satisfied, though extending limits to ±1.0 results 70% satisfaction which could be proposed when resources are limited. Then Fanger comfort equation on the effect of climatic factors on thermal sensation was done by Fanger (1970) which is widely used when defining thermal comfort. International standard ISO 7730 on the ergonomics of the thermal environment relies heavily based on the studies done by Fanger (1970), Gagge's (1972) and others. Designers have relied on these standards as a general guide to define thermal comfort when designing buildings in warm-humid climates.

Table 5 Thermal sensation scales (based in part on Markus and Morris 1980)

Perception	**ASHRAE**	**Fanger (PMV)**	**Rohles & Nevins**	**Gagge's DICS**	**SET (°C)**
Painful			+5	+5	
Very hot			+4	+4	37.5 -
Hot	7	+3	+3	+3	34.5 – 37.5
Warm	6	+2	+2	+2	30.0 – 34.5
Slightly warm	5	+1	+1	+1	25.6 – 30.5
Neutral	4	0	0	±0.5	22.2 – 25.6
Slightly cool	3	-1	-1	-1	17.5 – 22.2
Cool	2	-2	-2	-2	14.5- 17.5
Cold	1	-3	-3	-3	10.0 – 14.5
Very cold			-4	-4	

The standard effective temperature (SET) developed by Gagge's et al. (Markus and Morris 1980) describes uniform environment with.

- 50% relative humidity,
- Air speed of 0.125 m/s
- Activity level 1 met (sitting) and
- Clothing of 0.6 clo (indoor cloths')

An air temperature of 20 °C in these conditions will result in SET of 20 °C. A change in any of the parameters will result in a change of SET (Rosenlund 2000).

3.3.1 Operative temperature

The indoor temperature of the building was similar to the outdoor temperature with difference of between 1-3°C. The operative temperature of the different rooms was measured using laser pistol. The operative temperature, also known as resultant temperature is defined as a uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. Some references also use the terms 'equivalent temperature" or 'effective temperature' to describe combined effects of convective and radiant heat transfer. In design, operative temperature can be defined as the average of the mean radiant and ambient air temperatures, weighted by their respective heat transfer coefficients. This can be shown mathematically as;

$$t_0 = \frac{h_r t_{mr} + h_c t_a}{h_r + h_c} \qquad \text{Equation 3}$$

Where,

h_c = convective heat transfer coefficient

h_r = radiative heat transfer coefficient

t_a = air temperature

t_{mr} = mean radiant temperature

Or simplified

$$T_0 = \frac{T_{air} + T_{mr}}{2} \qquad \text{Equation 4}$$

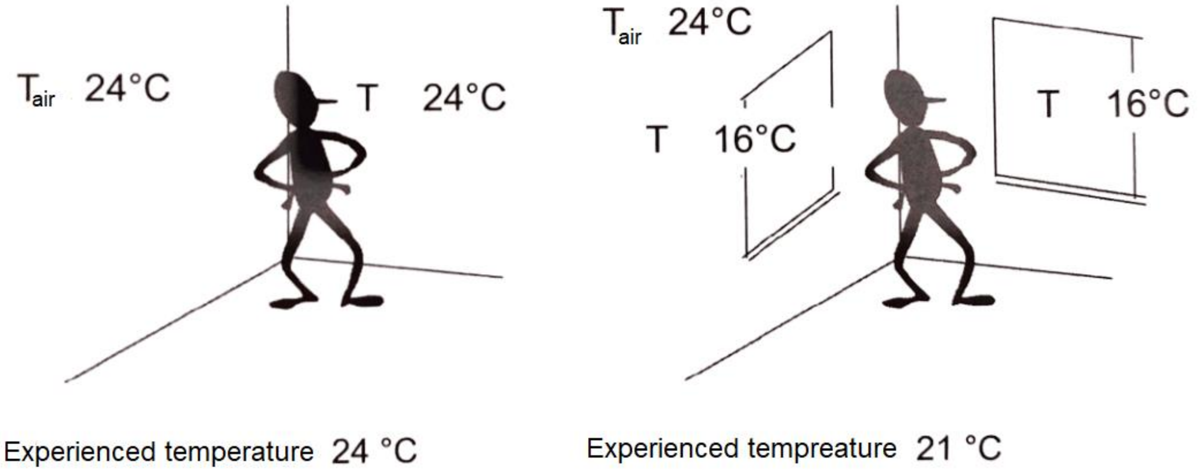


Figure 16 Experienced temperature can differ despite same air temperature (Dahlblom 2010).

The operative temperature measured in the different rooms for the modern home taken on the 12^{th} of April at 10:30 showed an air temperature of 28° and surface temperature of 30°. This gives simplified operative temperature of 29 °C assuming the respective heat transfer coefficients of 1.

$$T_0 = \frac{28+30}{2} = 29°$$

According to the ASHRAE standard 55-2017, an operative temperature of between 23.9 – 30.9 gives thermal comfort with an acceptability limit of 80% whereas an operative temperature of between 24.9 – 29.9 allows thermal comfort with acceptability limit of 90%. Using the PMV/PPD model developed by P.O. Fanger which uses heat-balance equation and empirical studies about skin temperature to define comfort. Fanger's equation are used to calculate the Predicted Mean Vote (PMV) of large group of subjects for particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate and clothing insulation. Standard thermal comfort surveys ask subject about their thermal sensation on a seven-point scale as shown in Table 5. Zero is the value which represent thermal neutrality, and the comfort zone is defined by the combination of six parameters for which the PMV within recommended limits of PMV ±0.5. Fanger developed another equation to relate the PMV to the Predicted Percentage of Dissatisfied (PPD). This relation was based on studies that surveyed subjects in a chamber where the indoor conditions could be precisely controlled. This method treats all occupants the same and disregards location and adaptation to the thermal environment. It basically states that the indoor temperature should not change as the seasons do. Rather, there should be one set temperature year-round. This is taking a more passive stand that humans do not have to adapt to different temperatures since it would always be constant.

ASHRAE Standard 55-2010 uses the PMV model to set the requirements for indoor thermal conditions. It requires that at least 80% of the occupants be satisfied.

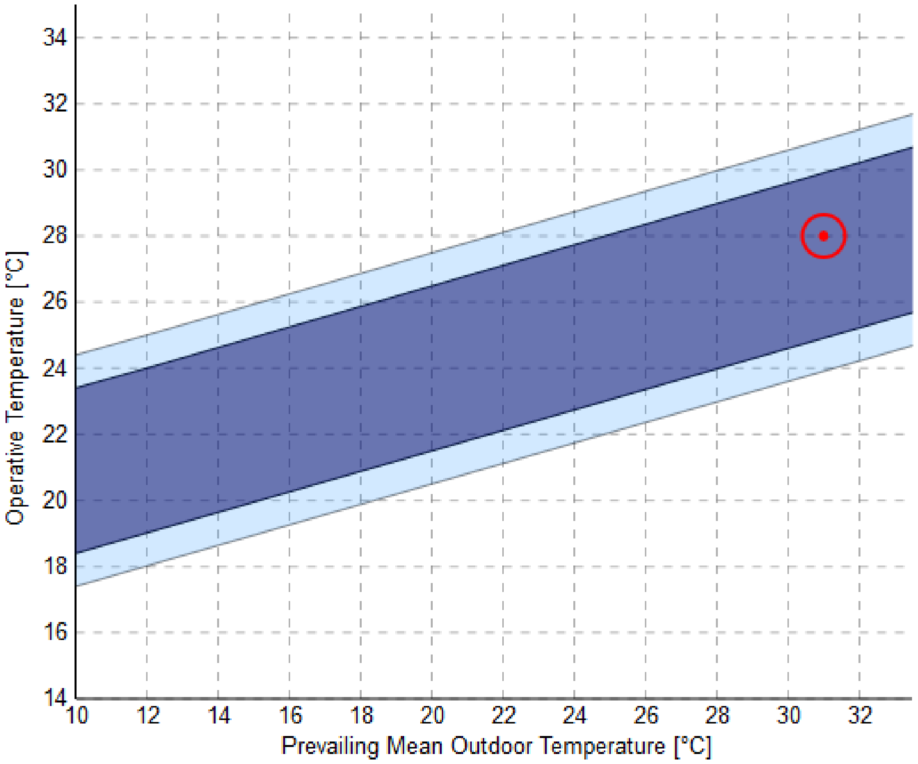


Figure 17 Temperature adaptive chart (Hoyt et al 2017)

ASHRAE standard 55 also includes an adaptive comfort standard for naturally ventilated buildings. Method is applicable only for occupant-controlled naturally conditioned spaces that meet all of the following criteria:

a) There is no mechanical cooling system installed. No heating system is in operation;
b) Metabolic rates ranging from 1.0 to 1.3 met; and
c) Occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5-1.0 clo.

The building in question do have cooling system installed however, the cooling system was not in operation because of the rainy season with lower temperature than usual. With the result of the measurement regarding the operative temperature, an estimated PMV/PPD was obtained with the following parametric conditions;

a) Operative temperature 29°C
b) Air speed of 0.5 m/s
c) Humidity of 65%
d) Metabolic rate 1.0 (sitting) and
e) Clothing level of 0.5 clo (indoor cloths)

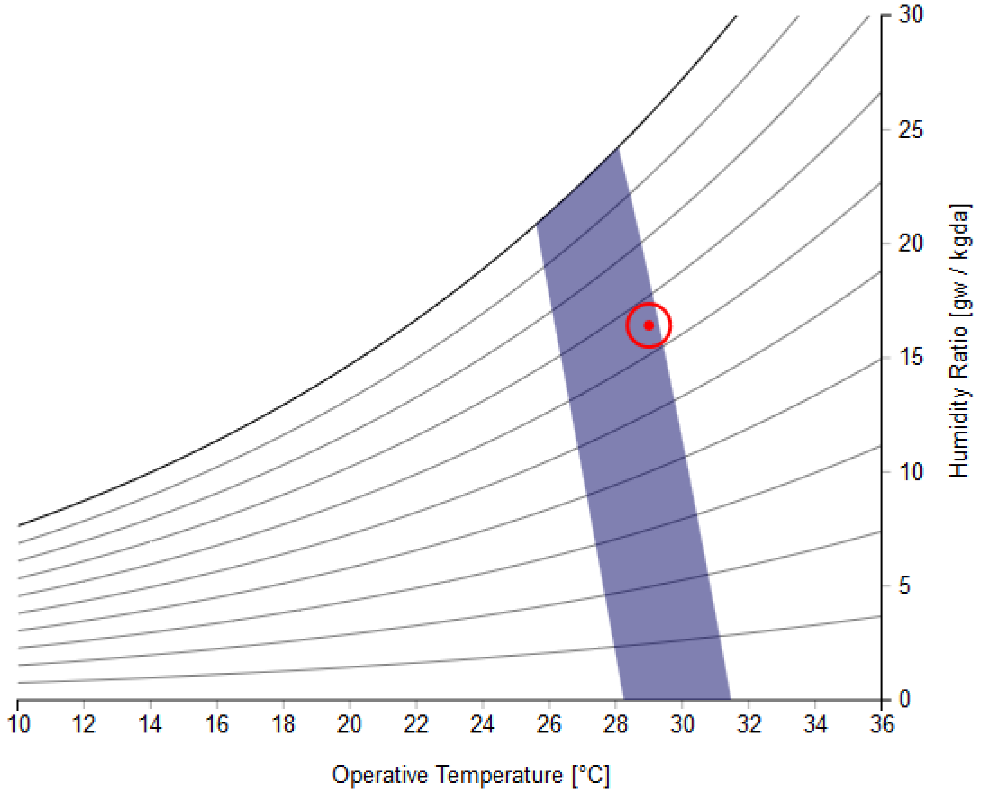


Figure 18 Psychrometric or temperature-humidity showing PMV/PPD (Hoyt et al 2017)

In warmer climates where the outdoor temperature is much higher than indoors, the air flow must be higher to allow for maximum cross-ventilation which can contribute to pleasant thermal comfort. Air circulation have a very significant influences how the thermal environment is perceived, the cooling effect of wind increases with lower temperatures and higher wind speed. In the above psychrometric chart, the abscissa is the operative temperature at 29 °C and for each point dry-bulb temperature equals mean radiant temperature (DBT = MRT). The comfort zone represents the combination of conditions with the same DBT and MRT for which the PMV is between -0.5 and +0.5, according to the standard.

4 Comparison study of housing types

The study looks at building designs and construction materials currently used in the country and is carrying out comparative studies and design analysis on three typical architectural designs. The designs that will be studied includes Swahili, Contemporary and Modern house.

The Swahili house represent the traditional housing models which has proved to be functional and easily produced using the locally available building materials. The Swahili house is assimilation of both traditional buildings techniques found in Tanzania with influence from the early Arab traders and settlers. The Contemporary house which is now the most common house type in the country was partly introduced in its current design forms by the European settlers. The design of the buildings follows to large extend international trends or the architecture of temperate countries. Due to the design choose, most of the contemporary are active climatized house, i.e. an air-conditioned house.

The Modern house and its building designs aims to produce climate conscious buildings that addresses the humans thermal comfort while at the same time leaving minimal ecological footprints. This is done through research-based studies of building material to develop and produce locally sourced and low-cost materials. The new materials which are introduced by the National Housing and Building Research Agency (NHBRA), is hoped to reduce the construction cost and the environmental impact with focus on availability and affordability of the material without compromising the technical and physical properties. The study has looked at the general design of the house in terms of plan layout, room size, window types and size and roof type. Other aspects that are examined include orientation of the house in relation to solar radiation and wind condition as well as the general topography of the site. Material properties are also examined and compared in terms of thermal properties, environmental impact as well as access and affordability.

4.1 House one – Swahili house

4.1.1 Building description

The Swahili house is the most common house type along the East Africa including Dar es Salaam and was first introduced by the earlier Arab traders who later settled down along the East coast of Africa. The building design and construction materials are determined by the topography of the area, regional climate conditions, available construction materials, family constellation and cultural traditions. The coastal area of East Africa has similar climate and cultural traditions which is known as Swahili culture. The Swahili house in its design consist of single-story rectangular double-banked house with wide central corridor that runs from the front to back, with rooms arranged symmetrically on either side. The main entrance usually facing the street and fenced yard with separate outer building for kitchen, store, and bathrooms. Many houses have a communal seating area or baraza (Kiswahili for council) at the front also known as verandah where men would spend their leisure time, while women socialized in the rear courtyard – a typical gender division of space in Muslim tradition.

The Swahili house has become very popular partly because its most suitable for large extended or polygamous family that's common among traditional and Muslim families. In urban areas along the coastal towns and many adjacent inland towns it is most suitable for letting, with tenants occupying one or several rooms according to the paying abilities and household size. This pattern of sub-letting is particularly evident in coastal towns but can be seen in many inland towns as well. This system of sub-letting may cause overcrowding hence most people can rarely afford more than one or two rooms. However, this still remains popular as most people who move to urban areas in search for opportunities such as education and work tend to be single. Because of the high cost of living in urban areas, those who move to cities seeking work tend to leave their families behind and commute home whenever possible.

4.1.2 Design, geometry, and orientation

The general design and the building techniques of the Swahili house do not necessarily take into consideration the prevailing climatic conditions, particularly the solar radiation and wind conditions. Most of the building designs are placed to maximize the available plot size, this remains true even today particularly in built up areas as the building spaces are limited. The signature rectangular form of the Swahili house is partly determined by the size and form of the plots which the house is built on. The large family constellation that's common in the Swahili culture gives the reasons for having many rooms in Swahili house because for the need of separate rooms for the different gender, common customs in traditional and Muslim families.

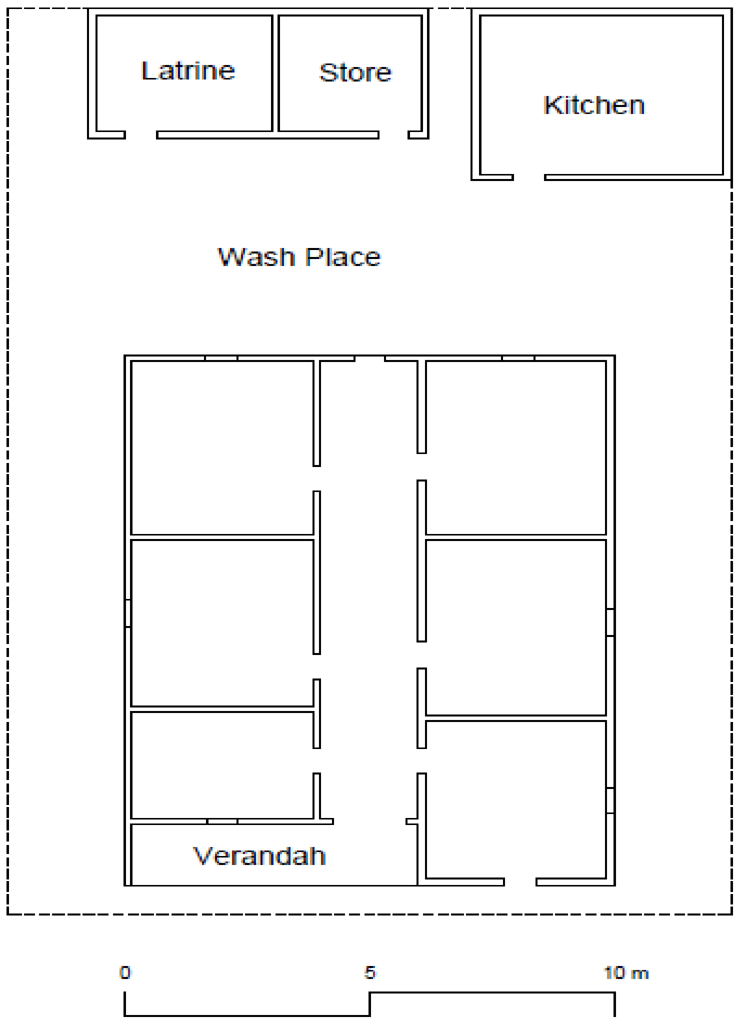


Figure 19 Swahili floor plan and room layout.

Social customs and security plays central rule to the design requirements of Swahili house with regards to courtyard and is often surrounded by high walls that serves both privacy and security purposes.

4.1.3 Properties of construction materials

The building designs and the construction techniques are determined by the local situations such as available resources and building materials. There is abundance of constructions materials along the coastal areas, such as clay soil, lime, coral stone, timbers, and palm fronds which have been used extensively in the buildings of Swahili house. Traditional Swahili house constructions materials can be traced to two main sources.

1. A non-durable light weight construction based on poles, sticks grass and palm leaves.
2. The mud and pole structure probably influenced by Arab house building traditions. The Arab traditional construction can be seen in e.g. the existing buildings in Zanzibar, Bogamoyo and other trading centers. These houses were built of dressed limestone, sometimes several stories high, with flat roofs or vaulted domes.

The vernacular Swahili has constructional elements from both traditional buildings. The mud and pole structure consist of straight poles dug into the ground. Split poles are tied horizontally on the outside and inside of these poles. This framework is then covered with mud, usually plastered on the inside. Sometimes the framework is packed with coral stones before plastering (Bodoegaard 1981).

The wall thickness is usually 150 mm however, over period of several years of repairs and re-plastering the thickness tend to increase. Walls for the Swahili house usually consist of from outside; plaster, coral stones filled with muds and packed in between horizontally tied split poles which are supported by poles dug into the grounds. The traditional materials for the support structure are termite resistance mangrove poles, or when unavailable or too costly, other timbers. The traditional roofing materials are palm fronds (Makuti) which give high insulations values, low thermal capacity allow for certain amount of ventilations through the roof. The traditional roof is hipped or gambrel which has its structure partly supported by internal walls. Such a roof has fairly complex roof trusses but has two advantages from climatic point view (Bodoegaard 1981).

1. Both roof types protect the four walls from the direct sun light, and
2. Particularly the gambrel roof provides excellent ventilation of the roof space.

Most of the structure used for the Swahili house do fairly well from climate point and can be considered passively climatized house. However, with modern ventilation systems, buildings are becoming more actively climatized.

Some of the reasons why the structure of Swahili do so well is because of its building materials that have high porosity which results low density structure. This is excellent properties in warm and humid climate as this gives the walls low thermal storage and short time lag. In addition to lighter structural materials, the Swahili house has reflective outer walls because of lighter colouring which characterizes building along the coastal areas thereby contributing lower indoor temperature.

4.1.4 Natural ventilation and passive cooling means

Most of the traditional Swahili houses are naturally climatized buildings, e.g. do not have mechanical ventilation systems. Hence the buildings have outdoor open kitchen and people spend time outside of their rooms most of the day, the indoor temperature remains relatively within range. Nonetheless, given the double-banked design of the building leads to inadequate natural ventilation since the air cannot flow freely through the building from one side to the other. From a comfort point view, houses along the coastal climate zones should be single-banked to allow for maximum cross-ventilations. If carefully sited, single-banked houses may be given L, U-or H-shaped plan bearing in mind that the bedrooms and possible living rooms should be located where the air movement is maximum. Internal walls should provide minimum obstructions and kitchen can most suitably be located in a roofed out-door space adjacent to the house (Bodoegaard 1981).

However, due to the recent economic development in the country, some of the well-off families have opted to install HVAC system, heating, ventilation, and air conditioning which improves the thermal comfort and the air quality in the buildings notwithstanding the high cost for acquisition, use of electricity and maintenance.

4.2 House two – Contemporary house

4.2.1 Building description

It is common held conceptions that contemporary housing designs is less sympathetic to the warm and humid climate than the vernacular housing. The are many reasons to this conception, one of them being contemporary designs emanates from temperate climates and were introduced with the introductions of modern building designs and materials. This is certainly true for Tanzania as most buildings considered contemporary were introduced by the early Asian and European settlers. The Contemporary houses remains popular and are the most set up building types today and comes in different design forms and building materials. The underlying common factors in contemporary housing is that it requires large capital to set up and therefore, they are owned or rented mostly by working class families with good economy, or with backings from institutions in form of mortgage. Design of the buildings often reflects the need of the family.

4.2.2 Design, geometry, and orientation

There are wide range of designs, geometry as well as orientation regarding contemporary housing. However, they have some common features, and this includes wide open plan layout, well equipped modern kitchen, and preferably separate rooms for each children of the family. This is made possible because most modern families have fewer children. Apart from open plan layout with the kitchen and the living room easily accessible, its characterized by large windows proportions of about 20-30% depending on the design and size of the building.

For instance, a building containing three bedrooms, a living room and kitchen would have a minimum of two bathrooms where one bathroom is set for master bedroom and the second shared among other rooms. There could possibly be third bathroom if one of the rooms is allocated as guestrooms. The overall size of the rooms is usually larger in comparison to traditional housing. This is because rooms in contemporary house are designed to serve multifunctional purposes, in other words, they are not used only for sleeping but also functioned as study and/or office rooms. In addition to built-in closets, individual rooms may have separate bathrooms which necessitates large space areas than normal. Each room have at least one or two windows which allows sufficient light into the room with average room size of between 12-20 m^2 of floor space.

4.2.3 Properties of construction materials

There are varieties of building materials used in contemporary housing, this is partly due to the ability and preferability of the owners. The principle building materials are nonetheless the same, the difference occurs in detailing of the interior design of the building. Some of the building materials used in contemporary housing include concrete cement blocks or concrete supported pillars for the bearing walls, bricks and gypsum for inner walls and ceilings. Wall thickness is usually about 150-300mm depending on the type of material and number of layers.

In terms of construction, the contemporary housing imitates international building standards of temperate climates with rather than the prevailing regional climate. The walls may contain more than one layers, and this can lead to walls with high thermal storage and more time lag. The buildings also tend to be airtight which is a disadvantage in warm and humid climate, as this makes it harder to get rid of the thermal heat gain of the building making the need for mechanical ventilation ever more inevitable.

4.2.4 Natural ventilation and passive cooling means

Most of the contemporary buildings have some form of mechanical ventilation because thermal comfort is greatly emphasized. This could be explained by the fact that these types of houses are built or rented by middle income families who are better off financially. Unlike the traditional housing, the contemporary housing has better design layout in terms of indoor air flow due to wide-open areas and large window proportions. Larger windows can be used to allow greater air flow through the building to lower the indoor temperature. However, the overall design of the contemporary house makes it harder for the house to be completely independent of mechanical ventilation. This is because the house is designed to meet the thermal comfort by any means necessary.

4.3 House three – Modern house

4.3.1 Building description

Traditional building designs and construction methods were influenced primarily by the limited resources and lack of understanding of the impacts of the prevailing climate conditions. The modern designs and construction materials are to large extend designed while taking the climatic conditions into considerations. This has led to what can be termed as climate conscious building designs; that's environmentally sound and economically viable.

In the third house, the study is looking at building designs that uses recently introduced building materials and building techniques which are locally sourced materials with minimal ecological footprints. The building in question was designed and built by the NHBRA which is tasked with producing affordable high-quality services and products of appropriate housing technologies and techniques with aim of reducing construction costs through researched based innovative solutions. As of today, very few houses of this type, using the new building materials, have been built. The goal is to make it mainstream among the population, to improve affordability and to reduce environmental impact. Informational and educational work is currently in progress to increase the production rate of this, modern building type.

The modern method and techniques aims at reducing the cost of building which remains beyond the reach of most people through various means. Most of the construction materials in the country are imported, this leads to higher price tag for basic construction materials. NHBRA is working through research-based approach to produce low cost construction materials that can replace the high-priced import materials. Cement is the most used product in building construction, the price for a 50-kilo cement bag in Tanzania is around 5$. In country where monthly average wages of around 150$ a month for highly educated person working in the private sector whereas a domestic worker earns an average $2 a day (National Bureau of Statistics 2017).

4.3.2 Design, geometry, and orientation

The house is designed based on compact living which comprises of four bedrooms, an open living room, hall and a kitchen. Main building materials used for the house is soil-cement interlocking bricks for the walls, and roof tiles which was developed by NHBRA as shown in Figure 12. The building is made of four bedrooms, a living room which opens to the hall and kitchen. The living room sits between the master bedroom on one side and kitchen and other bedrooms on other side. The design of the roof shape is a mix of gamble on short side and gambrel on the longer side. The gambrel roof is combination of gamble and hipped roof which gives high level of ventilations and good protections from direct sun for the all four walls.

Based on climate design, the house should be able to reflect the prevailing climatic conditions with regards to solar radiations and wind conditions. However, the location and the size of the plot made it hard to adhere to the prevailing climate conditions and thus the house is exposed to the morning and the evening solar rays. This has significant impact on the ability of the building to be able to maintain desirable thermal comfort naturally given the geographical location being near to equator with high temperature and solar radiations throughout the year.

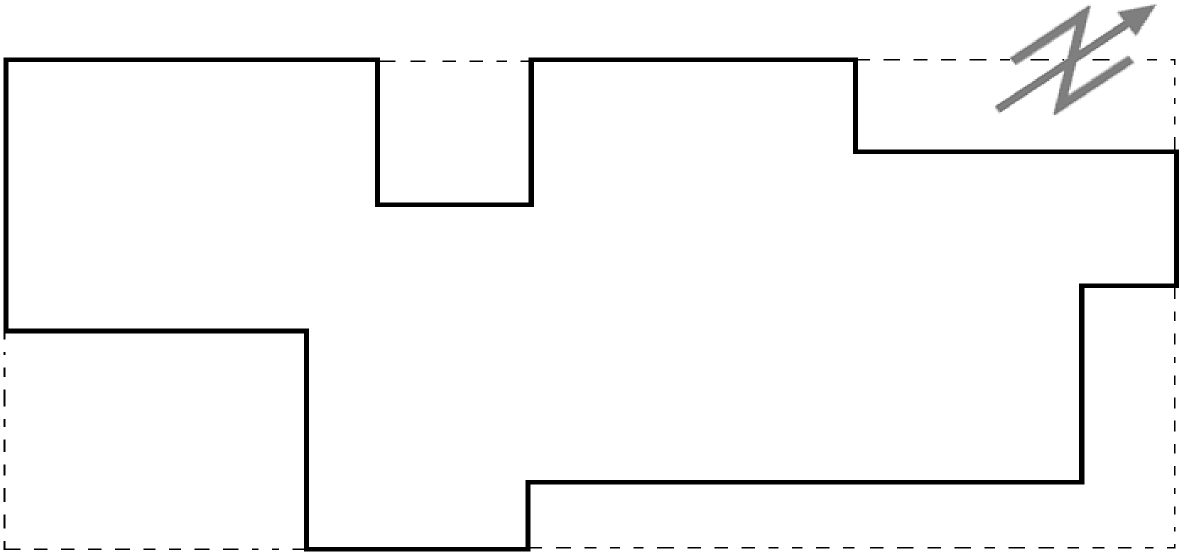


Figure 20 Orientation of the house

The house in its current orientation faces Northeast to Southwest directions, this means the building is not well placed given the prevailing solar radiation and wind directions. The sun rises from the East and goes down in the West and thus the best orientation for the protection from the sun is along the west-east axis. Exposing the buildings longer side to the East and West elevations makes it difficult to protect from the low sun, and may require special devices, whereas the South and North sides can easily be protected by an overhang roofing. The house in its current orientation is exposed to both the morning sun and the afternoon sun in large parts of the building while having large windows.

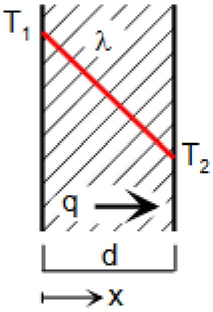
4.3.3 Properties of construction materials

The primary materials used for the house is soil-cement interlocking bricks for both the walls and the roofing tiles according to *2.4.3 Modern building design and construction materials*. The wall construction consists of the soil-cement interlocking bricks so called hollow blocks masonry with one thickness in cavity. From the outside, the blocks are not treated or plastered whereas inside the walls are plastered and painted. Since the bricks are interlocking, there is no need of mortar to hold them together. Thickness of the wall is 150 mm with about 20 mm of plastering. The soil-cement blocks carry the whole weight which is being transferred to the foundation of the house as shown by Figure 56, see appendix.

4.3.3.1 Heat transfer coefficient U-value and heat flow of the wall

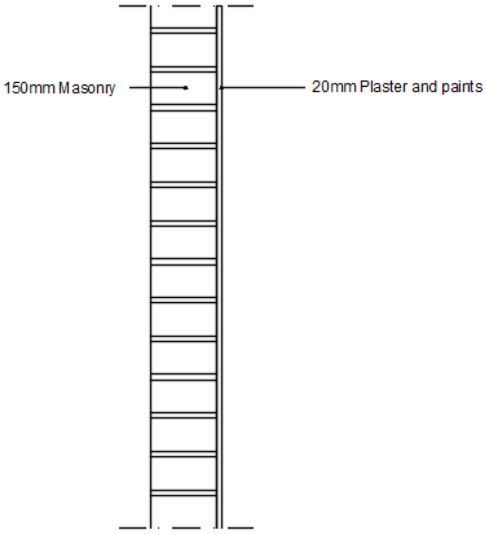
Apart from the 20 mm plastering and the paintings, the wall of the house can be considered as homogenous. Therefore, the heat flow through the wall could be seen as homogenous with linear distribution of temperature throughout the wall. However, due to the hollow blocks this is slightly less homogenous.

The heat transfer coefficient, U-value is a measurement of how effective building material or building element such as floor, wall and roof is at reducing heat transfer. The lower the value, the better the material is when used as an insulator. However, in naturally climatized buildings in warm and humid climates, the heat transfer coefficient of walls and the roofs are much higher since the aim is to allow heat to escape from building. The aim is to lower the indoor temperature, whereas the opposite is true for buildings in cold climates. In more technical terms, the U-value is the rate of transfer of heat (in watts) through one square metre of a structure, divided by the difference in temperature across the structure.



$$q = \lambda \cdot \frac{T_1 - T_2}{d} \; W/m^2 \qquad \text{Equation 5}$$

$$T_x = T_1 - \frac{x}{d} \cdot (T_1 - T_2) = T_2 + \frac{d-x}{d} \cdot (T_1 - T_2) \qquad \text{Equation 6}$$



Properties of the soil-cement interlocking bricks, one cavity in thickness. (Johansson 2017)

Table 6 Material properties

Thickness (mm)	Resistance, R (W/m^2K)	P (Kg/m^3)	Spec.heat (Wh/kgK)
150	0.15	1100	0.25

Figure 21 Cross section of the wall with the soil-cement block.

Plaster and paints 20mm (negligible physical properties)

Out & indoor air resistance, $R_{si} + R_{se} = 0.17\ W/m^2K$

Heat transfer coefficient, U-value of the wall is

$$U = \frac{1}{total\ resistance} = \frac{1}{0.15+0.17} = 3.125\ W/m^2K \qquad \text{Equation 7}$$

4.3.4 Natural ventilations and passive cooling means

The building in its current design is actively climatized house, e.g. relies heavily on mechanical ventilation, a total of five A/C are placed in the bedrooms and the living room. At the time when the study was carried out on the building, the A/C systems were off due to the lower direct heat gain because of the rainy season. However, there was a small fan mounted on the ceiling in the living room that was partly active. The building has large window proportions with excellent potentials for utilizing cross-ventilation.

Measurements taken inside the house regarding wind speed gave an inconclusive result. However, the wind speed taken just outside of the building were rather good despite the building surrounded by 2-3 meters high outer walls. This could also be explained by the fact that most openings in the building were closed due to the lower than normal temperature during the rainy season. Other explanation could be the instruments was not sensitive enough to detect the low wind speed.

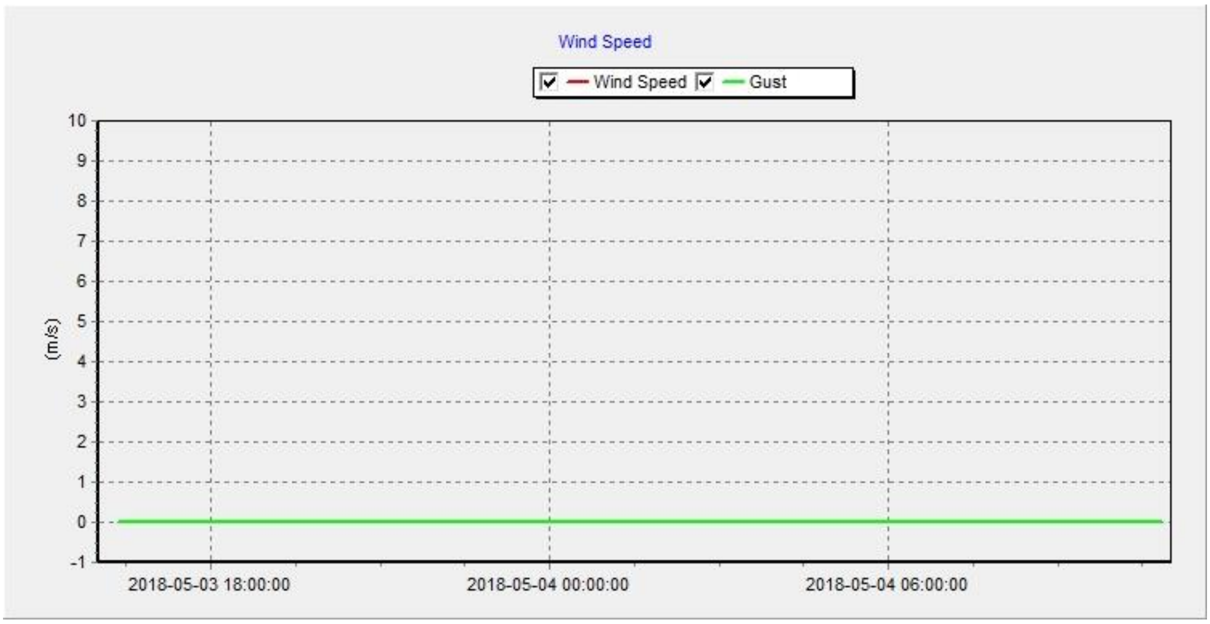


Figure 22 Indoor wind conditions taken inside the building shows inconclusive.

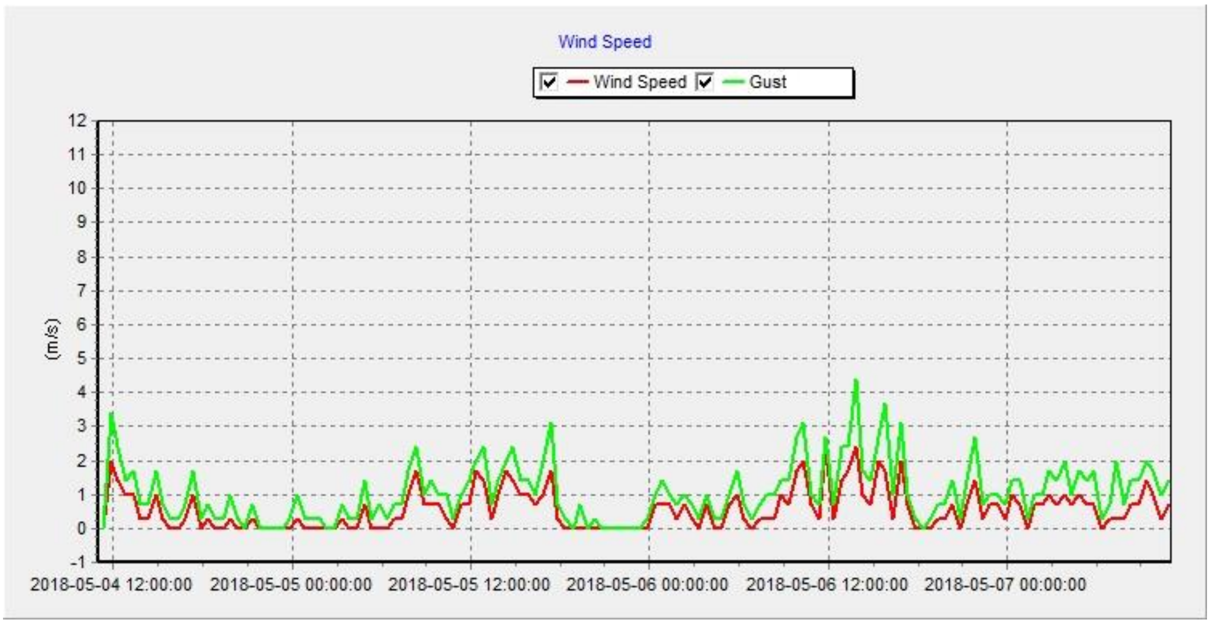


Figure 23 Outdoor wind conditions taken roughly 9-7 meters in front of the building

The indoor measurements of the building were followed up by similar measurement taken outside of the building to assess the immediate climate conditions surrounding the building. The measurements were taken roughly 6-7 meters in front of the building using small weather station. The measurements taken were;

a) In and outdoor temperature, dew point and wind chill
b) Both in and outdoor humidity
c) Absolute and relative pressure
d) Wind speed and wind gust
e) Rainfall (outdoor measurement)

The indoor measurements were taken between May 3 - 4th 2018 and the outdoor measurements were taken between May 4 - 7th 2018. Data for the different measurements, see appendix.

5 Parametric model simulations

The model simulations phase is carried out using the home designed and built by the NHBRA as a reference object. The software used for the simulation is DEROB-LTH, see Section 1.6.3. The structure of the simulation process is carried out in the following way.

1. Two different reference designs are created. The rooms and layout of the house are identical in both reference designs. The materials used in the outer walls is the only thing that is varied in the reference designs.
2. In each of the reference designs, only one design parameter is changed at a time. For example, the orientation of the building is changed, or shading devices are added to the windows. Every design parameter change is done individually and independently from the others. The exact same parameter change is done on both reference designs.
3. When all individual design parameter changes have been made, they are all combined into the same model to see if there are any synergetic effects on the outcome.

All presented temperatures are dry-bulb air temperatures. Internal loads are not included in the simulations, as also noted in 1.5 Scope of the study.

5.1 Reference designs

Outer wall material choices for the reference designs are the ones being defined as contemporary and modern according to Section 2.4. These materials are solid concrete blocks and hollow soil-cement blocks respectively. All the building elements and their respective properties are listed in Table 7. Materials are listed in the order outside-inside. The properties apply for the reference designs only.

Table 7 Material properties for building elements on reference designs.

Floor: U = 3.872 W/m^2,°C						
Material	**Thickness [mm]**	**Conductivity [W/m,°C]**	**Specific heat capacity [Wh/kg,°C]**	**Density [kg/m^3]**	**Absorptance front/back [%]**	**Emittance front/back [%]**
Concrete	150	1.7	0.24	2,300	70/70	87/87
Wall outer soil-cement: U = 2.915 W/m^2,°C						
Material	**Thickness [mm]**	**Conductivity [W/m,°C]**	**Specific heat capacity [Wh/kg,°C]**	**Density [kg/m^3]**	**Absorptance front/back [%]**	**Emittance front/back [%]**
Hollow soil-cement block	150	1.0	0.25	1,100	70/70	87/87
Plaster	30	1.3	0.28	2,050		
Wall outer concrete: U = 3.045 W/m^2,°C						
Material	**Thickness [mm]**	**Conductivity [W/m,°C]**	**Specific heat capacity [Wh/kg,°C]**	**Density [kg/m^3]**	**Absorptance front/back [%]**	**Emittance front/back [%]**
Hollow soil-cement block	230	1.7	0.24	2,300	70/70	87/87
Plaster	30	1.3	0.28	2,050		
Windows: U = 5.88 W/m^2,°C g = 0.624						
Material	**Emittance front [%]**	**Emittance back [%]**	**Transmittance [%]**	**Reflectance [%]**		

Single glass absorbing grey	83.7	77	28	11		
Ceiling: U = 4.280 W/m^2,°C						
Material	**Thickness [mm]**	**Conductivity [W/m,°C]**	**Specific heat capacity [Wh/kg,°C]**	**Density [kg/m^3]**	**Absorptance front/back [%]**	**Emittance front/back [%]**
Gypsum	14	0.22	0.23	900	70/70	87/87
Roof: U = 5.479 W/m^2,°C						
Material	**Thickness [mm]**	**Conductivity [W/m,°C]**	**Specific heat capacity [Wh/kg,°C]**	**Density [kg/m^3]**	**Absorptance front/back [%]**	**Emittance front/back [%]**
Soil-cement roofing tiles	15	1.2	0.25	2,200	70/70	87/87

The reference designs have the following general properties:

- Only one volume/room.
- Brown colour on outer walls, inner walls, roof tiles, eaves and ceiling.
- Inner dimensions 8x10 m, ceiling height 3 m.
- Gable roof, 25 degrees.
- 2 equally sized single layer windows on each wall, 1.8 m wide, 1.5 m tall, 1 m parapet.
- Windows to wall ration, (WWR) of 25% (excluding openings)
- All windows are 35% open all the time.
- Ventilated attic.
- Roof overhang/eaves 0.6 m.
- The building long-axis oriented north-south

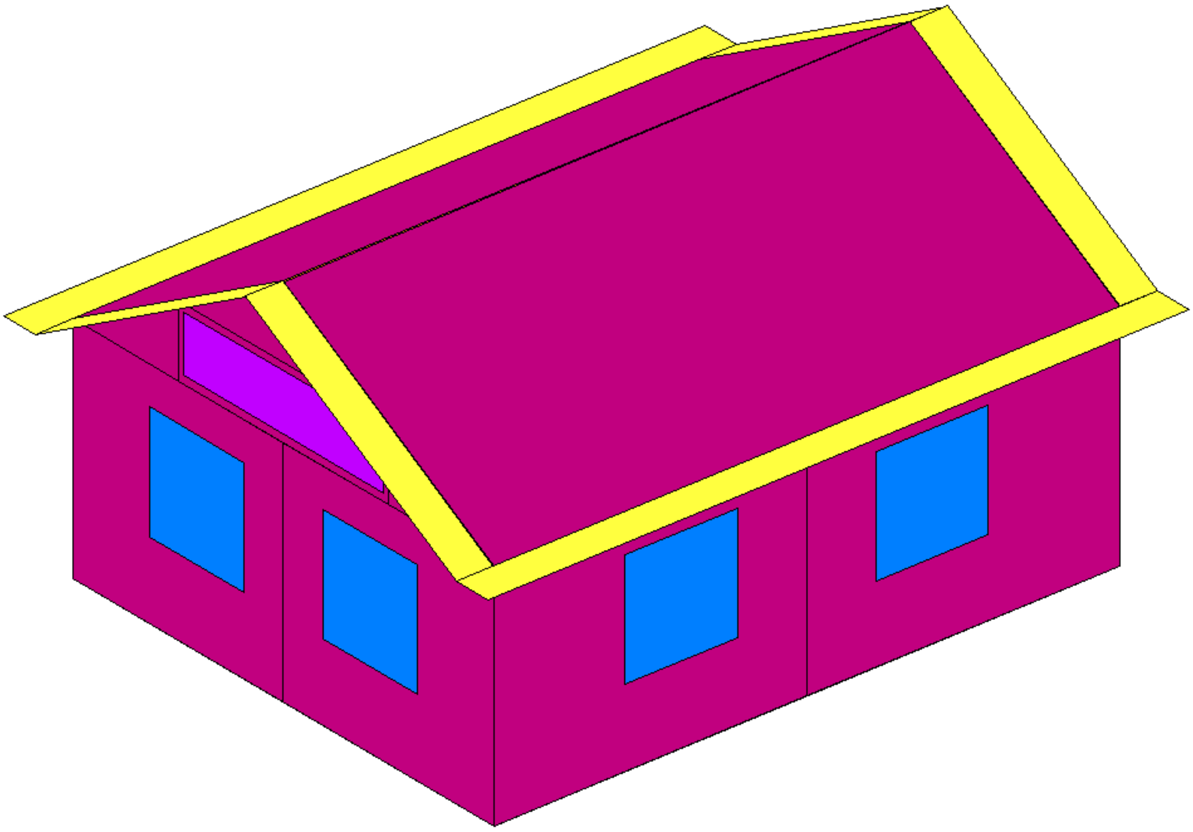


Figure 24 Visualization of reference design.

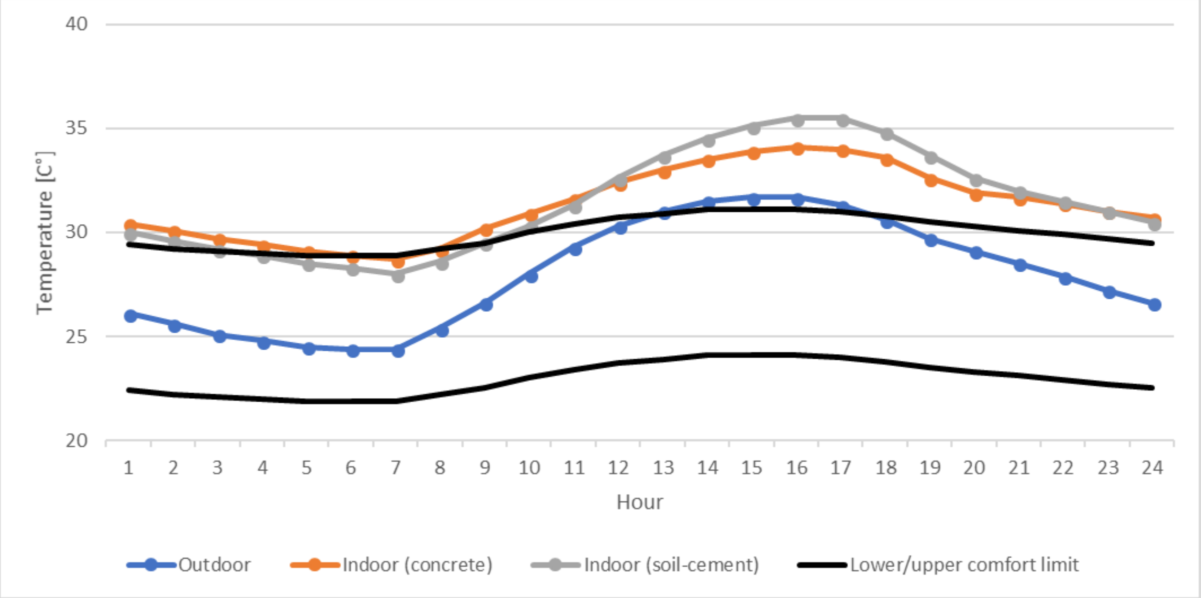


Figure 25 Simulation of reference designs, typical hot day in February.

Table 8 Temperature summary.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	28.7	34.1	31.3
Indoor soil-cement	28.0	35.5	31.5
Outdoor	24.4	31.7	28.0

Figure 25 shows simulations of the two reference designs. The two black lines are the lower and upper limit of thermal comfort according to chapter 3.3. The thermal comfort limits are based on the outdoor temperature and the indoor wind speed. If the indoor operative temperature falls between the black lines, comfort is achieved. The presented temperatures are dry-bulb temperatures and not operative. However, it can still be used to get an approximation of the comfort (or discomfort) level and to find out the most critical hours of the day. The indoor temperature lays consistently about five degrees above the outdoor temperature. The thicker and heavier concrete wall manages to even out the temperature slightly throughout the day. In Table 8 above, the min, max and average temperatures are summarised. These temperatures are compared with the resulting temperatures in subsequent simulations.

5.2 Changes of design aspects

The parameters that will be changed and simulated on include the following.

- Orientation regarding solar radiation and wind
- Use of light colour on facades, roofing, window shading louvers and ceiling
- Extended roof overhang/eaves
- Window shading louvers
- Higher proportion of windows
- Night flushing
- Shape and geometry of building
- Combining design changes

5.2.1 Orientation regarding solar radiation and wind

Orienting the building regarding sun and wind patterns have a considerable impact on the indoor climate. Minimizing the area which receives direct sun radiation is perhaps one of the most important aspects to reducing the indoor temperature. Making use of wind patterns to achieve good natural ventilation can also have a big impact on the indoor climate. The optimal orientation may be contradictory to each other, i.e. the optimal orientation regarding the sun may not be the same as the one regarding the wind.

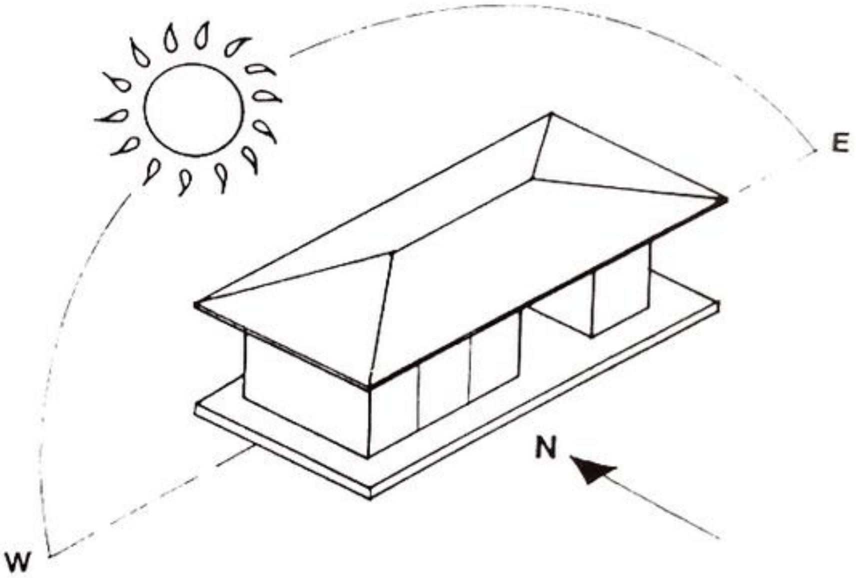


Figure 26 Row house with hipped roof, elongated in E-W direction provides best shading (Gut, Ackerknecht 1993)

The radiant heat from the sun is an extreme source of energy. It is therefore of significant importance to minimize the radiant heat gain. Finding the optimal orientation in respect to the sun is rather easy since the sun path and direction is predictable. This can be done by orienting the building so that the short facades face the east-west direction where the low morning and evening sun is dominant.(Svard 1980) It should also be mentioned that the use of unshaded windows in the facades facing the east and west direction is highly advised against.(Givoni 1997)

Orientating the building regarding the wind may not be as easy as the wind patterns can vary heavily depending on topography, surrounding buildings and vegetation. Moreover, variations throughout the day and seasons are almost guaranteed.(Svard 1980) However, studies have shown that there is a distinct wind pattern in the coastal areas of Dar es Salaam. During daytime, the wind breezes are predominantly coming from the sea. During nighttime, the wind direction is reversed and becomes land-sea breezes. This suggests that the building should be oriented with the long facades facing the east-west direction, which is indeed contrary to the suggested optimal orientation regarding the sun.(Bodoegaard 1981) To achieve good cross ventilation, windows in the facades facing the east and west direction is preferred but should be equipped with shading devices as discussed earlier.(Givoni 1997) Local wind patterns should be carefully studied on the building site in order to find an optimal orientation. In Tanzania, there is a tradition to have high walls surrounding the building/garden. These walls may heavily influence or obstruct the wind breezes and should therefore be taken into consideration.

The simulations are evaluating the effect that the orientation has on the indoor climate regarding sun and wind respectively and independently. Thereafter, an optimal compromise between the two is examined according to the predefined wind direction in the simulation software.

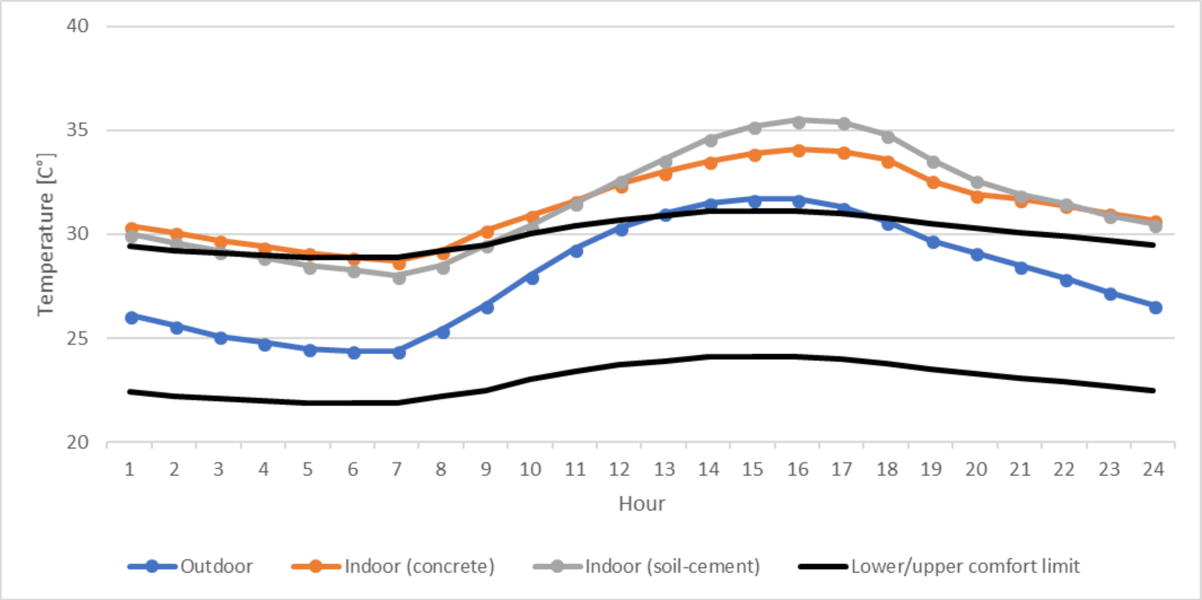


Figure 27 Simulation, orientation regarding the sun, short facades facing the east-west direction.

Table 9 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	28.7 (±0.0)	34.1 (±0.0)	31.3 (±0.0)
Indoor soil-cement	28.0 (±0.0)	35.5 (±0.0)	31.5 (±0.0)
Outdoor	24.4	31.7	28.0

The building was rotated 90 degrees counter-clockwise so that the short facades face the east-west direction where the low morning and evening sun is. The change doesn't influence the indoor temperature in any of the reference designs. See Figure 28 and Table 9 above. This could be explained by the facts there are windows on short-axis facing the east-west.

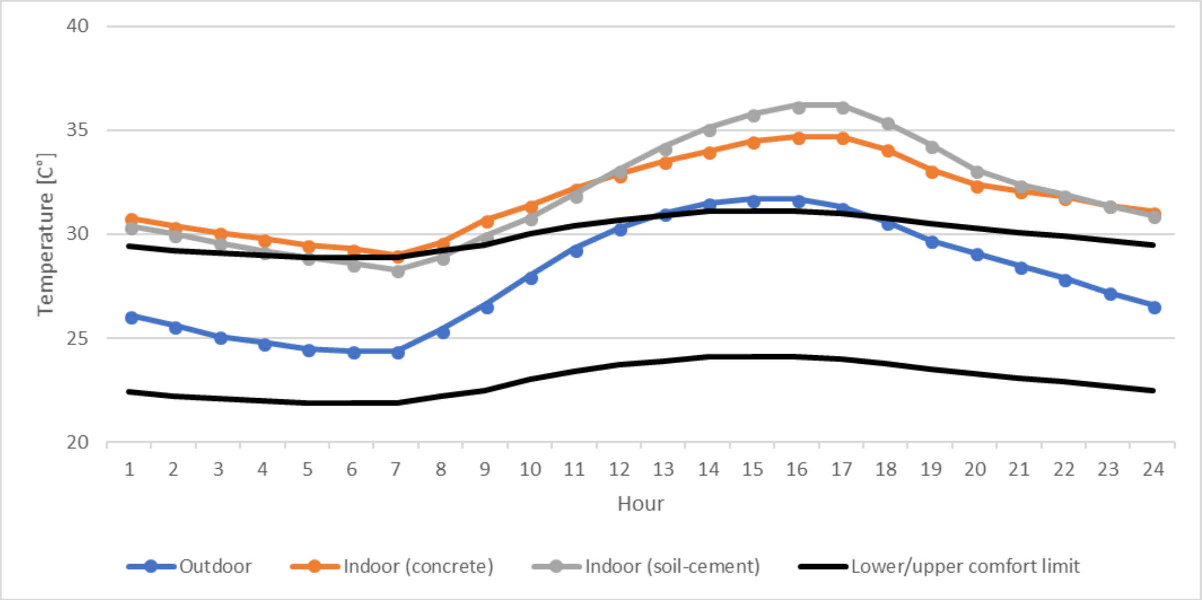


Figure 28 Simulation, orientation regarding the wind, long facades facing the predefined wind direction.

Table 10 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	29.0 (+0.3)	34.7 (+0.6)	31.8 (+0.5)
Indoor soil-cement	28.3 (+0.3)	36.2 (+0.7)	31.9 (+0.4)
Outdoor	24.4	31.7	28.0

The building was rotated 45 degrees counter-clockwise so that the long facades face the wind direction. The change results in a slight increase with about 0.5 °C of the indoor temperature for both reference designs. See Figure 28 and Table 10 above.

Given that the orientation change theoretically should lead to increased wind speed, the simulations suggest that long facades perpendicularly facing the wind direction necessarily doesn’t have to be optimal regarding natural ventilation and passive cooling, as stated in some of the literature.

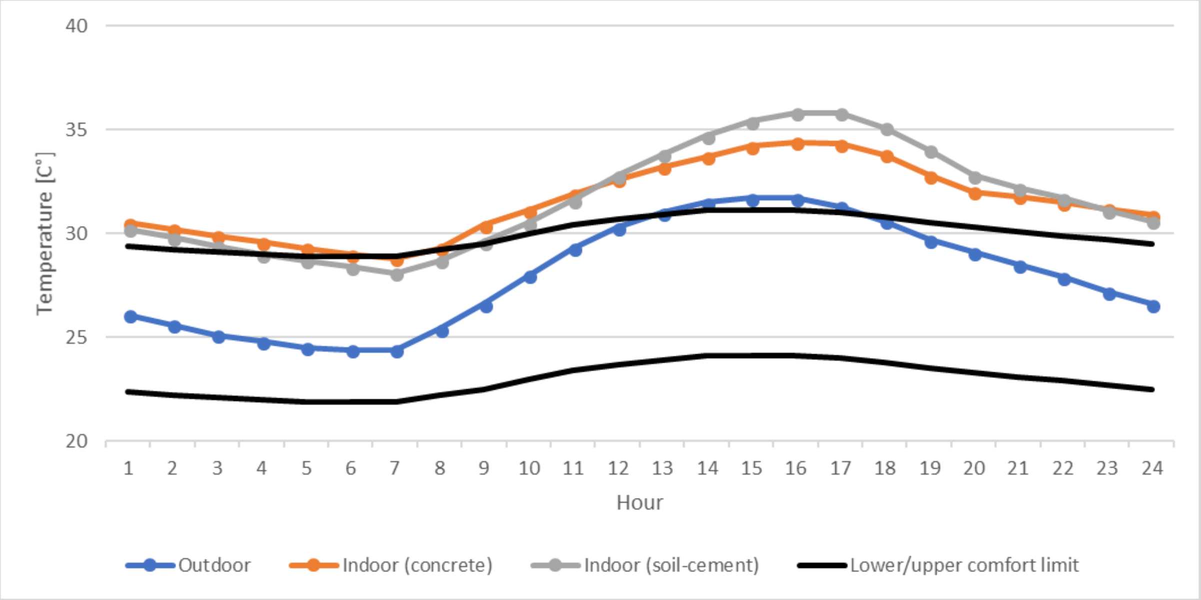


Figure 29 Simulation, orientation compromise 50/50 regarding sun/wind.

Table 11 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	28.8 (+0.1)	34.4 (+0.3)	31.5 (+0.2)
Indoor soil-cement	28.1 (+0.1)	35.8 (+0.3)	31.7 (+0.2)
Outdoor	24.4	31.7	28.0

The building was rotated 67.5 degrees counter-clockwise, which is a 50/50 compromise regarding both optimal sun and wind directions. The change results in a slight increase with about 0.2 °C of the indoor temperature for both reference designs. The increase is not as big as when the building was oriented regarding wind only, most possibly because the wind now again hits the facades at a tilted angle. See Figure 29 and Table 11 above.

The simulations show that orienting the building in any way regarding optimal sun and/or wind directions doesn't have as big impact on the indoor temperature as the literature suggest, at least not for the current building shape. Moreover, the simulations suggest that the optimal orientation regarding wind is not when the facades are perpendicularly facing the wind direction, but rather when tilted at about 45 degrees to the wind direction.

Later in the report, an additional reference design with the shape of an elongated rectangle is created to evaluate how that building shape respond to change of orientation, considering the indoor temperature.

5.2.2 Use of light colour on facades, roofing, window shading louvers and ceiling

The amount of solar radiation absorbed by the external surfaces of the building is highly dependent on the surface colour. Part of the absorbed heat is then transmitted to the inner surfaces where it is being further transferred to the indoor air by radiation and convection. Brown colours are absorbing about 70% of the solar radiation, while white colours only absorb at about 25%.(Givoni 1997) The difference is high, suggesting that the choice of colour might have a big impact on the indoor temperature. The simulations are evaluating the effect of having white colours on outer walls, inner walls, roofing tiles, eaves and ceiling.

The material properties that were changed in these simulations are listed in Table 12 below. The back side is always facing indoors.

Table 12 New/changed material properties.

Building element	**Absorptance front/back [%]**
Walls	25/25
Ceiling	50/25
Roof and eaves	30/30

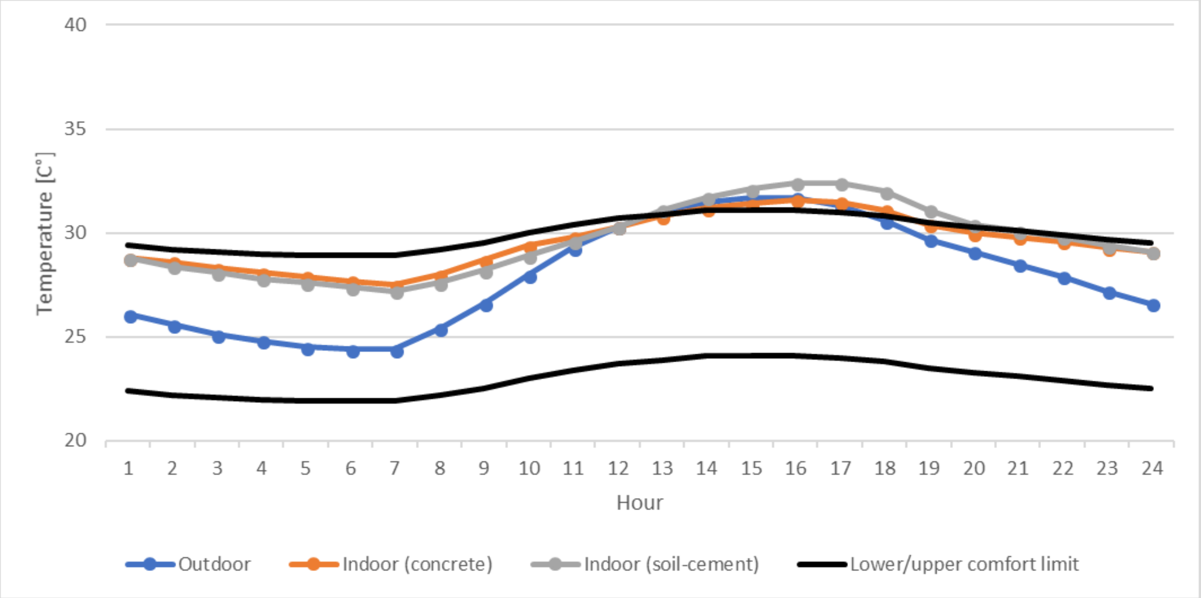


Figure 30 Simulation, white colour on outer walls, inner walls, roofing tiles, eaves window shading louvers and ceiling.

Table 13 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	27.5 (-1.2)	31.6 (-2.5)	29.5 (-1.8)
Indoor soil-cement	27.2 (-0.8)	32.4 (-3.1)	29.6 (-1.9)
Outdoor	24.4	31.7	28.0

The effect of changing the colour to white is significant, lowering the min/max/average temperatures with about 1, 3 and 2 °C respectively on both reference designs. For the concrete reference design, the max temperature even goes below the outdoor temperature. For the soil-cement reference design, the max temperature is only slightly higher than the outdoor temperature. See Figure 30 and Table 13 above.

5.2.3 Shading techniques

Proper shading from the strong sun is crucial in warm and humid climates like Dar es Salaam. Shading can be achieved by either fixed or operable, external or internal shading devices. Roof overhangs/eaves, wooden louvers for the windows and vegetation such as trees are some examples of shading devices. External devices by far provide the highest level of protection from heat radiation. (Givoni 1997, Bodoegaard 1981, Svard 1980)

Roof overhangs should be at least 0.6 m but preferably 1 m to provide effective protection against direct sun radiation. (Bodoegaard 1981, Svard 1980) The first simulation is evaluating the effect of extending the roof overhang from 0.6 m to 1 m.

The second simulation is evaluating the effect of equipping all windows with openable wooden louvers that provide thorough shading while allowing air to ventilate through the building.

5.2.3.1 Extended roof overhang/eaves

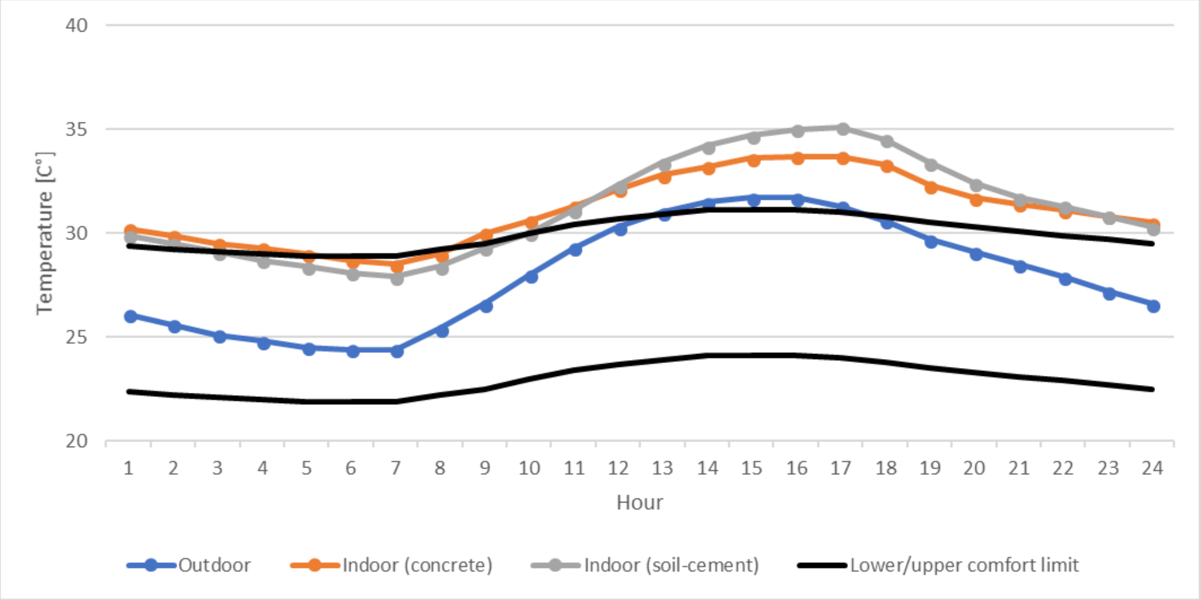


Figure 31 Simulation, roof overhang/eaves extended to 1 m.

Table 14 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	28.5 (-0.2)	33.7 (-0.4)	31.0 (-0.3)
Indoor soil-cement	27.9 (-0.1)	35.1 (-0.4)	31.2 (-0.3)
Outdoor	24.4	31.7	28.0

The roof overhang was extended from 0.6 m to 1 m. The change results in around 0.3 °C reduction of the indoor temperature in both reference designs. See Figure 31 and Table 14 above.

Although the simulation shows that extended roof overhangs/eaves produce some improved results, the extent of these improvements are not according to what is suggested in the literature.

5.2.3.2 Window shading louvers

The window shading louvres is a window blind or shutter with horizontal slats that are angled to admit light and air, but to keep out rain and direct sunshine. The angle of the slats may be adjustable, usually in blinds and windows, or fixed as illustrated below.

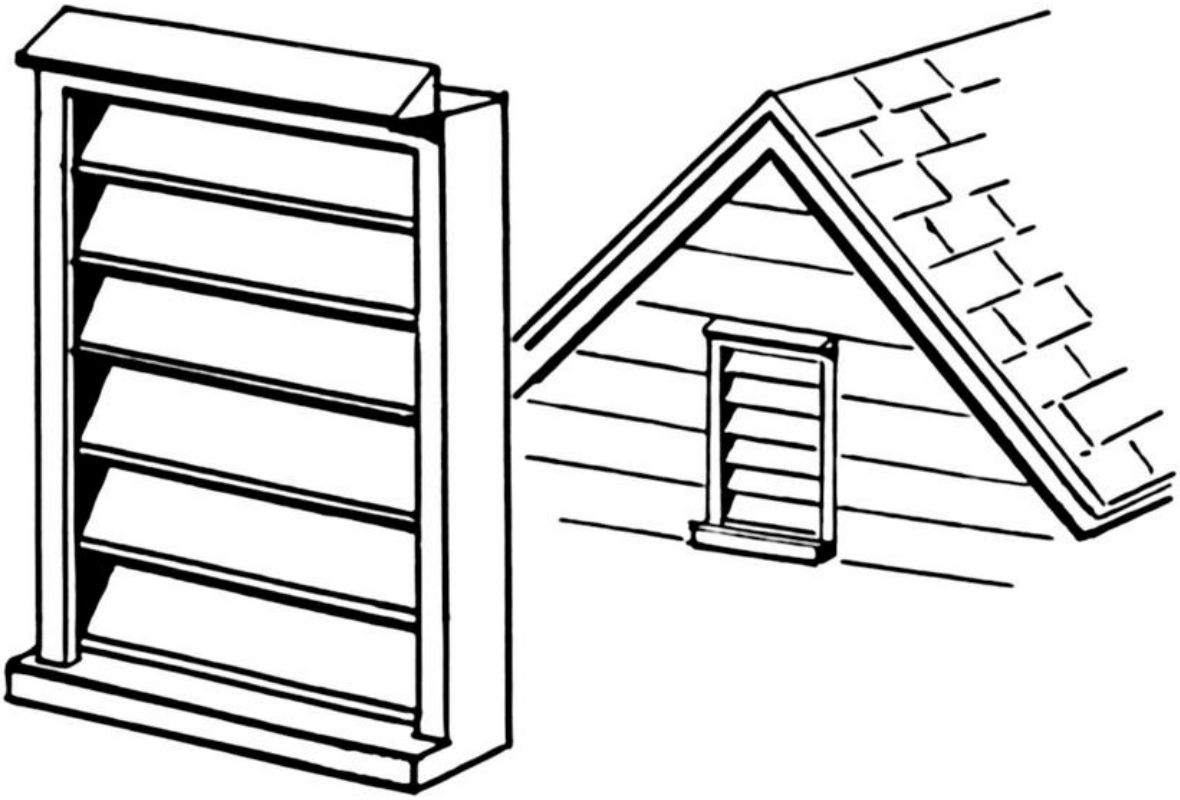


Figure 32 window shading louvre (Wikipedia)

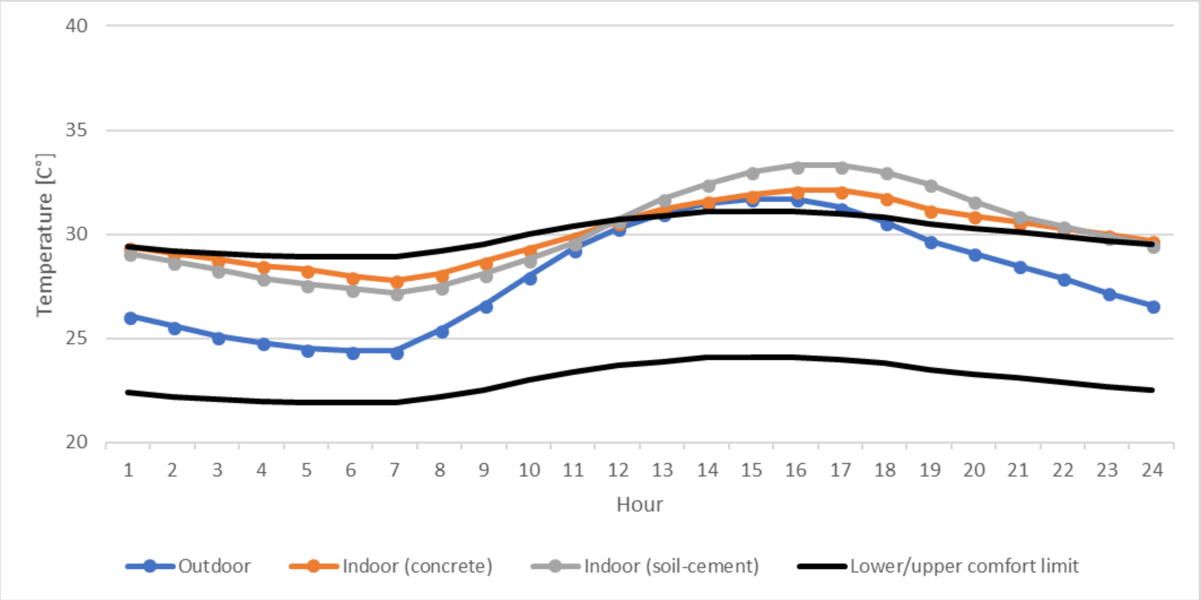


Figure 33 Simulation, shading wooden louvers placed on all windows.

Table 15 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	Min [°C]	Max [°C]	Average [°C]
Indoor concrete	27.8 (-0.9)	32.1 (-2.0)	30.0 (-1.3)
Indoor soil-cement	27.2 (-0.8)	33.3 (-2.2)	30.0 (-1.5)
Outdoor	24.4	31.7	28.0

All windows were equipped with openable wooden louvers that covers the whole window area. The solar absorptance and transmittance values on the louvers are 70 and 20% respectively. The louvers don’t influence the air movement through the windows in any way. The change results in significant reduction of the indoor temperature, lowering the min/max/average temperatures with about 1, 2 and 1.5 °C respectively. About the same effect is seen on both reference designs. See Figure 33 and Table 15 above.

The simulations show that external window shading devices are very effective ways to reduce the solar heat gain and confirm what is suggested in the literature.

5.2.4 Natural ventilation and passive cooling

The main purpose of climatic building design is to provide comfortable living conditions with minimal and meaningful input of energy with the aim of reducing the investment and the running cost as well as ecological damage. Natural ventilation of buildings can be provided by utilizing several methods depending on the size and geometry, building materials and the orientation.

The high humidity and the warm temperature require maximum ventilation, which leads to very open building both as regards design and plan. This can be achieved by having large openings in outer walls, for instance, large window proportion of preferably 40% or more of the outer walls as well as carefully placed ventilation openings. In areas with warm and humid climate, the need for more opening for ventilation purposes is greater especially around the coastal areas and areas close to the great lakes. This is because, the openings sufficient for daylight purposes are far from sufficient to get enough ventilation for comfort. In order to obtain good cross-ventilation, which is essential in warm and humid areas, there should be multiple openings in more than one wall, preferably opposite walls. In double banked buildings, in addition to the openings in outer walls, there must be openings in forms of doors and/or permanent ventilation in internal walls to allow free flow of air indoors (Svard 1980).

The literature is clear on the advice to have light walls with as little thermal mass as possible in combination with many big openings to allow for good cross ventilation. Night flushing, i.e. increasing the ventilation at night to get rid of stored up heat in the walls and to allow for the cooler walls to lower the indoor temperature during the day, is advised against in warm and humid climates due to the lows in temperature during night and day. High thermal mass is even said to have a negative impact on the indoor temperature as the heat stored up in the walls during the day is transmitted through radiation, heating the indoor air up during the night when people are sleeping.(Svard 1980, Bodoegaard 1981, Gut, Ackerknecht 1993)

5.2.4.1 Higher proportion of windows

In warm and humid climates, a high level of air movement is required as one of the most important means of controlling the indoor temperature. Therefore, it is advised to have a higher proportion of window openings in the façade, at least 50% of the wall area (Bodoegaard 1981). More and bigger openings allow for more sun light and radiant heat to enter the building, which is not the intended purpose. It is therefore important to use shading devices to the windows, otherwise the positive effect is reversed. The simulation is evaluating the effect that an increased window area has on the indoor temperature. The windows are equipped with wooden louvers and the results will be compared both with the reference design and with the results from the simulation of shaded windows (see 5.2.3 Shading techniques).

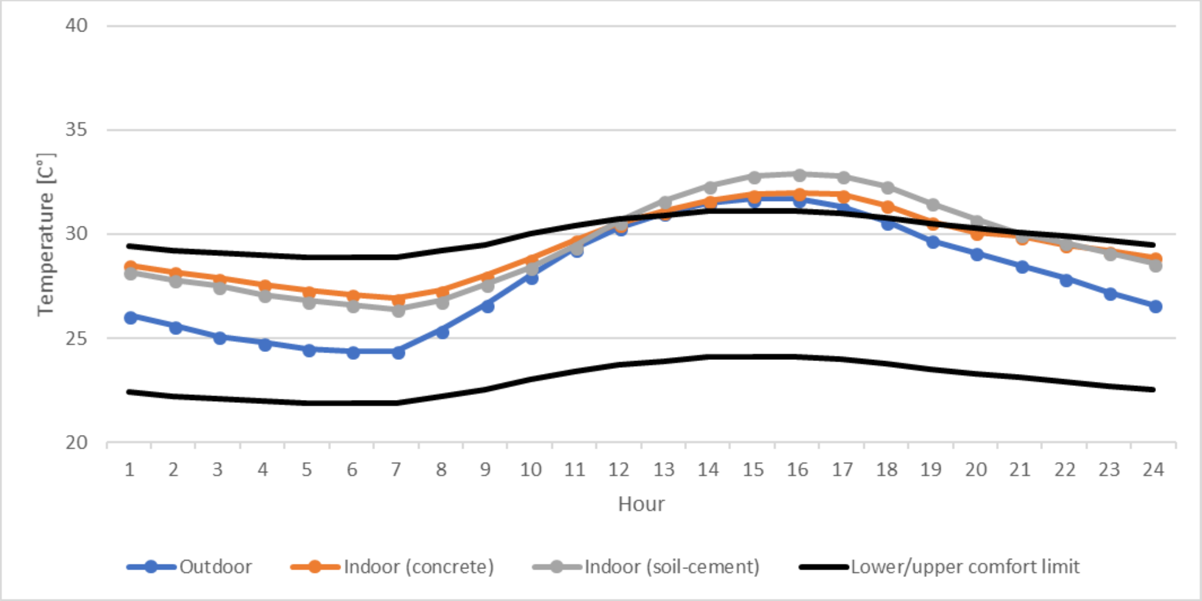


Figure 34 Simulation, higher proportion of windows, window area doubled.

Table 16 Temperature summary, values in parenthesis represents the temperature change from reference design and reference design with added window shading respectively.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	26.9 (-1.8) (-0.9)	32.0 (-2.1) (-0.1)	29.4 (-1.9) (-0.6)
Indoor soil-cement	26.4 (-1.6) (-0.8)	32.9 (-2.6) (-0.4)	29.5 (-2.0) (-0.5)
Outdoor	24.4	31.7	28.0

The total window area was doubled so that it accounts for 67% of the total wall area as opposed to the earlier 25%. All windows were equipped with openable wooden louvers that covers the whole window area. The louvers don't influence the air movement through the windows in any way. The change results in significant reduction of the indoor temperature. Compared to the results from the prior simulation where the originally sized windows were equipped with openable wooden louvers, the temperature was reduced with up to 0.9 °C. Compared with the pure reference designs, the temperature was reduced by 2 °C. For the max temperatures, the soil-cement reference designs tend to drop more than what it does for the concrete reference designs. See Figure 34 and Table 16 above.

The simulations confirm what is suggested in the literature, that bigger windows for ventilation purposes are important means for controlling the indoor temperature and increase wind speed to cool the perceived temperature and comfort.

5.2.4.2 Night flushing

The simulation is evaluating the effect that night flushing has on the indoor temperature.

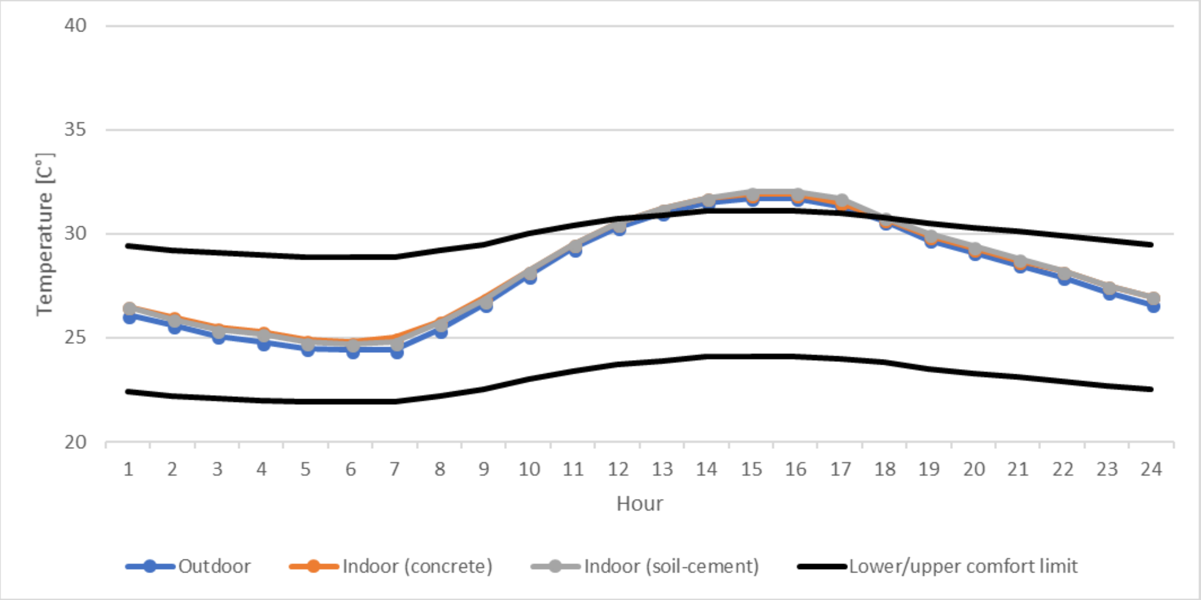


Figure 35 Simulation, night ventilation flushing.

Table 17 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	Min [°C]	Max [°C]	Average [°C]
Indoor concrete	24.8 (-3.9)	31.9 (-2.2)	28.3 (-3.0)
Indoor soil-cement	24.7 (-3.3)	32.0 (-3.5)	28.3 (-3.2)
Outdoor	24.4	31.7	28.0

All the windows were 65% open during night time, between 18:00 and 07:00. During the other hours, the windows were back to 35% open as in the reference design. The change results in significant reduction of the indoor temperature, lowering the temperatures with 2-4 °C so that the indoor temperature is only slightly higher than the outdoor temperature throughout the entire day, for both reference designs. See Figure 35 and Table 17 above. Other simulations could be looking at the effect this could have when building is closed after night flash as well as varying the thermal masses of the building to see how it changes.

The simulations show, contrary to what is universally suggested in the literature, that medium high thermal mass and night flushing has significant positive impact on the indoor temperature. The effect is apparent throughout the entire day.

5.2.5 Shape and geometry of building

Continuing on the same idea as in section 5.2.1 Orientation regarding solar radiation and wind, a new reference design is created for the sole purpose of evaluating the effect that the orientation has on a building with the shape of an elongated rectangle. The same considerations and recommendations as in section 5.2.1 about orientating buildings regarding sun and wind applies.

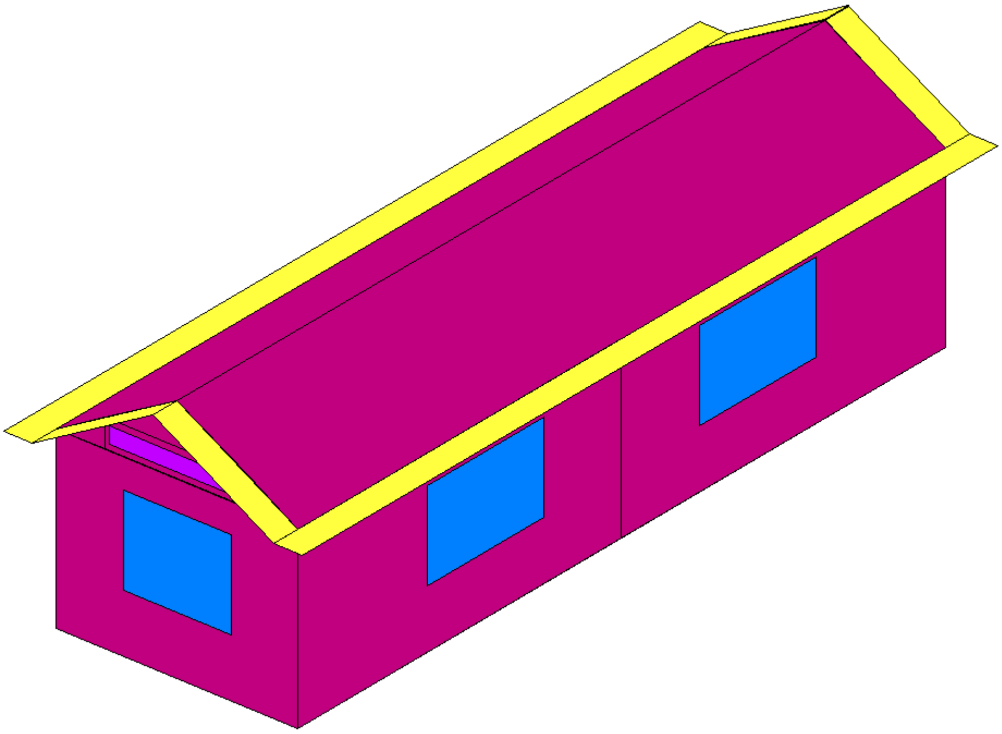


Figure 36 Visualization of new reference design, with the shape of an elongated rectangle.

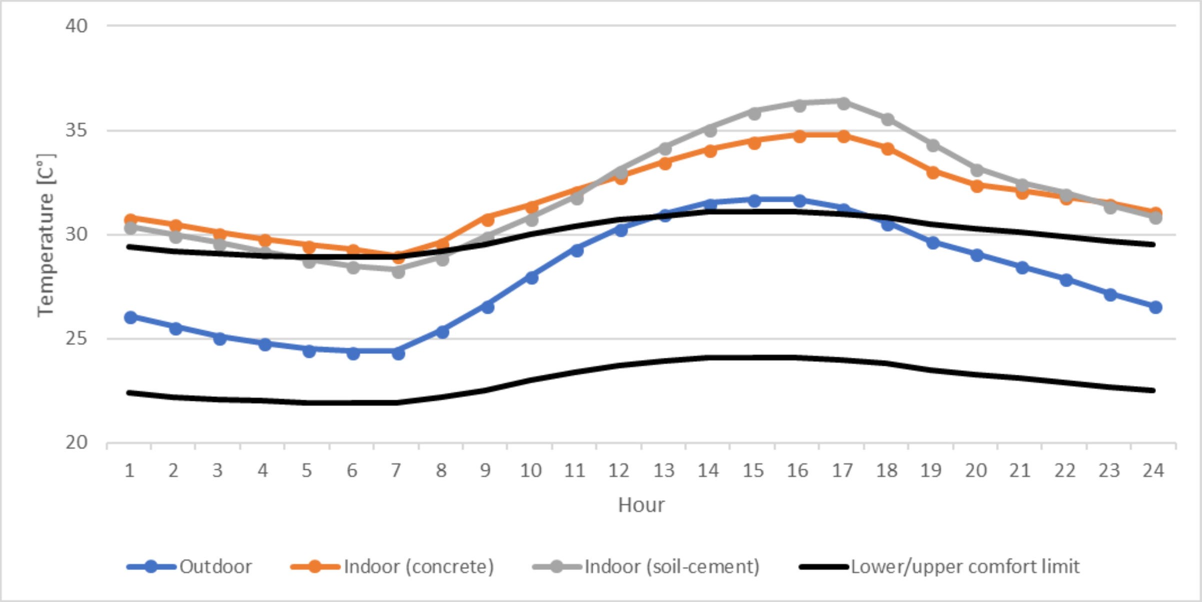


Figure 37 Simulation of new reference models, typical hot day in February.

Table 18 Temperature summary.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	29.0	34.8	31.8
Indoor soil-cement	28.3	36.4	32.0
Outdoor	24.4	31.7	28.0

In Figure 37 and Table 18, the simulation results on the new reference designs are presented. The coming simulations are evaluating the effect that the orientation has on the indoor climate regarding sun and wind respectively and independently. Thereafter, an optimal compromise between the two is examined according to the predefined wind direction in the simulation software.

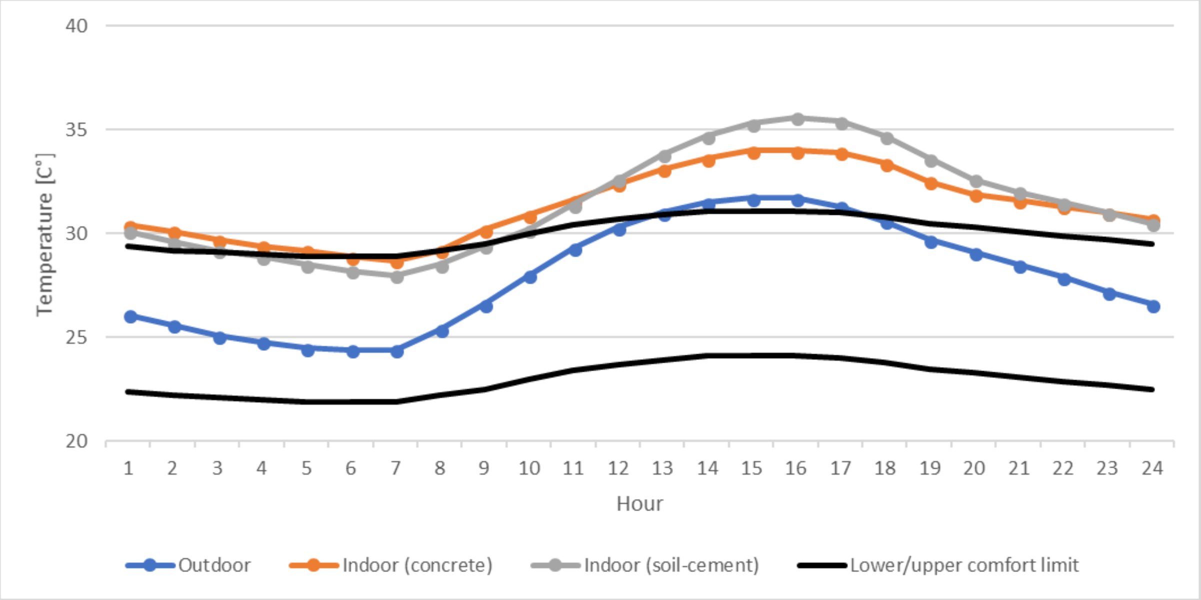


Figure 38 Simulation, orientation regarding the sun, short facades facing the east-west direction.

Table 19 Temperature summary, value in parenthesis represents the temperature change from new reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	28.7 (-0.3)	34.0 (-0.8)	31.3 (-0.5)
Indoor soil-cement	28.0 (-0.3)	35.6 (-0.8)	31.5 (-0.5)
Outdoor	24.4	31.7	28.0

The building was rotated 90 degrees counter-clockwise so that the short facades face the east-west direction where the low morning and evening sun is. The change results in a noticeable reduction of the indoor temperature, lowering the min/max/average temperatures with 0.3, 0.8 and 0.5 °C respectively on both reference designs. See Figure 38 and Table 19 above.

The simulations show that for the building shape of an elongated rectangle, an optimal orientation regarding the sun produces a slight improvement in the indoor temperature, but the extent of the improvement is still not on par with what is suggested in the literature. Again, this could be explained by the building having windows on short-axis facing east-west orientation.

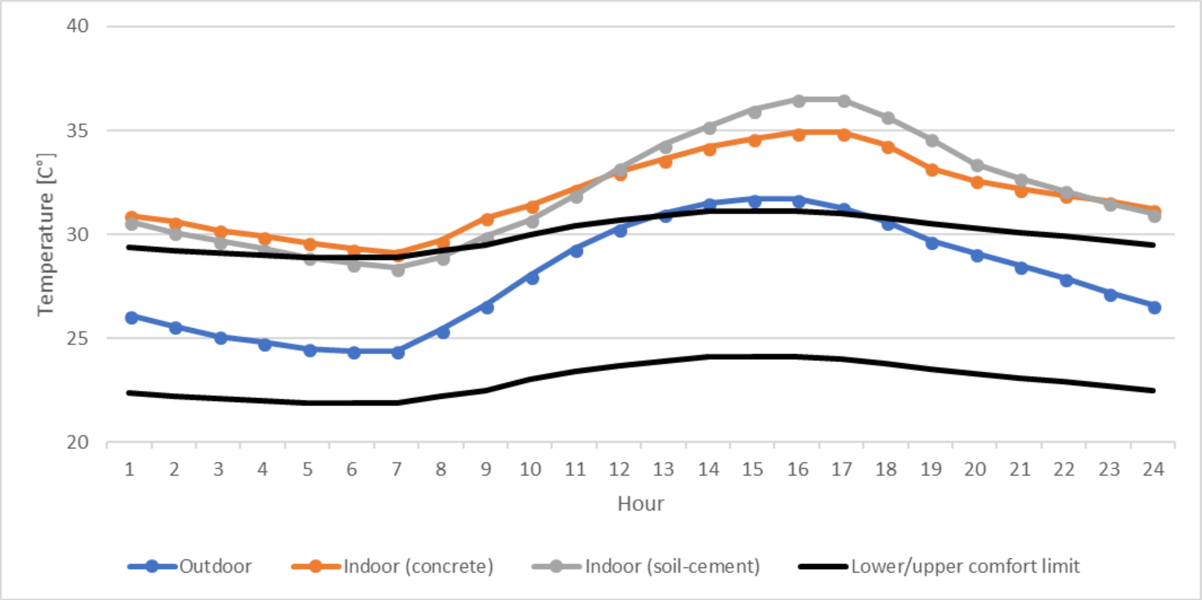


Figure 39 Simulation, orientation regarding the wind, long facades facing the predefined wind direction.

Table 20 Temperature summary, value in parenthesis represents the temperature change from new reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	29.1 (+0.1)	34.9 (+0.1)	31.9 (+0.1)
Indoor soil-cement	28.4 (+0.1)	36.5 (+0.1)	32.1 (+0.1)
Outdoor	24.4	31.7	28.0

The building was rotated 45 degrees counter-clockwise so that the long facades face the wind direction. The change results in a minimal 0.1 °C increase of the indoor temperature. See Figure 39 and Table 20 above.

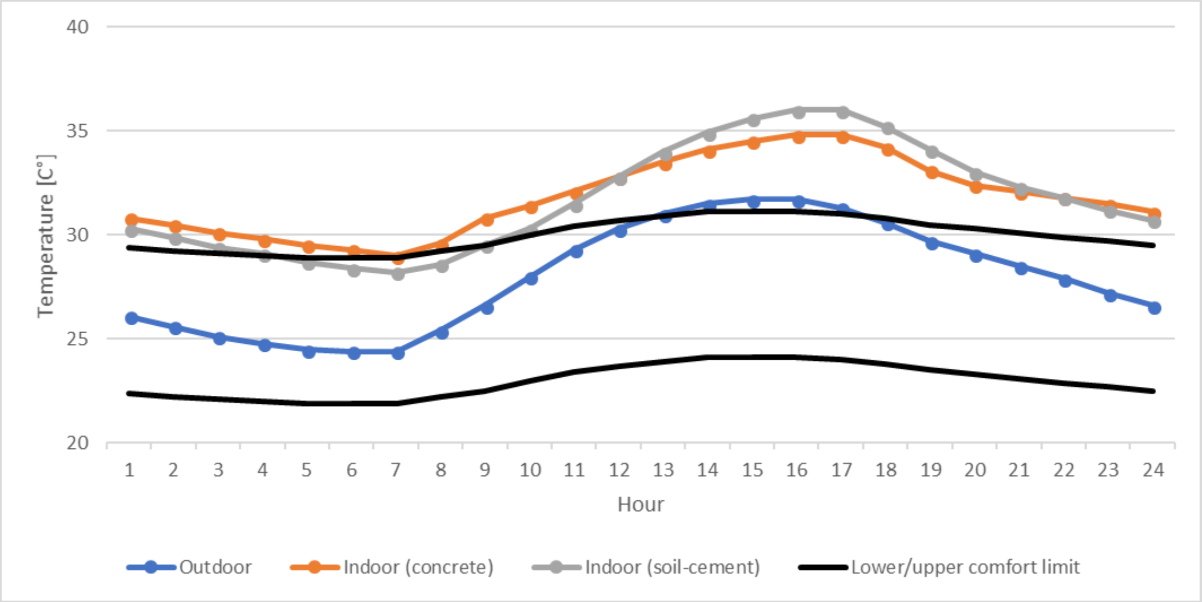


Figure 40 Simulation, orientation compromise 50/50 regarding sun/wind.

Table 21 Temperature summary, value in parenthesis represents the temperature change from new reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	28.9 (-0.1)	34.4 (-0.4)	31.6 (-0.2)
Indoor soil-cement	28.2 (-0.1)	36.0 (-0.4)	31.7 (-0.3)
Outdoor	24.4	31.7	28.0

The building was rotated 67.5 degrees counter-clockwise, which is a 50/50 compromise regarding both optimal sun and wind directions. The change results in a slight reduction of the indoor temperature, lowering the min/max/average temperatures with about 0.1, 0.4 and 0.3 °C respectively on both reference designs. The reduction is not as big as when the building is oriented regarding sun only. See Figure 40 and Table 21 above.

The simulations suggest that for building shapes of elongated rectangles, orienting regarding sun only, that is with long-axis oriented east-west is most effective in lowering the indoor temperature.

5.2.6 Combining design changes

In order evaluate the effect that all design changes that has positive impact combined has on the indoor temperature, simulations are conducted. All changes are combined on the original reference design as well as the new reference design with the building shape of an elongated rectangle. The design changes include:

- Orientation regarding sun
- White surface colours
- Extended roof overhangs/eaves
- Windows equipped with wooden louvers
- Higher window to wall ratio (WWR)
- Night flushing

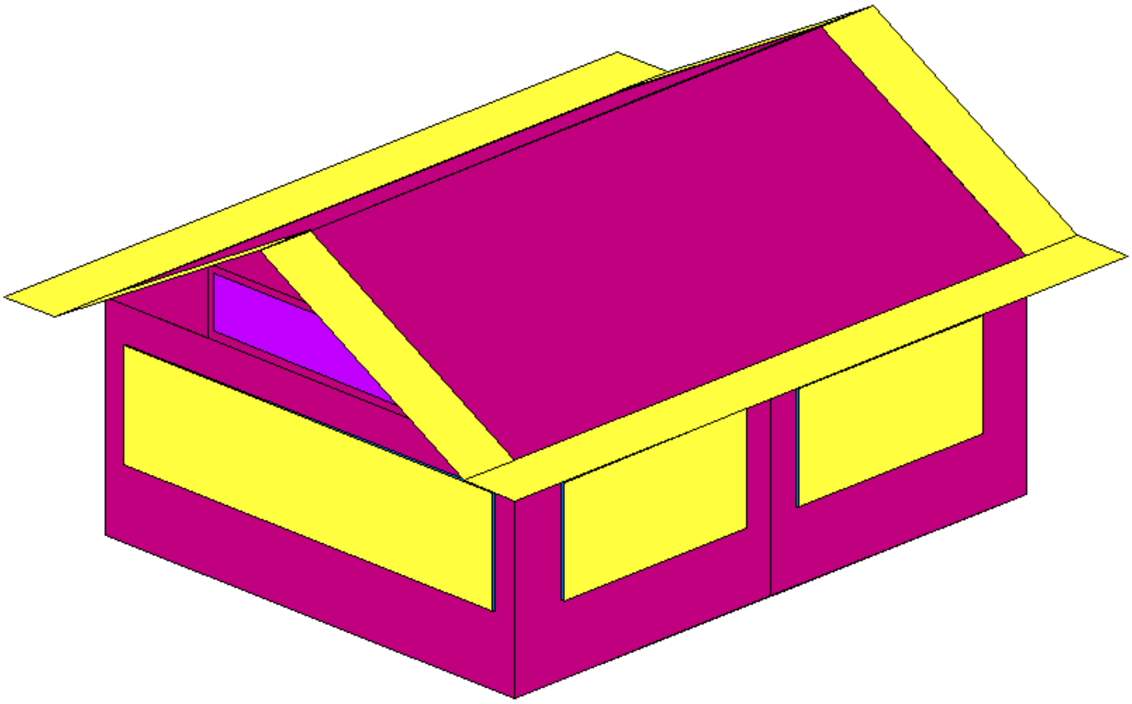


Figure 41 Visualization of combined design changes based on the shape of original reference design.

The material properties that were changed in these simulations are listed in Table 22 below. The back side is always facing indoors.

Table 22 New/changed material properties.

Building element	**Absorptance front/back [%]**
Walls and window shading louvers	25/25
Ceiling	50/25
Roof and eaves	30/30

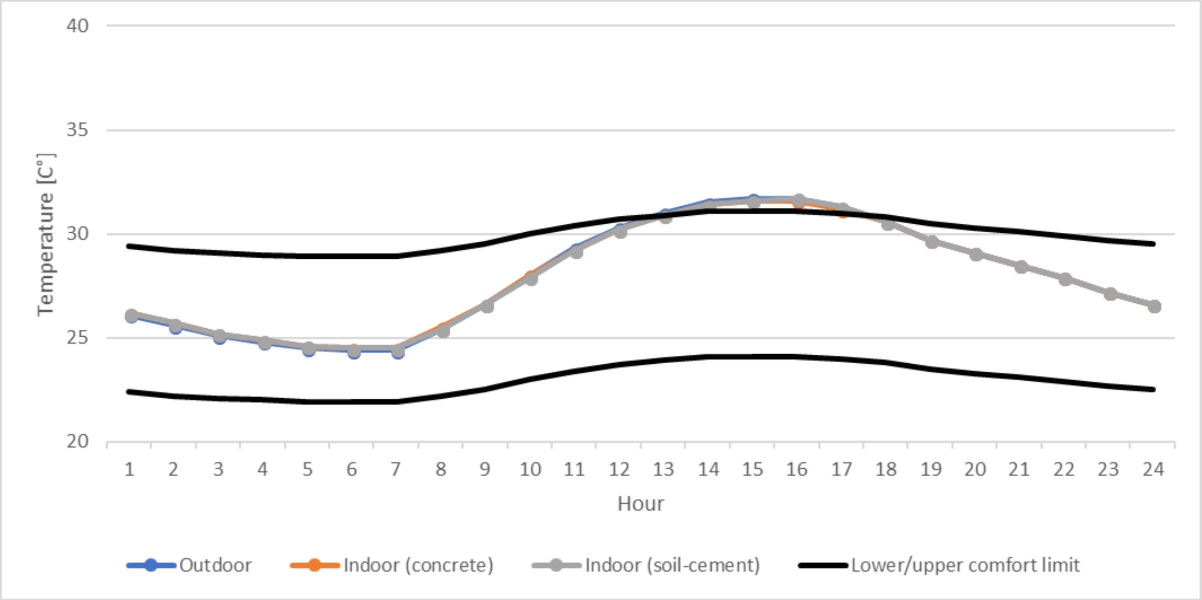


Figure 42 Simulation, building shape of original reference design, all design changes combined.

Table 23 Temperature summary, value in parenthesis represents the temperature change from reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	24.5 (-4.2)	31.6 (-2.5)	28.0 (-3.3)
Indoor soil-cement	24.5 (-3.5)	31.7 (-3.8)	28.0 (-3.5)
Outdoor	24.4	31.7	28.0

The combined changes results in significant reduction of the indoor temperature. For both reference designs, the indoor temperature is the same as the outdoor temperature throughout the entire day. See Figure 42 and Table 23 above.

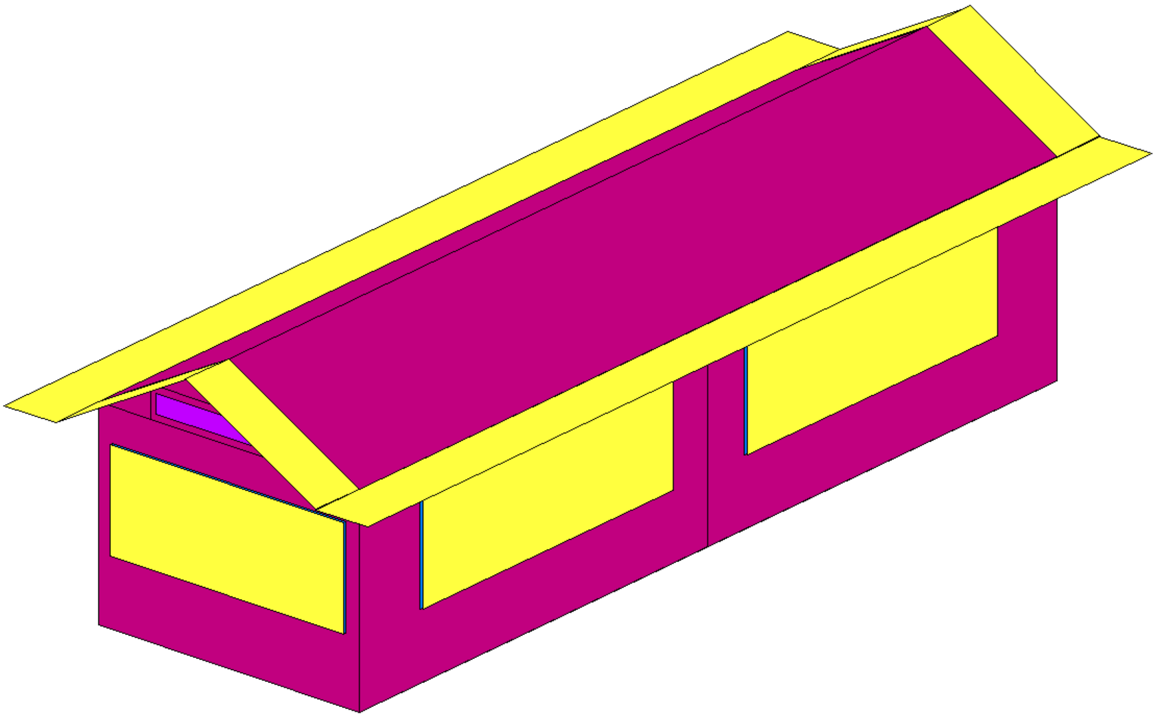


Figure 43 Visualization of combined design changes based on the shape of new reference design.

The material properties that were changed in these simulations are listed in Table 24 below. The back side is always facing indoors.

Table 24 New/changed material properties.

Building element	**Absorptance front/back [%]**
Walls and window shading louvers	25/25
Ceiling	50/25
Roof and eaves	30/30

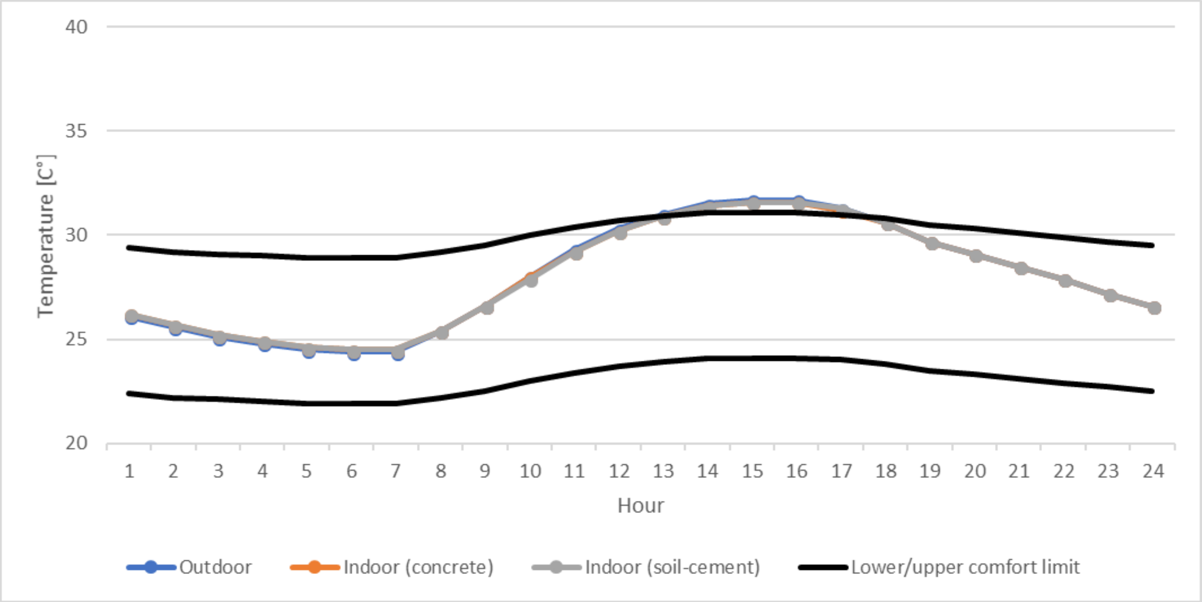


Figure 44 Simulation, building shape of an elongated rectangle, all design changes combined.

Table 25 Temperature summary, value in parenthesis represents the temperature change from new reference design.

Volume	**Min [°C]**	**Max [°C]**	**Average [°C]**
Indoor concrete	24.5 (-4.5)	31.6 (-3.2)	28.0 (-3.8)
Indoor soil-cement	24.5 (-3.8)	31.6 (-4.8)	28.0 (-4.0)
Outdoor	24.4	31.7	28.0

All the design changes were combined into the same simulation model. The changes were the same as for the original design plus changing the building shape to an elongated rectangle. The combined changes results in significant reduction of the indoor temperature. For both reference designs, the indoor temperature is the same as the outdoor temperature throughout the entire day. See Figure 44 and Table 25 above.

5.3 Annual energy use and energy savings when using A/C

Although passive design techniques for controlling the indoor temperature exist and are proven to work well, in many situations it is required to use air conditioning units anyway to achieve good comfort. For that reason, comparative simulations are conducted to show the extent of energy savings throughout the whole year, from using the design changes implemented above.

The first simulation is looking at the annual energy required to keep the temperature stable at 25 °C for the original reference design. To get realistic results, the windows are closed at all times.

The second simulation is looking at the annual energy consumption for the original reference design with the combined design changes. The temperature setpoint is 25 °C. Again, to get realistic results, higher proportion of windows and night flushing are left out of this simulation. The windows are also closed at all times.

The process is repeated on the new reference design with the building shape of an elongated rectangle.

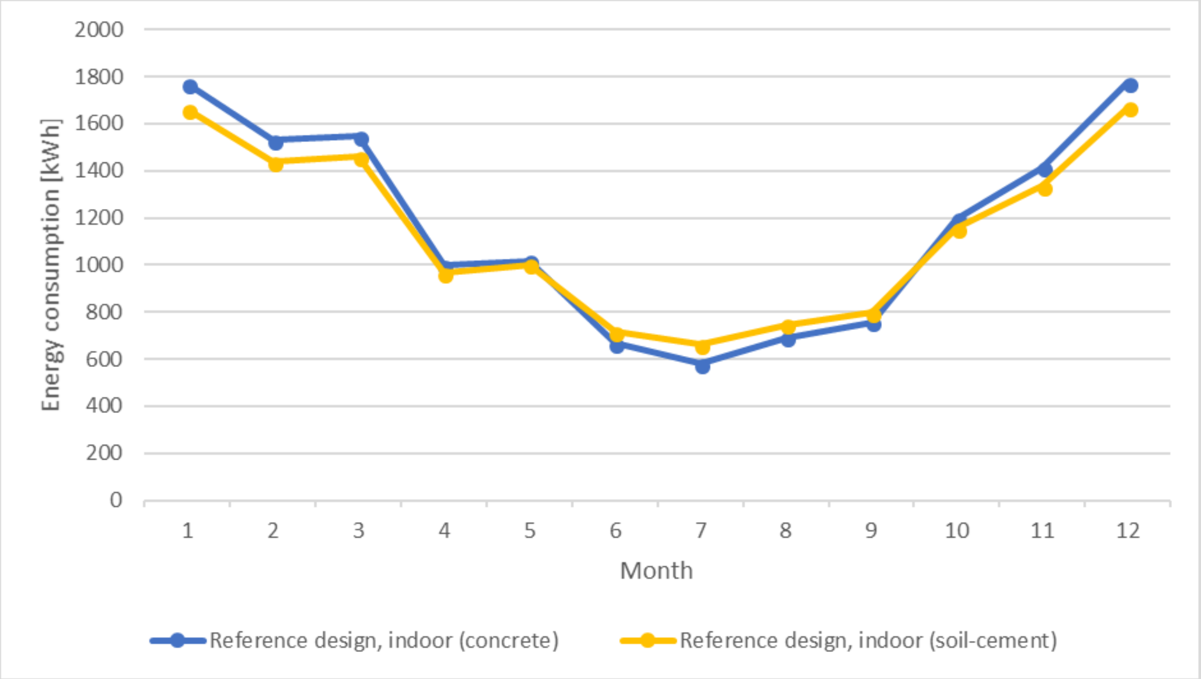


Figure 45 Simulation original reference design, annual energy consumption needed to keep the indoor temperature below 25 °C.

Table 26 Energy use summary.

Volume	**Total [kWh]**	**Min [kWh]**	**Max [kWh]**	**Average [kWh]**
Indoor concrete	13,935	581	1,775	1,161
Indoor soil-cement	13,600	663	1,667	1,133

The results show an annual energy use of 14,000 kWh for the original reference design. It is worth mentioning that the numbers don’t represent the actual electric energy consumption but rather the amount of energy needed to be transferred out of the building in order to keep the temperature at 25 °C. The actual electric energy use depends on the efficiency of the air conditioning unit and is 1/5 up to 1/2 of the presented numbers above. The soil-cement reference design has a slightly lower energy consumption. See Figure 45 and Table 26 above.

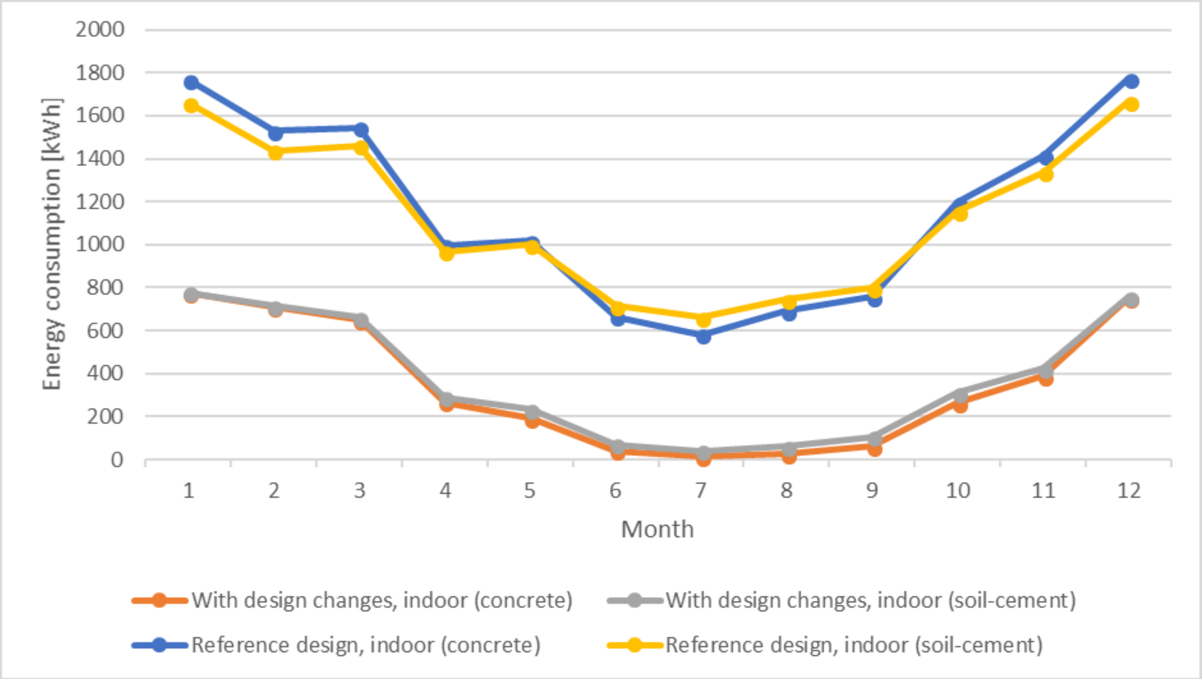


Figure 46 Simulation original reference design with combined design changes, energy consumption needed to keep the indoor temperature below 25 °C.

Table 27 Energy use summary, value in parenthesis represents the relative temperature change from reference design.

Volume	**Total [kWh]**	**Min [kWh]**	**Max [kWh]**	**Average [kWh]**
Indoor concrete	4,136 (-70%)	12 (-97%)	776 (-56%)	345 (-70%)
Indoor soil-cement	4,443 (-67%)	41 (-94%)	776 (-53%)	370 (-67%)

The simulation on the original reference design with the combined design changes show extreme reduction of the annual energy consumption. A bigger reduction is seen for the concrete design, 70% versus 67% for the soil-cement design. The resulting annual energy consumption is also slightly lower for the concrete design. See Figure 46 and Table 27 above.

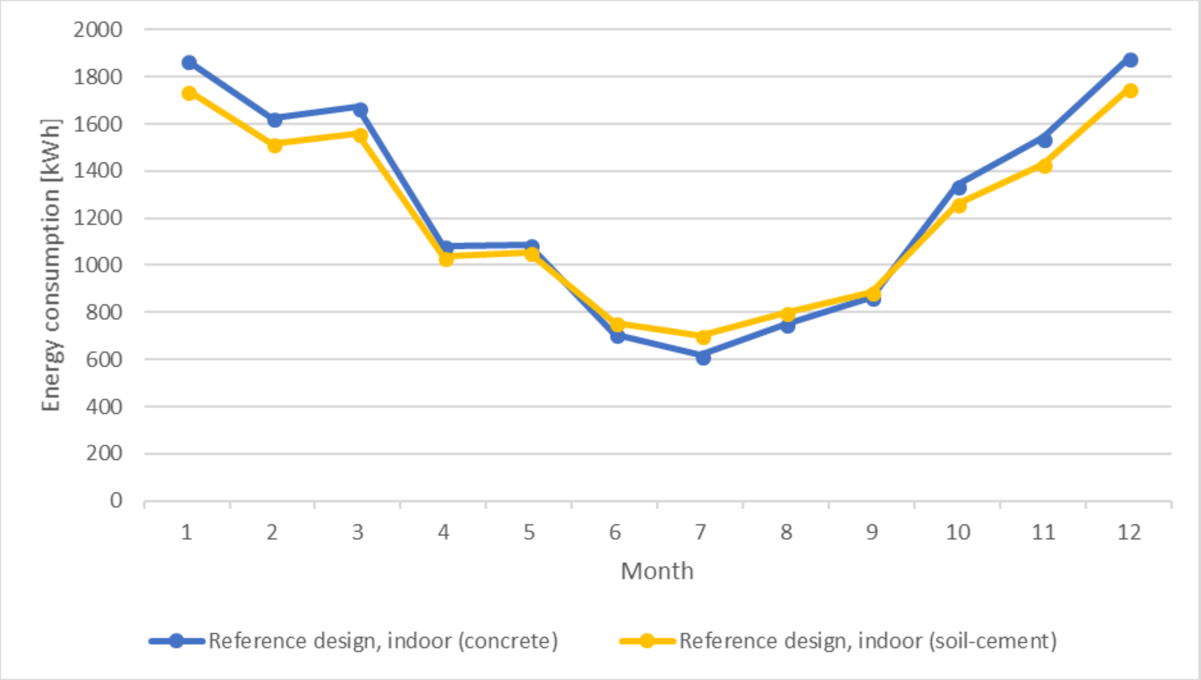


Figure 47 Simulation new reference design, energy consumption needed to keep the indoor temperature below 25 °C.

Table 28 Energy consumption summary, value in parenthesis represents the relative temperature change from reference design.

Volume	**Total [kWh]**	**Min [kWh]**	**Max [kWh]**	**Average [kWh]**
Indoor concrete	15,042	619	1,881	1,254
Indoor soil-cement	14,501	704	1,751	1,208

The simulation on the new reference design show an annual energy consumption of 15,000 kWh. The soil-cement reference design again has a slightly lower energy consumption. See Figure 47 and Table 28 above.

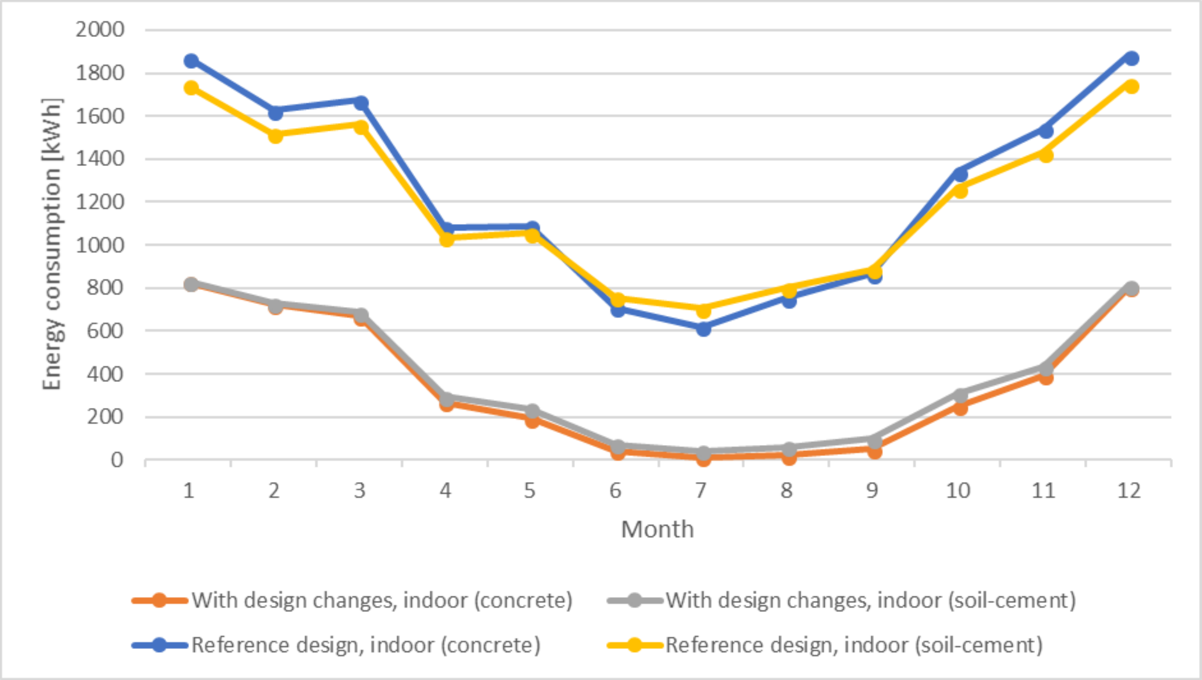


Figure 48 Simulation new reference design with combined design changes, energy consumption needed to keep the indoor temperature below 25 °C.

Table 29 Energy consumption summary, value in parenthesis represents the relative temperature change from reference design.

Volume	Total [kWh]	Min [kWh]	Max [kWh]	Average [kWh]
Indoor concrete	4,251 (-72%)	11 (-98%)	827 (-56%)	354 (-72%)
Indoor soil-cement	4,604 (-68%)	42 (-94%)	829 (-53%)	384 (-68%)

The simulation on the new reference design with the combined design changes show significant reduction of the annual energy consumption. A bigger reduction is again seen for the concrete design, 72% versus 68% for the soil-cement design. The resulting annual energy consumption is also slightly lower for the concrete design. See Figure 48 and Table 29 above.

5.4 Cost savings

Considering the high rate of urbanization, the extension of existing slums and creation of new, there is clear evidence that many households cannot afford to build a decent house. By using the modern, locally sourced low-cost building materials now available in Tanzania, the construction cost can be lowered, and the standard can be improved. Cost savings can also be achieved by more efficient use of materials, smarter design choices and by incorporating climatic design techniques into the architectural design, leading to less air conditioning needs. A couple of simple calculations can show an indication on the extent of potential cost savings.

For the simplification of the calculations, the same building dimensions as in the original reference design is used, i.e. 10x8 m and a ceiling height of 3 m. An additional 18 m of inner walls are added for realistic results.

First, the cost of contemporary way of building, using traditional materials and non-climatic design techniques is calculated. Then the cost of modern way of building, using modern material and climatic design techniques is calculated. The actual and relative cost savings are then calculated and presented.

The annual running cost of A/C use to keep the temperature at 25 °C is calculated as well. The A/C is assumed to have a COP-rating of 4 and the cost of electricity is 300 Tanzanian Shillings per kilowatt-hour electricity (*Jedwali Na. 1: Bei za umeme zilizoidhinishwa.* 2016). Other cost data according to chapter 2.4. Energy consumption numbers according to chapter 5.3.

Contemporary walls

$$(10 + 8 + 18)\,m \cdot 3\,m \cdot 28{,}000\,TSH/m^2 = 3{,}024{,}000\,TSH$$

Contemporary roof

$$2 \cdot 10\,m \cdot 4\,m/\cos 25 \cdot 10{,}000\,TSH/m^2 = 882{,}702\,TSH$$

Energy usage (A/C, 1 year, non-climatic design techniques)

$$13{,}935\,kWh \cdot 300\,TSH/kWh \cdot \frac{1}{4} = 1{,}045{,}125\,TSH$$

Contemporary walls and roof + Energy (A/C, 1 year, non-climatic design techniques)

$$3{,}024{,}000\,TSH + 882{,}702\,TSH + 1{,}045{,}125\,TSH = 4{,}951{,}827\,TSH\ (\sim 2{,}200\,USD)$$

Modern low-cost walls + Lowering of the ceiling height

In Tanzania, the standard ceiling height seems to be about 3 m. There is a belief that high ceilings are advantageous or even necessary in order to achieve good indoor thermal comfort. The ceiling height does not influence the thermal comfort, but the ceiling surface temperature, which suggests that increased ventilation in the attic space is a solution. Any increase beyond 2.4 m is a waste of wall material and money.(Bodoegaard 1981, Svard 1980)

The cost of the walls with the ceiling height of 2.4 m is calculated, using modern building materials. The percentage value in parenthesis is the relative change from the cost of traditional walls.

$$(10 + 8 + 18)\,m \cdot 2.4\,m \cdot 17{,}000\,TSH/m^2 = 1{,}468{,}800\,TSH\ (-51\%)$$

Modern low-cost roof

$$2 \cdot 10\,m \cdot 4\,m/\cos 25 \cdot 6{,}500\,TSH/m^2 = 573{,}757\,TSH\ (-35\%)$$

Energy usage (A/C, 1 year, climatic design techniques)

$$4{,}443\,kWh \cdot 300\,TSH/kWh \cdot \frac{1}{4} = 333{,}225\,TSH\ (-68\%)$$

Modern low-cost walls + Lowering of the ceiling height + Modern low-cost roof + Energy usage (A/C, 1 year, climatic design techniques)

$$\begin{aligned}1{,}468{,}800\,TSH + 573{,}757\,TSH + 333{,}225\,TSH \\ = 2{,}375{,}782\,TSH\ (\sim 1{,}000\,USD)\ (-52\%)\end{aligned}$$

Table 30 Cost summary, value in parenthesis represents the relative cost reduction from traditional way of building.

	Contemporary [TSH]	**Modern [TSH]**
Walls	3,024,000	1,468,800 (-51%)
Roof	882,702	573,757 (-35%)
Energy usage (A/C, 1 year)	1,045,125	333,225 (-68%)
Total	**4,951,827**	**2,375,782 (-52%)**

As seen in Table 30 above, significant cost savings can be made. Only by using modern roof and wall materials and by lowering the ceiling height, nearly half the material cost can be reduced. By climatically designing buildings, 68% of the electricity bill originating from the A/C can be cut. On the original reference design, up to 700,000 TSH (~300 USD) can be saved annually on the A/C running cost, which approximately equals 2-3 months' income in the country (, Tanzania Monthly Average Wages in Private Sector).

6 Analysis and discussion

6.1 Design features affecting the indoor climate

6.1.1 Orientation and shape of buildings

Orienting buildings to avoid insolation, is shown to have limited effect on the indoor temperature. This can be significantly improved by avoiding windows on short-axis facing east-west orientations or at minimum having window shutters. The simulations show that the building with the dimensions 16x5 m only reduced the indoor average temperature with 0.5 °C by orienting it regarding the sun, while the original reference design with the dimensions 10x8 m wasn't influenced by the change at all. The conclusions are that rather big changes in wall area are required to have any effect on the indoor temperature at all. Even with the unusually long shape of the new reference design and the difference in window area, the reduction was only marginal.

Although the study doesn't look at room placement and layout within the building, given the relatively high thermal mass of the outer walls in modern and contemporary buildings, it is still advised to at least have the bedrooms in the east side of the house, to avoid the radiant heat from the west facing outer wall in the evening and night.

Orienting the building regarding wind only, i.e. so that the long walls perpendicularly face the wind direction, results in slightly increased indoor temperatures for both building shapes. Theoretically, solar heat gain is reduced by the orientation change, so the resulting temperature increase is interesting. Perhaps the air molecules get greater contact with the wall when the wind is approaching at a tilted angle, rather than perpendicularly which logically could create a protecting air-cushion, limiting the convective cooling effect that the wind has on the walls. Furthermore, studies have shown that tilted angles create more air turbulence inside the building, which could explain the results. Simulations have not been conducted on orienting the building so that the long walls are parallel with the wind direction. There is a possibility that air flowing parallel to the long walls even have the best cooling effect, however, it cannot be confirmed in this study.

The study doesn't suggest there is any compromise between optimal orientation regarding sun and wind that produce better results than orientations regarding sun only. However, considering the complex nature and effects of orientating buildings regarding both sun and wind, no certain conclusions can be made on this subject only from the results of the simulations in this report. More simulations and studies need to be done to be able to draw any conclusive conclusions on the matter.

Regarding perceived temperature, the lowest indoor temperature doesn't necessarily have to be optimal in terms of human comfort. In warm and humid climates like Dar es Salaam, high air velocities are perceived as comfortable by humans as the body is being cooled more effectively. In that respect, orientations that are making effective cross ventilation possible may be the most optimal in terms of human comfort, even if the indoor air temperature is slightly higher. An entire report can be produced on the sole purpose of studying the effects that the orientation of the building has on perceived temperature and human comfort.

6.2 Climate consideration and building design in general

The climate consideration is essential when it comes to planning for building of any type in any given climate. Assessment of the prevailing climatic conditions must be well established to be able to design buildings that are appropriate and meets the human requirements regarding indoor climate. The main objective of climatic design is to provide comfortable living conditions with a minimum and meaningful input of artificial energy. This reduces the investment and running costs as well as ecological footprints.

In general, the daytime temperatures in warm and humid climates are uncomfortably high, particularly during the warmer season and in low altitude locations such as that of Dar es Salaam. Air humidity is also of great importance. This factor influences the precipitation pattern and the amount of solar radiation that reaches the earth's surface. The influence of a cloud cover is most obvious, but invisible humidity in the atmosphere also alters the amount of radiation. Whereas with dry air the radiation is strong and direct, humid air causes a weaker but diffuse radiation and also reduces the amount of re-radiation to the night sky(Gut, Ackerknecht 1993).

6.2.1 White surface colours

The simulations on changing the colours on exterior and interior surfaces from medium dark colour with absorption of about 70% to white had very significant impact on the indoor temperatures and should be among the highest priority design changes. The reduced amount of radiation heat absorbed by the walls is clearly contributing to the improved indoor climate. In the simulations, the roof colour was also changed, which theoretically should lower the temperature in the attic space. The contribution of having white roof surfaces on the indoor temperature is unknown. Even if it wouldn't influence the indoor temperature by much, it is known that ceiling surface temperatures heavily influence the perceived (operative) indoor temperature, suggesting that low attic space temperatures should be of importance.

6.2.2 Material properties and thermal performances

Using building materials with high thermal mass can manage to even out the temperature variations throughout the day and can even be helpful if night flushing is used correctly (more on night flushing further down). In the individual simulations, the solid concrete block design often manages to even out the variations slightly, especially by lowering the max temperature.

However, when combining all design changes, there is no advantage in using either the concrete or the soil-cement blocks, considering the indoor temperature.

6.2.3 Natural ventilation and passive cooling of buildings

6.2.3.1 Higher proportion of windows

The results from the simulations with regard to higher proportion of window openings in the facades confirm that ventilation is one of the most important means of controlling the indoor temperature. As stated earlier, it is required that the windows have shading devices attached to them, otherwise the effect could be severely reversed.

The increased ventilation doesn’t necessarily have to be accomplished using higher proportion of windows. It could just as well be from permanent openings in the walls, e.g. special building blocks in the upper part of the wall that allows free air movement through the building.

If A/C is used as the primarily way to keep the temperature low, this method will obviously not work and would only lead to increased energy usage and higher cost of operation.

6.2.3.2 Night flushing

The results from the night flushing simulations were surprising to say the least. The effect that opening the windows during night time had on the indoor temperature was much greater than what the literature suggests. The effect was even clear during all the hours of the day, keeping the indoor temperature stable just slightly above the outdoor temperature. Although the effect is very positive, it is dependent on the knowledge, understanding and action of human beings.

This is also one of the methods that don’t work if air conditioning is used in the building. Since the maximum effect of passive cooling techniques is keeping the indoor and outdoor temperature the same, the indoor temperature will not drop below 31 °C during a typical hot February day. This makes the probability of using A/C devices rather high. However, if A/C is not used, night flushing has great potential to reduce and stabilize the indoor temperature.

6.2.3.3 Shading devices

Of all the simulations conducted, shading techniques have proven to be one of the most effective means of lowering the indoor temperature in this climate.

Extending the roof overhang/eaves from 0.6 m to 1 m has small impact on the indoor temperature but does to some extent lower the amount of time that the east and west facing facades are exposed to direct sun radiation. To save money, a compromise could be to extend the eaves shading the east and west facing facades only, since the north and south facing facades barely are exposed anyway.

When it comes to equipping the windows with external shading devices though, the simulations show great improvements. Again, east and west facing windows are crucial but north and south facing windows are potentially taking advantage of it as well, as the heat radiation in humid areas is very diffuse and originate from all possible directions. It is important that the shading devices do not obstruct the wind to flow through the window openings, as this could have a reversed effect on the human comfort as discussed earlier regarding perceived temperatures.

6.3 Combined design changes and the contribution of individual design changes

Combining all design changes into the same simulation model result in keeping the indoor temperature the same as the outdoor throughout the entire day. This is regardless of the building shape or construction materials used. Knowing what individual design changes contribute most to the lowering of the indoor temperature is of course impossible when only looking at the results from the simulations of the combined design changes. However, by looking at the simulations of the individual and independent design changes, one can get an idea of which ones contribute most to the temperature reduction. Looking at the combined design changes on the original reference design, the approximate distribution of the contribution of the individual design changes looks as following.

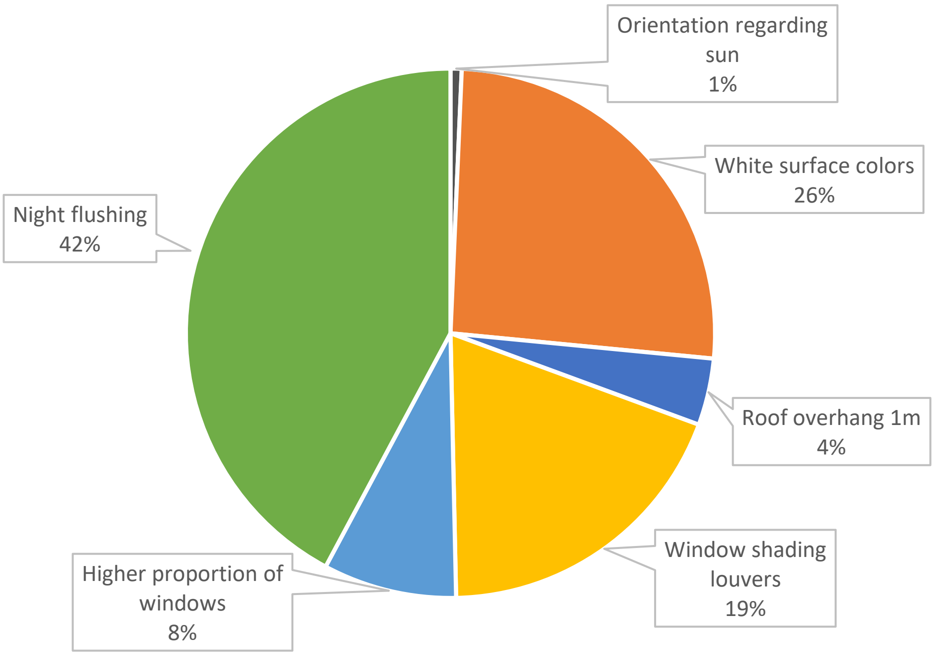


Figure 49 Approximate distribution of the reduction of indoor temperature, contributed by individual design changes – Original reference design (10x8m).

The problem with distribution charts as the one above is that it's very difficult to make them completely accurate. With the current method used for the simulations, the distribution charts can only be approximate since the individual design changes are dependent on each other, e.g. an orientation change of the building also influences the effect of roof overhangs since the exposed wall area is changed. However, as for the original reference design which has almost the shape of a square, a change of orientation should not have any major impact on the effect of other design changes. Moreover, the window area on each wall is the same, meaning the amount of radiation entering through window openings doesn't change when the building is oriented. The effect distribution between night flushing and higher proportion of windows is more difficult to find out when combined. The distribution chart above should be fairly accurate though.

Combining all design changes into the same simulation model also make it impossible to know whether all the changes are needed to keep the indoor and outdoor temperature the same. An additional simulation not shown in this report, applying all design changes but the ones leading to increased ventilation, i.e. higher proportion of windows and night flushing, shows same indoor and outdoor temperatures throughout the entire day. This suggests that all design changes necessarily don't have to be applied simultaneously, and that one or more can be reduced or entirely left out, still managing with the entire temperature reduction.

When it comes to the distribution chart Figure 50 Approximate distribution of the reduction of indoor temperature, contributed by individual design changes – New reference design (16x5m).below of the new reference design with the shape of an elongated rectangle, the probability of high accuracy is much lower for several reasons. Firstly, the only simulated design change on this reference design is orientation regarding sun, wind and a compromise between sun and wind. No other simulations have been conducted on this building shape. Therefore, the results from the simulations on the original reference design have been used, with slight modifications to adjust for the new building shape. Secondly, the building shape is the one of an elongated rectangle. Thirdly, the window area varies between the long and short facades. This increases the amount of dependency that the individual design changes have on each other. To account for this, the effect of the extended roof overhangs/eaves, white surface colours and window shading louvers have been reduced by a third. The distribution chart below is hence very approximate but can nonetheless be used as an indication on how building shapes of elongated rectangles are influenced by combining climatic design changes.

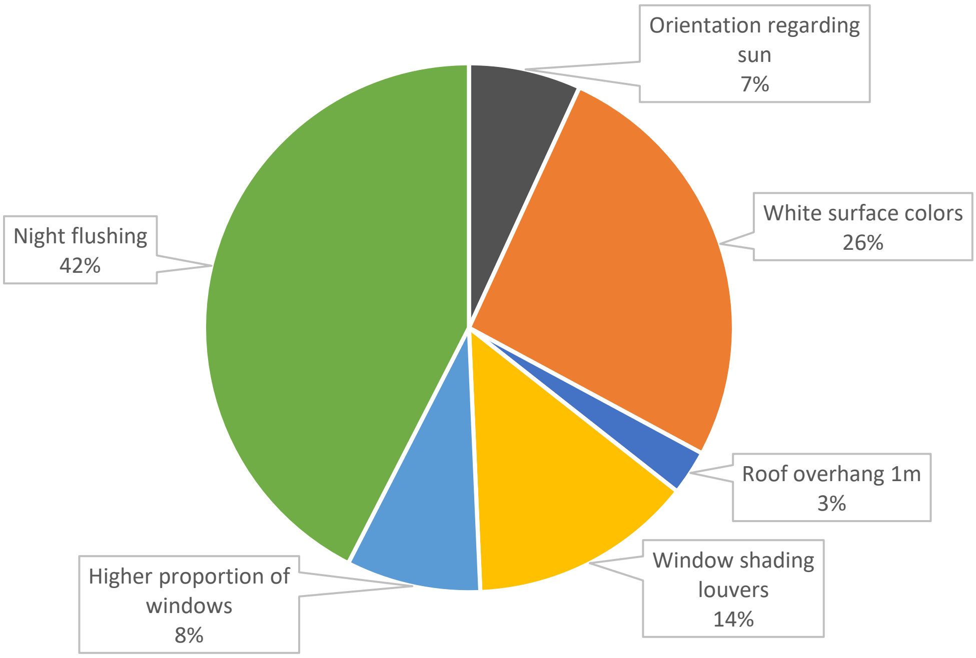


Figure 50 Approximate distribution of the reduction of indoor temperature, contributed by individual design changes – New reference design (16x5m).

Common conclusions are that orientation of the building regarding the sun only, has limited effect on the indoor temperature, even for buildings with the shape of elongated rectangles. Increased window shading, white surface colours and increased ventilation has the greatest effect on lowering the indoor temperature, especially if night flushing is utilized correctly.

6.4 Cost savings and energy assessment

The potential energy savings on implementing climatic design techniques are significant, up to 72%. The reduction is slightly higher on the concrete reference designs. Before the design changes were implemented, the soil-cement reference designs used less energy than its concrete counterparts, which is understandable since the soil-cement blocks have a higher thermal resistance. After the design changes were implemented though, they switched positions so that the concrete designs instead used less energy. The same phenomenon can be seen on both building shapes. The reason for this is most probably the differences in thermal mass between the wall blocks. Either way, the difference in energy usage between the two is minimal.

The actual cost savings on the A/C electricity bill are up to 68%, which on the original reference design corresponds to approximately 2-3 months of income in Tanzania per year. Or to put it in other words, a 20% raise in salary, which is significant.

The cost savings potential for using modern low-cost materials and to lower the ceiling height go up to a combined 43%, which also is significant. Of course, the 20% lower ceiling height contributes to a noticeable part of the cost savings. Lowering the ceilings however might not be a well-received advice for people in Tanzania as high ceilings may be considered as an important architectural aspect, signaling status and economic welfare. Moreover, ceiling-mounted fans are very common and extend to about 0.5 m below the ceiling, which could be used as an argument to keep the 3 m ceiling height.

6.5 General simulation discussions

It is clear that the solar radiation is contributing immensely to the increase of indoor temperature, and that it needs to be hindered from reaching the boundaries of the house to the greatest extent possible. Judging from the simulation results, it seems that the whole temperature increase can be prevented by using shading techniques and bright exterior surface colours only. Bright surface colours significantly reduce the absorbed radiation by the walls and roof, while window shading louvers take care of the radiation that would otherwise uninhibitedly enter the house through window openings. Increased ventilation doesn't seem to be needed to remove excess heat but is probably still desirable for the cooling effect it has on the body. If darker exterior surface colours are used, or if the window shading isn't as effective, increased ventilation may be necessary to remove excess heat from inside the building.

Other means of shading techniques exist. Growing a green cover is one that is suggested in the literature but is rarely seen in reality. A green cover over the entire building, encapsulating it and protecting it from radiation not only from the sun, but also from surrounding air, buildings and ground. A green cover could be an effective way to shade not only the windows, but walls and roof as well. Other benefits of a green cover include sound dampening, filtering of the air, another layer of wind and rain protection and more. Disadvantages may be obstruction of wind, lowering the effect of cross ventilation and attraction of insects. If A/C is used as the primary way of lowering the indoor temperature and if mosquito and insect nets are used as they should, a green cover could have a great additional effect on lowering the energy consumption and running cost. For a visualization of a green cover as a computer simulation model, see appendix.

7 Conclusions

The results from the field study confirm what is already known about the need and the importance of climatic building designs. The main is to provide buildings that fulfils the human requirements for adequate and affordable housing with comfortable living conditions that is energy efficient. The lack of proper architectural designs of buildings in warm and humid climates can be attributed to the fact that architecture and the building designs in developing countries follows international trends or the architectures of temperate countries without any climatic considerations. This has resulted where architectures in developing countries rely entirely on engineers to fix the indoor climates. This can be done, but at high annual costs for energy and maintenance. Generally, in developing countries buildings are set up rather quickly due to lack of proper assessment on building sites. This results in building with orientations that contradict the prevailing climatic conditions with regards to solar radiations and wind.

According to the simulations, buildings in warm and humid climates have the potentials of obtaining and meeting the human requirements for adequate indoor climate given the buildings are properly designed according to the prevailing climatic conditions. Previous studies have found that buildings in these climates rely heavily on mechanical ventilation to regulate the indoor temperatures. It is very common in residentials homes that average electricity used for HVAC systems can accounts for up to 60-70% of the total electricity where there is one air conditioning system for every room. The use of overall electricity required for the HVAC systems can be eliminated or significantly reduced by up to 70-80% if the buildings are properly designed and the climate conditions is met according to the simulations. There is no single design feature that provides optimal indoor climate, but a combination of two or more features is required in warm and humid climates in order to obtain comfortable thermal conditions. There some parameters that need to be compromised in cases where is these parameters maybe contradictory to one another such as solar radiation and wind directions. The result on this study confirms what previous studies on the subject have concluded on the extent of building designs in equatorial tropical climates.

There are extensive studies and literatures on the need for proper building designs in warm and humid climates available. But because of lack of proper building regulations in terms of both design and energy requirements, combined with lack of resources contributes to high cost of housing with poor design features which requires the need for mechanical ventilations systems to regulate the indoor climate. Buildings in urban areas in developing countries have high walls surrounding almost every residential building because of the need for security. However, this an inadvertently reduces the air flow around the building and the potential use of natural ventilations.

Results from this study validates the previous study done on the subject regarding climatic building designs but also provides additional information on the extent of passive performance in warm and humid climates, particularly in Dar es Salaam, Tanzania.

7.1 Recommendations

7.1.1 Technical design aspects

Comprehensive climates assessment of the site locations must be established before setting up any buildings types as previously studies have concluded. The foundation of buildings must properly be designed such way that the house is well placed and have proper draining systems. The surface water has to be drained away from the house and stagnant water should be avoided.

The use of roof gutters and V-sloped ground gutters for water draining has proven successful and should be used as illustrated in figure below. Generally, the ground around the house should slope away at a gradient of at least 1:10 and if possible, the house should be located at the high point of the site. The base of the house should be at least 300 mm high above the ground to minimize splashing on the walls and make it easier to protect from the walls and the floor from raising during the rainy seasons.

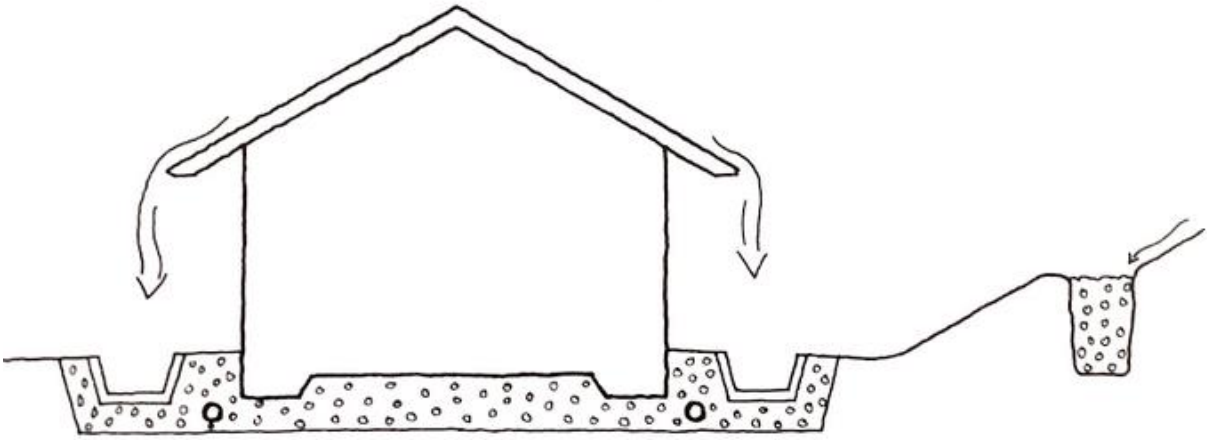


Figure 51 Drainage for surface and roof water (Adamson, Aberg 1993)

7.1.2 Sun and wind orientation

Regarding orientation of the building, optimal orientation regarding the sun does have substantial impact on the lowering of the indoor temperature. Therefore, design and room layout should be considered to facilitate cross ventilation. The optimal orientation regarding wind seems to be when the preferred wall is slightly tilted to the wind direction. The preferred wall should be the one enabling effective cross-ventilation. Local wind patterns should be carefully examined at the actual site where the house is built, and the orientation chosen accordingly.

7.1.3 Constructions and materials

Construction materials in warm and humid climates should be as light as possible with minimal heat storage capacity and time lag. Such materials should be permeable to air but provide protection from the precipitations. Thermal insulation has shown to be ineffective and should be avoided except on surfaces exposed to direct solar radiation, or if A/C is used extensively. The outer surfaces of walls should be made of bright colours to enable high reflectivity and emissivity for keeping the indoor temperature and inner surface temperature low. If possible, roof overhang should be extended to 1 m to provides shade for walls.

7.1.4 Shading devices and façade colours

Bright colours (preferably white) should be used for as many external surfaces as possible as it has enormous impact on the indoor temperature and the A/C energy use and running cost. Extended roof overhangs have limited effect on the indoor temperature. A compromise for lowering construction and material cost could be to only extend eaves on the east and west facing facades. Window shading devices should be used as it has considerable impact on the indoor temperature and the A/C energy use and running cost. Louvers covering the whole window area while allowing air to ventilate through is advantageous as much of the radiation is diffuse, originating from all possible angles.

7.1.5 Increased ventilation

If and when A/C is not used or needed, as high ventilation as possible should be desired as it effectively keeps the indoor and outdoor temperature the same. This can be achieved by having higher proportion of windows, provided they are open to allow for the air to flow through. Night flushing is shown to have especially good effect if utilized correctly but is probably not needed if the other design recommendations are applied. Moreover, night flushing (or excessive ventilation by other means) should not be utilized if/when A/C is used.

7.2 For further research

7.2.1 Orientation

We recognize that there are many factors that influence what orientation is the optimal one regarding sun and wind in warm and humid climates. The ratio between wall area/air volume, number of stories, building shape, room layout, ventilation openings, topography and local wind patterns are just some of the things that may heavily influence the way a building should be oriented to achieve not only lower indoor temperatures, but optimal indoor human comfort. The scope of this thesis is only covering the very basics about orientating buildings with regard to sun and wind. Further research is needed in this area.

7.2.2 Roof colour

The simulations on exterior surface colours in this report doesn’t show the extent of importance that the roof colour has on the indoor temperature. It is known that humans are sensitive to high ceiling temperatures, i.e. the perceived temperature is easily influenced by the temperature of horizontal surfaces above our heads. More research need to be done on the effect that roof colours have on the indoor and ceiling surface temperatures.

7.2.3 Window shading techniques

The simulations conducted on equipping windows with wooden shading louvers is optimal as it blocks indirect, reflected radiation in addition to direct solar radiation. Diffuse radiation as apparent in humid climates, suggests that shading devices covering the whole window area are used. However, more research need to be done on other window shading techniques to see if there is any noticeable change in indoor temperature. If not, other types of window shading devices may be desirable for the inlet of daylight.

7.2.4 Construction materials

The simulations looked at only two construction materials for the walls, both with relatively high thermal masses. More research need to be done on the potential benefits of having walls constructed with low-density materials, which is advised in most of the literature.

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9 Appendix

Figure 52 Mikocheni house.

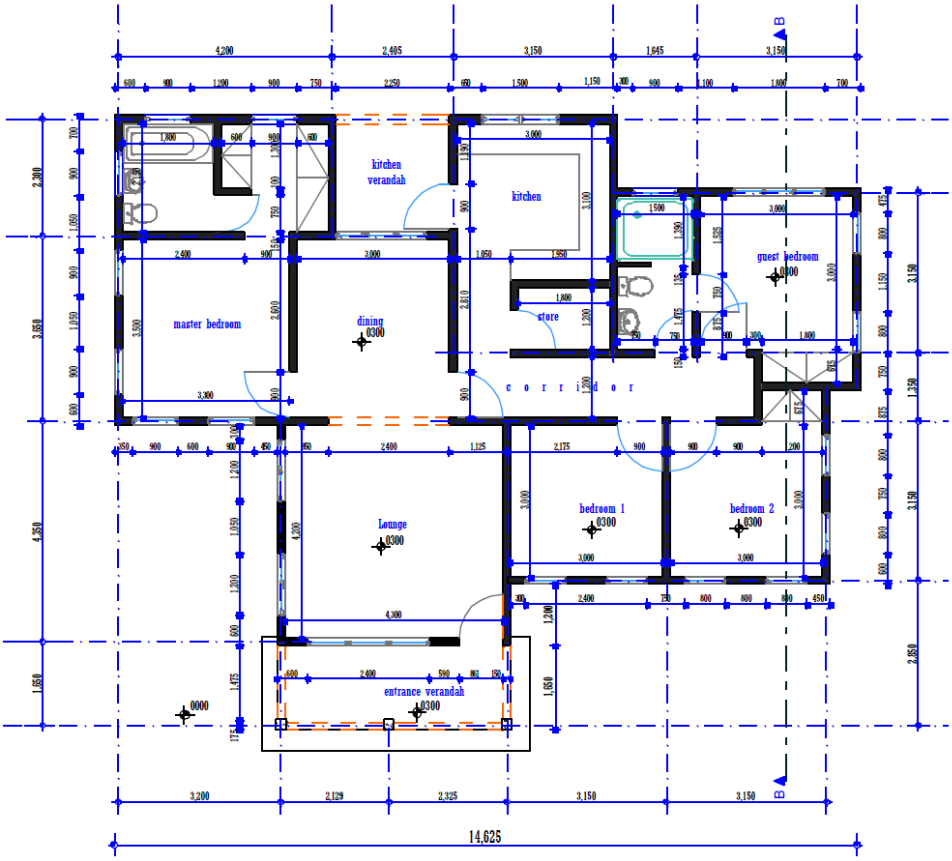

Figure 53 Floor plan and room layout Mikocheni house.

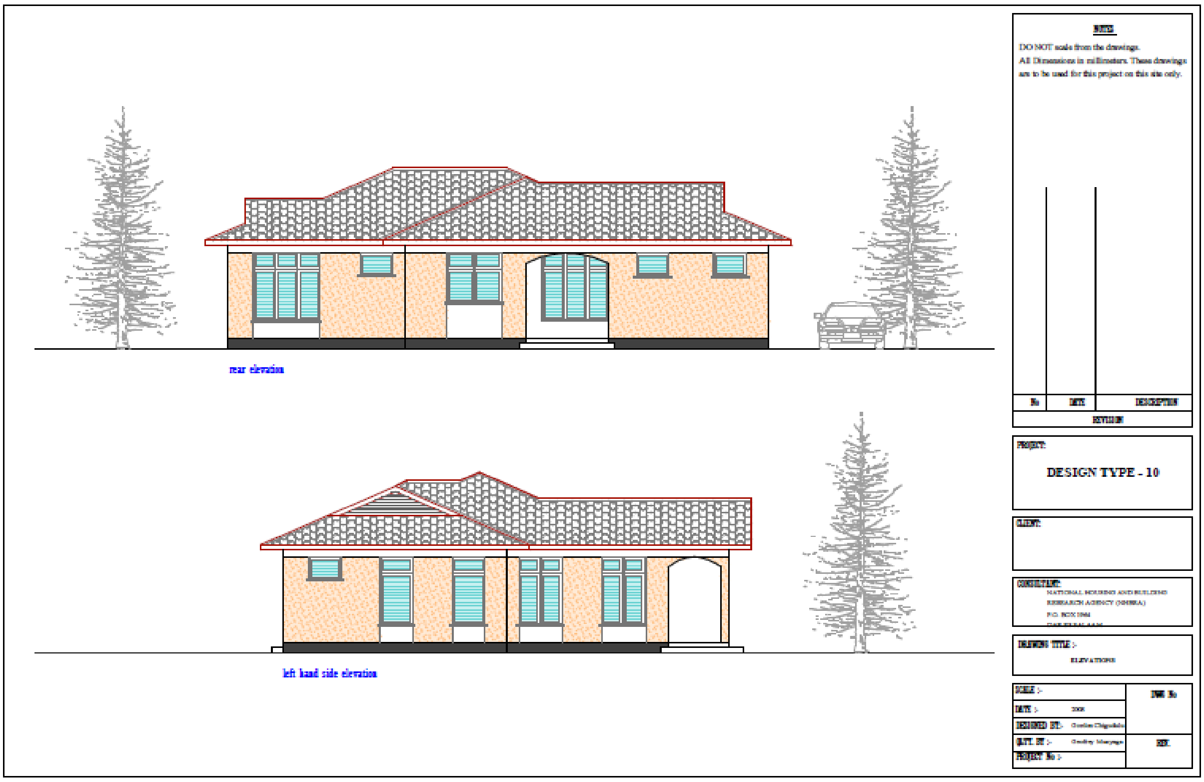

Figure 54 Elevation views, rear and left side Mikocheni house.

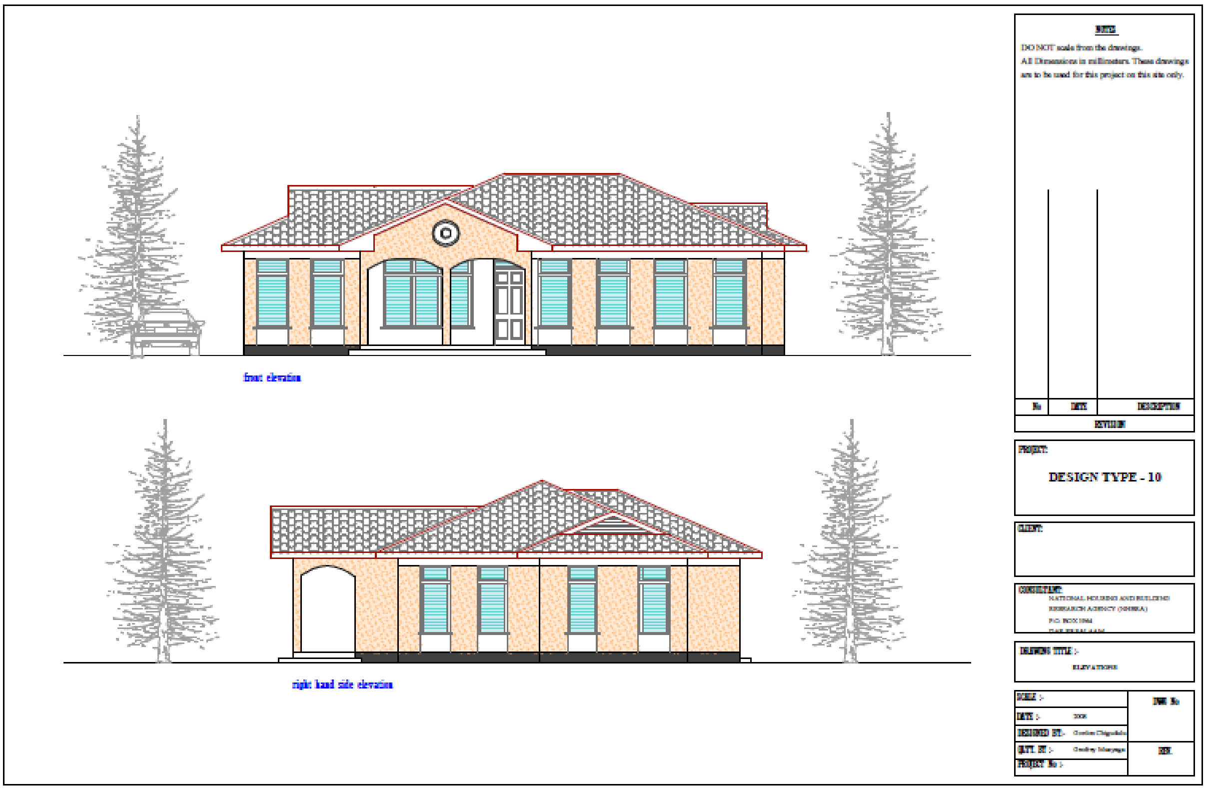

Figure 55 Elevation views, front and right side Mikocheni house.

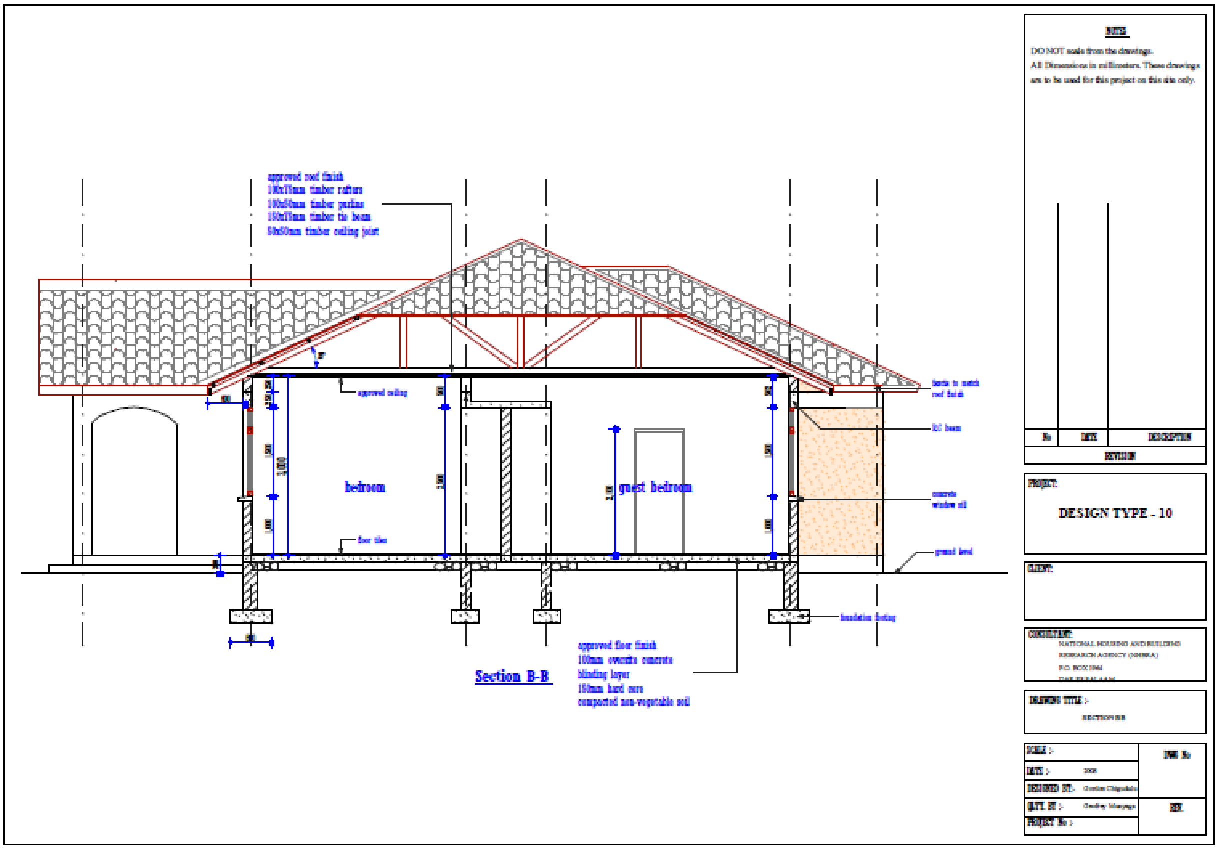

Figure 56 Cross section, view from right side Mikocheni house.

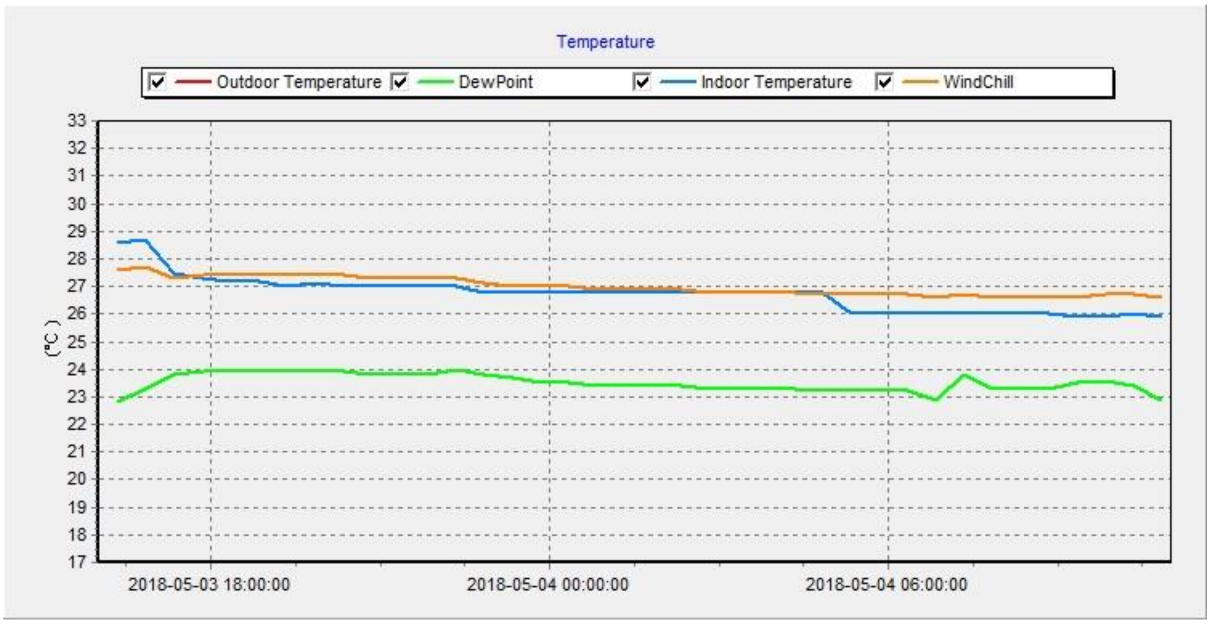

Figure 57 Temperatures measurements taken inside the building Mikocheni house.

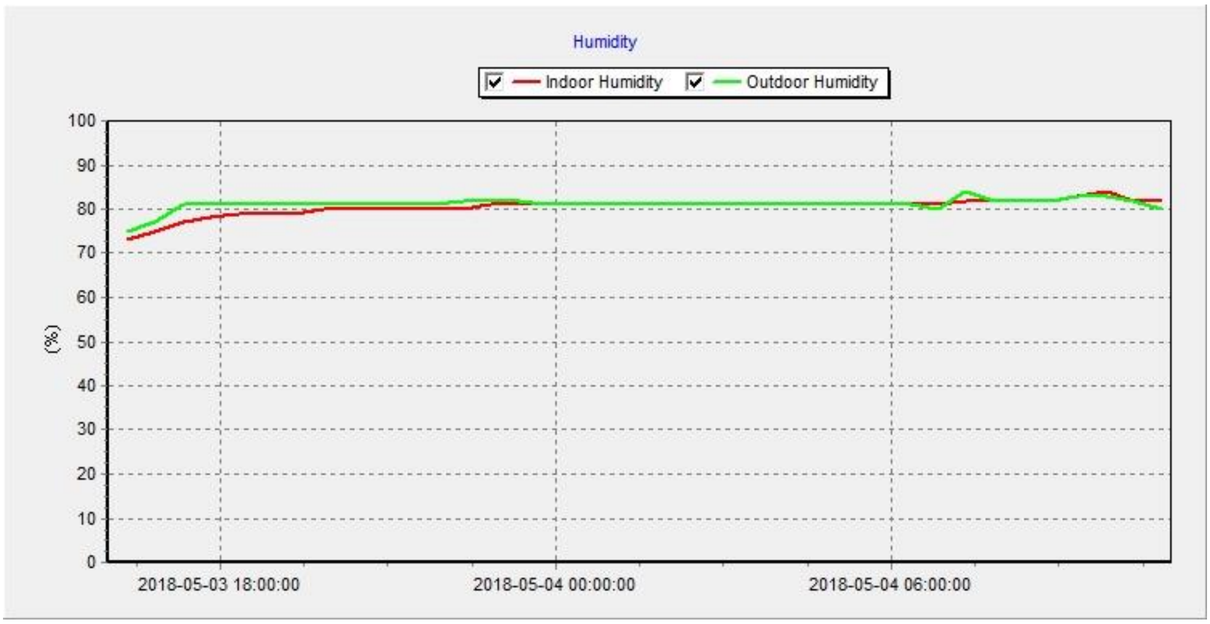

Figure 58 Humidity measurements taken inside the building Mikocheni house

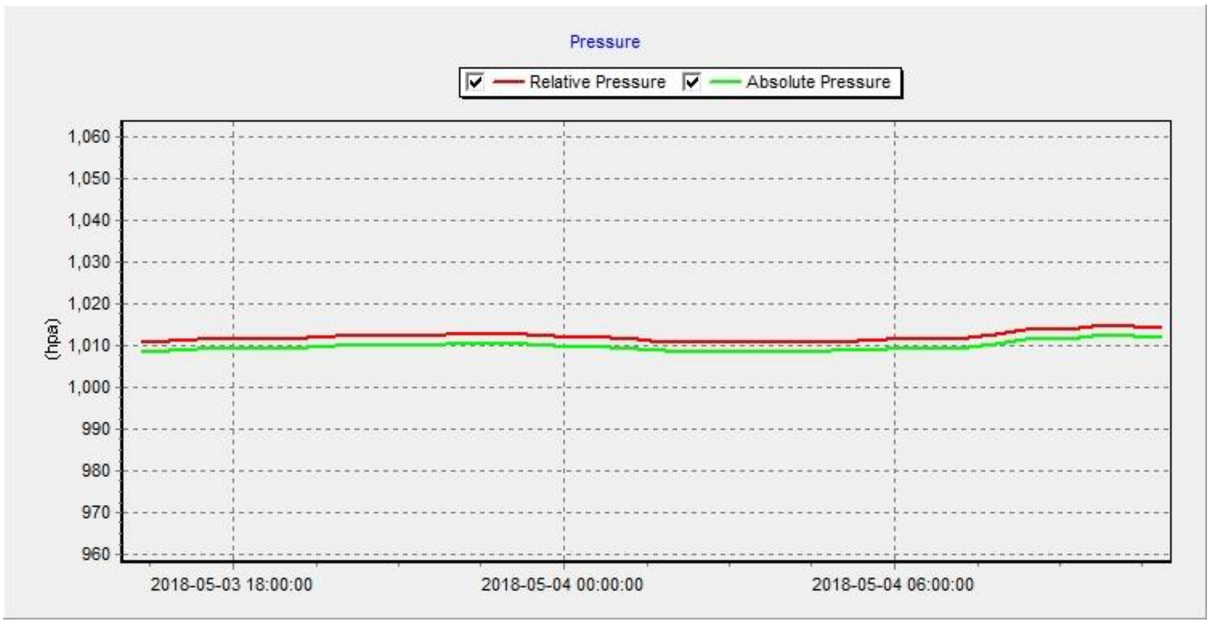

Figure 59 Pressure taken inside the building Mikocheni house

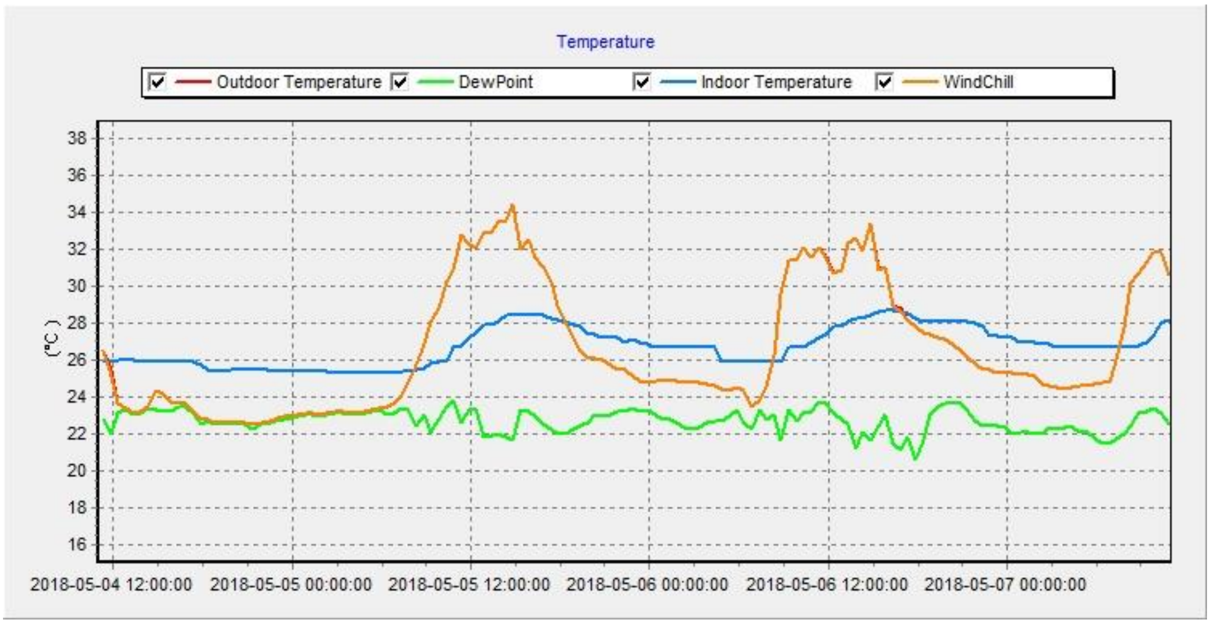

Figure 60 Temperature taken outside the building Mikocheni house

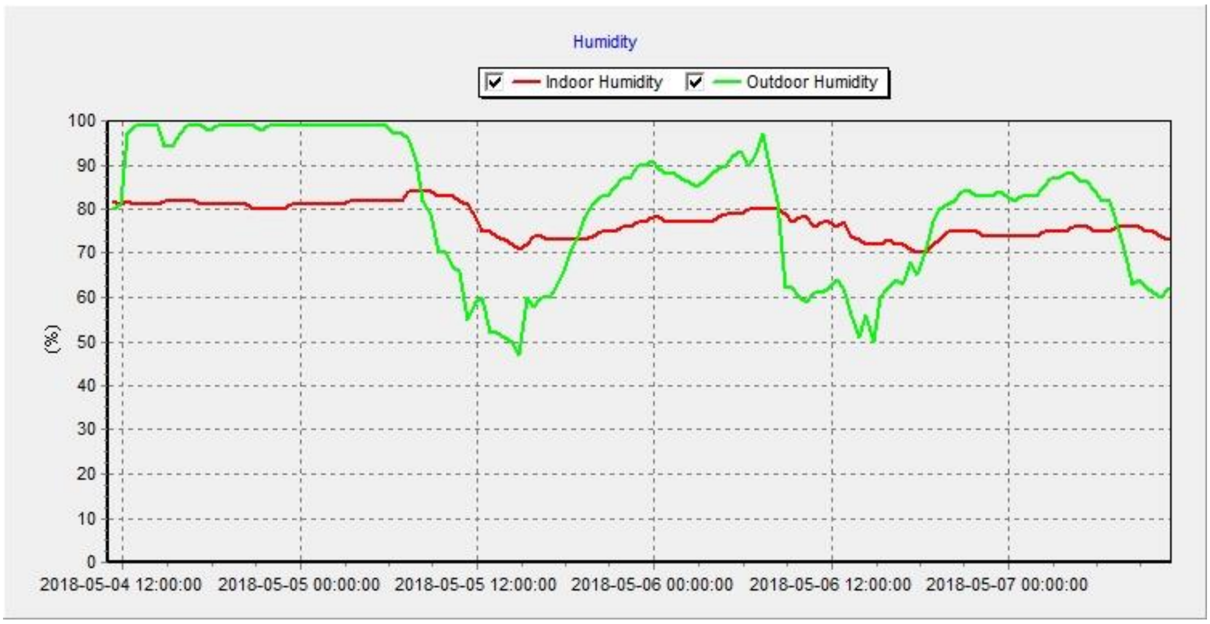

Figure 61 Humidity taken outside the building Mikocheni house

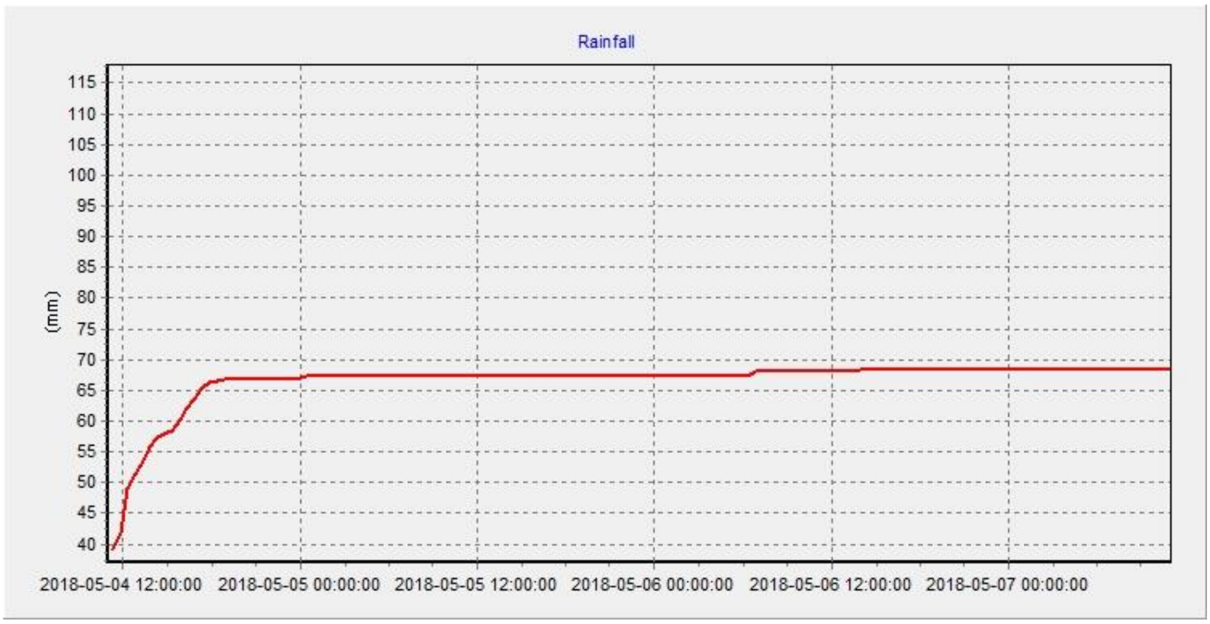

Figure 62 rainfall measured outside the building because measurements were carried during the rainy season

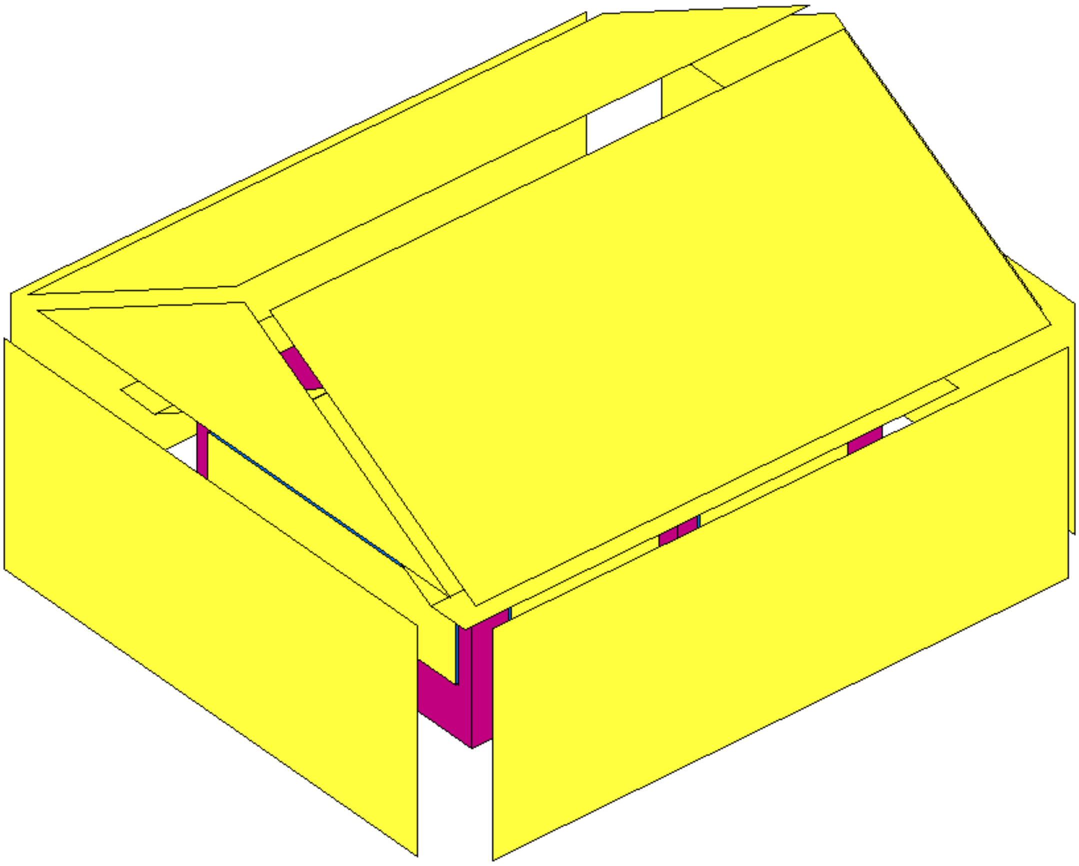

Figure 63 Simulation model visualization, green cover.