University of Cambridge

Department of Engineering

Part IIB Research Project

Transition in Housing Design in Rural Tanzania's Temperate Tropical Regions: An Analysis of Thermal Comfort Performance and Possible Design Improvements

by

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in Group D, 2014/2015

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work

Signed: . . . .

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Technical Abstract

Climatic conditions are severe in upland regions of rural Tanzania with large daily oscillations in air temperature reaching maximum values of 36°C and minimum values of 14°C in a typical year. High levels of solar radiation exacerbate the problem and make overheating in homes a serious problem which can affect the health and wellbeing of people living in these regions. With 71% of Tanzanians living in rural areas and 28% of this population living below the national poverty line, the problem of having adequate shelter from these conditions is a serious one which affects many people. For this reason, the project focuses on thermal comfort in low-income housing design in these temperate tropical regions with a view to contributing to a discussion on how passive building design can provide thermal comfort for these environmental conditions.

Low-income housing design for rural Tanzania has started to change over the last decade. Traditional materials of mud and poles walls, thatched roofing and earth floors from which these houses have been constructed are rapidly being replaced by modern building materials, namely baked bricks, corrugated iron and cement floors. Additionally, there has been a slight increase in the prevalence of concrete houses with iron roofs, which is expected to increase further in the future. For the purpose of this project, this transition has been described by reference to three styles of houses which will be known as: the traditional house, transition house and future house. This project challenges the assumption that modern building materials are 'better' by evaluating the performance of three houses at providing thermal comfort for their inhabitants in this climate.

Weather data and knowledge of building physics theory were used to predict critical areas of house design that would govern performance in providing thermal comfort. The performance of the three houses across a study year was then simulated using IES computer software and compared against five criteria chosen to assess thermal

comfort. This was then investigated in greater detail by looking at the behaviour of the houses over shorter time frames. Detailed analysis of specific areas of the building envelope and rooms was used in conjunction with building physics theory to explain the results and identify the critical areas of design that govern thermal comfort performance for the specific context of this project.

The analysis found that the traditional house overheated significantly less often than the other two houses and demonstrated smaller diurnal indoor temperature swings. This was found to be because of the better insulation properties of the thatched roof and larger thermal mass of its mud walls. . The corrugated iron roofs were found to be particularly poor for performance with roof conduction gains reaching peak values of 2kW in each room, compared with just 0.1kW for the thatched roof. Analysis of the walls showed that the mud walls were much better at heat storage as they absorbed heat during the hottest periods of the day and re-emitted it during the night-time. This results in the traditional house also experiencing uncomfortably low temperatures the least, but with the downside that on hot evenings it will be warmer than the other two houses. On detailed analysis of ventilation gains, it was found that the ‘transition’ and ‘future’ houses outperformed the traditional house with constant heat rejection throughout the day and night. The traditional house’s lower standard of workmanship gives it a more open structure which resulted in high daytime ventilation gains and night-time heat rejection. The analysis also highlighted the need for specific design for rooms as critical areas for thermal comfort differed depending on their position within the house and their internal gains.

The study showed that the traditional design provides greater thermal comfort, but more importantly it describes how, with the use of modern building materials, thermal mass, roof insulation and ventilation can be designed to improve performance and the health and welfare of inhabitants.

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1 Introduction

1.1 ELITH Project

This project is part of the Energy and Low Income Tropical Housing (ELITH) project, a research collaboration which partners the University of Cambridge and the University of Warwick with two East African institutions (the Uganda Martyrs University and the National Housing and Building Research Agency) and two East Asian universities.[1] It sits within ELITH as part of a discussion on tropical vernacular architecture in Tanzania and how good building design can improve thermal comfort in a low-income context.

1.2 Motivation

The aim of this project is to understand how building design affects thermal comfort in impoverished rural areas which are subjected to a severe climate. The focus country for the project is Tanzania, where in 2012 71% of Tanzanians lived in rural areas. This is equivalent to just under 31 million people living in 6 million homes.[2] As a high proportion of these homes are situated in regions with a temperate tropical climate (see Section 1.3) this project only considers the specific case of rural temperate tropical regions in Tanzania. Furthermore, 28% of the rural population is also currently living below the national poverty line,[3] supporting the decision to only consider low-income cases. Thus, this project aims to be applicable to a large number of homes within Tanzania, and also to other low-income regions with similar temperate tropical climates.

Thermal comfort has been identified as being particularly critical in these regions as air temperatures can exceed 35°C. This, combined with heat gains from high levels of solar radiation, can result in excessively high indoor temperatures that seriously affect the quality of life of inhabitants. High temperatures have been shown to cause heat stroke, confusion, heat exhaustion and heat syncope, among other conditions. Effects of thermal discomfort also include low sleep quality, confusion, behavioural disorders and exacerbation of health problems in susceptible groups (young children and the elderly).[4] Thermal discomfort can also be caused by the large daily temperature swings and colder nights found in these regions. Given the limited resources of low-income inhabitants, intelligent use of passive building design is a important way to provide thermal comfort.

Tanzanian housing has started to transition away from more traditional designs, in particular with the use of modern building materials. This project challenges the assumption that the transition is beneficial for occupants, which is largely assumed to be the case.[5] The decision to move away from vernacular design is often a result of factors which are not related to environmental concerns, including social aspirations, security, durability and aesthetics. However, as environmental conditions in these regions are harsh and the protection of shelter essential, they must be addressed by house design. Given that vernacular design evolves over time to adapt to local environmental conditions, it is likely to incorporate design aspects which provide thermal comfort for inhabitants. It is therefore important to assess the performance of new designs against traditional house design to ensure that the transition in house design is well informed and takes into consideration its effects on thermal comfort and health. This analysis is also a useful tool for the identification of critical areas for good thermal comfort performance and suggestions of how this can be improved.

1.3 Tropical Climate

The term ‘tropical climate’ encompasses a range of different climates that are found within the tropics. However, not all parts of the tropics exhibit a climate which is commonly described as ‘tropical’. The Köppen-Geiger climate classification system splits tropical climate into three subtypes: Tropical rainforest climate (Af), Tropical monsoon climate (Am) and Tropical wet and dry/savannah climate (Aw).[6] As can be seen in the Köppen-Geiger climate map below, Tanzania’s land mass sits predominantly in the third category, a tropical wet and dry/savannah climate.

However, not all of Tanzania is classified as being tropical, with the large plateau in the centre of the country containing dry (arid and semiarid) climates denoted BWh and BSh on the map.[7]

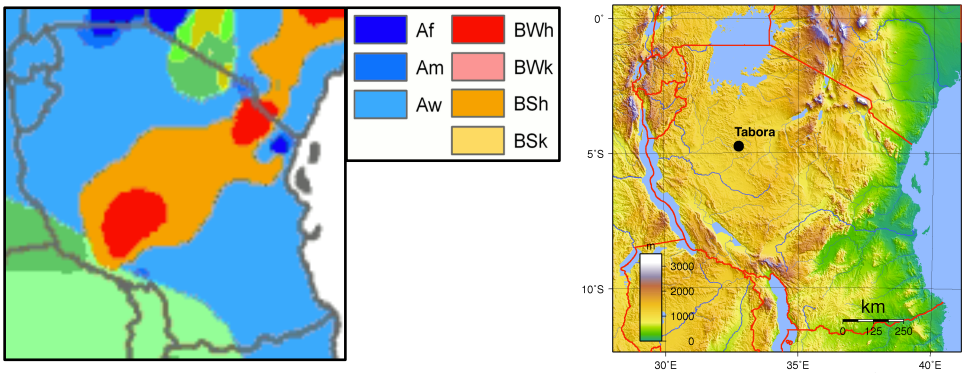


Figure 1.1 Maps of climatic zones and topography of Tanzania[7,8]

The large variation in topography across Tanzania results in different climates within the Tropical climate zone, with a hot and humid coastal region (including Zanzibar) and more temperate climate upland.[9] This study will only consider the case for tropical upland regions which have an altitude range of 800m-1200m above sea level (see Figure 1.1), excluding the low-altitude coastal region and the dry central plateau.

1.4 Objectives of Project

The main objectives of this project are to:

- Investigate housing design in rural Tanzania, gather background information on the situation and identify three houses which best describe the transition in designs used.
- Assess the environmental conditions found in temperate tropical Tanzania and their implications for low-income housing design.
- Analyse and compare the performance of each house type in these conditions with regards to thermal comfort.
- Identify critical areas of design which can improve thermal comfort.

2 Methodology

Data for this project was collected in a literature review as well as from site visits and surveys by a colleague. It was used to define the technical aspects of housing design in temperate tropical rural Tanzania which included house layouts, material properties and building openings. A review of the region's climate and relevant building physics theory was undertaken. Simulations conducted in IES were then used to compare the thermal comfort performance of three house designs and identify reasons for the differences.

3 Preliminary Work

The preliminary work for this project was a critical stage to provide the necessary information to define the problem and accurately analyse it. It largely consisted of collecting relevant information on the region and its housing. This included specific information on climate, house designs and occupancy behaviour in the chosen region of rural Tanzania, as well as more contextual information which gave a greater understanding of the overall situation. Information came from a literature review and internet searches, as well as a visit to three locations in rural Tanzania by a colleague. The analysis tools used for the project were also assessed during this stage.

3.1 Region Weather

Tabora (marked in Figure 1.1) was chosen to be the region of focus for this project due to the availability of weather data and the fact that its climate, altitude and location make it representative of the temperature tropical upland climate which this project intends to study. The weather data chosen for this region is given in hourly form with radiation data taken from the years 1991-2010 and temperature data from 2000-2009 to give a historically averaged weather set or Typical Meteorological Year (TMY). The source for this data is Meteonorm, a widely used tool which provides the user with a large range of weather parameters including (but not limited to) dry-bulb temperature, solar radiation, cloud cover, relative humidity and wind velocity. Meteonorm has a total of 14 weather stations in Tanzania, one of which is in Tabora.[10] From this point onwards, only this data set will be used for discussion of the climate and modelling.

3.1.1 Air Temperature

Figure 3.1 shows the variation in air temperature (dry-bulb) across the year in Tabora. The region experiences a typical temperate tropical climate, with a hotter season from September to May (average 25°C) and a cooler, drier season from June until August (average 22.5°C). It can be seen that the cooler season only has a marginally lower average temperature in comparison with the hotter season.

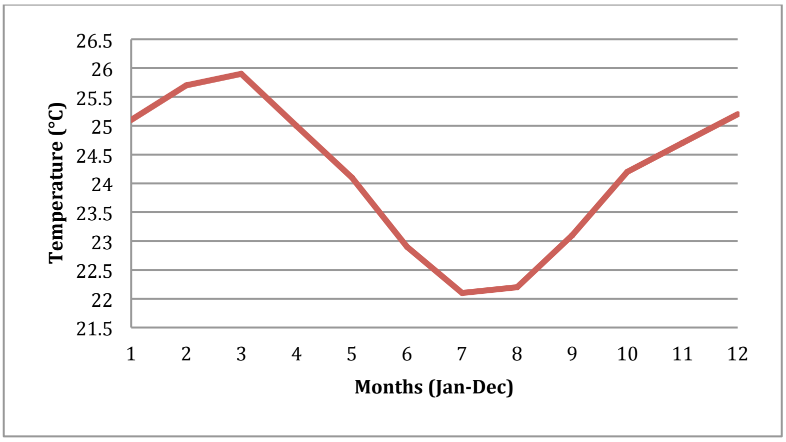
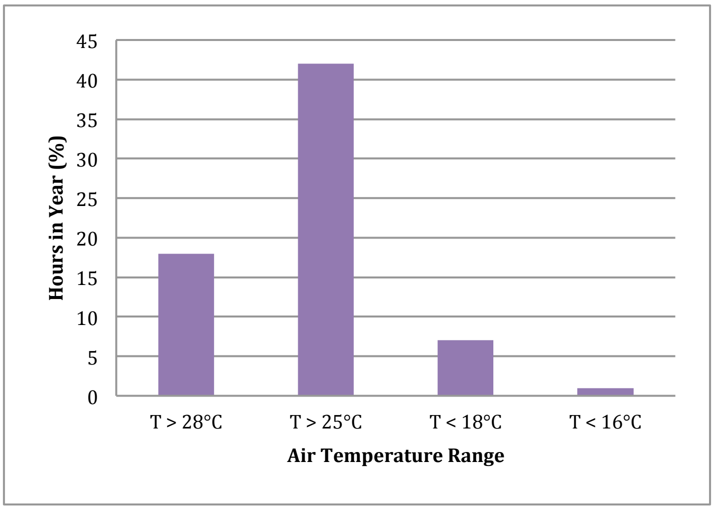


Figure 3.1 Average monthly air temperature in Tabora for study year

By grouping the outdoor dry-bulb temperature into 'hot' and 'cold' ranges inGraph 3.1, we can see the percentage of total hours in a year that sit within these ranges. As UK criteria for overheating is usually based on the percentage of hours spent above 25°C and 28°C[4], shows that overheating will be a critical area for achieving thermal comfort in the study region as such a large proportion of time is spent in excess of these temperatures. It can also be seen that there is a significant proportion of time (6.6%) spent below 18°C which will also make consideration of thermal comfort at lower ambient temperatures important. Temperatures below 20°C and 15°C are generally described as being slightly uncomfortable and uncomfortable in conventional comfort charts, making night-time temperatures an area which does need to be addressed.[11] However, given the high proportion of overheating hours, preventing overheating will be the main priority.

Although housing design must cater for the relatively minor seasonal changes, the key factor for housing design will be ensuring acceptable thermal comfort at both high daytime temperatures (with intense radiation) and cooler night time temperatures which can fall below comfort levels. Daily temperature swings of 4-18°C were observed in every 24 hour period throughout the year.



Graph 3.1 Distribution of hours in year with ambient temperatures in hot and cold ranges

3.1.2 Relative Humidity

Relative humidity does not change with the seasons and has an average of 65-70% throughout the year. However, it varies significantly each day with high humidity in the early mornings (usually in the range 80-100%) and low humidity in the afternoons (in the range 30-60%). Although the humidity is high in the mornings this is the coolest part of the day, when temperatures are usually less than 21°C. This will affect thermal comfort less as humans are affected by humidity when sweat is unable to evaporate. According to CIBSE A, a relative humidity of 40-60% is the acceptable level for moderate thermal conditions, with inhabitants unlikely to notice its effect on warmth, although this may change as temperatures increase above 28°C.[4] Consequently, when temperature levels are high, relative humidity will be at the lower end of the acceptable range or slightly drier and therefore it will not significantly exacerbate the effects of higher temperatures.

3.1.3 Solar Radiation

Global radiation across the year is relatively constant, although it increases very slightly in the dry season from June to September when cloud cover is marginally lower and radiation is more direct. Due to its position close to the equator this region experiences high solar radiation for 12 hour days throughout the year. This makes solar gain a key area for house design considerations. As can be seen in **Error! Reference source not found.**, there is a slight variation in the sun's path during the year, although this is relatively small. Furthermore, an even amount of time is spent north and south of the 90°-270° path, which will balance solar radiation on north and south facing walls across the year.

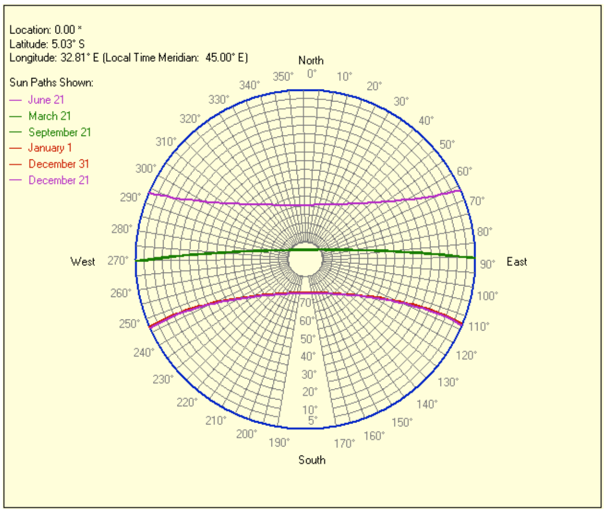


Figure 3.2 Sun path diagram for Tabora

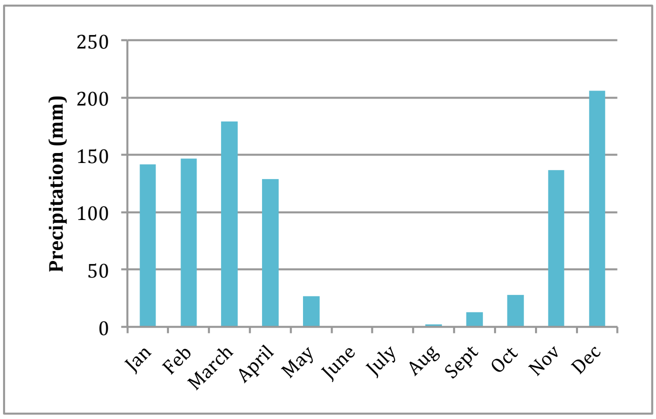


Figure 3.3 Average monthly precipitation in Tabora[1]

3.1.4 Precipitation

There are high levels of rainfall in the rainy season from November to April and a dry season from May to October. A typical year can be seen in Figure 3 . The intense periods of rain make roofing material and quality of construction important in house design.

3.1.5 Wind

Average monthly wind speed is relatively high (3-4m/s) and constant throughout the year, while the prevailing wind direction predominantly comes from an eastern or southern direction depending on the season.

3.2 Housing in Rural Tanzania

Although the weather data used for this study is specific to Tabora, this report aims to provide a discussion on low-income housing design for all rural regions of Tanzania with a temperature tropical upland climate. Literature about low-income housing design in these areas of Tanzania (or in similar climate bands in East Africa) is relatively scarce but there are a number of papers which discuss architecture and the modernisation of the typical house.[5,12] This transition towards a more 'modern' house is an interesting one, with a transition from traditional huts towards the 'Swahili' house (the characteristics of which can be seen in all three houses chosen for this study) having taken place over the last century.[12,13,15] This study concentrates on the more recent development of housing design, which has been largely focussed on different building materials used in construction.

In this project 'house design' is defined as containing all aspects of the house, including the size, shape and position of every part of the house, the building materials used and the partitioning of each thermal zone. Housing designs chosen for analysis in this project are based on the houses described in relevant literature and are supported by the 2002 and 2012 Tanzanian Government Housing and Population Censuses[2,14], as well as the site visit to Tanzania undertaken by a team member. A particularly useful source has been "Traditional and contemporary building styles used in Tanzania and to develop models for current needs" by A. Mwakyusa[15], which has an extremely comprehensive set of information on housing design across

Tanzania. This source and other literature have been used to guide and support the choice of house designs to be studied.

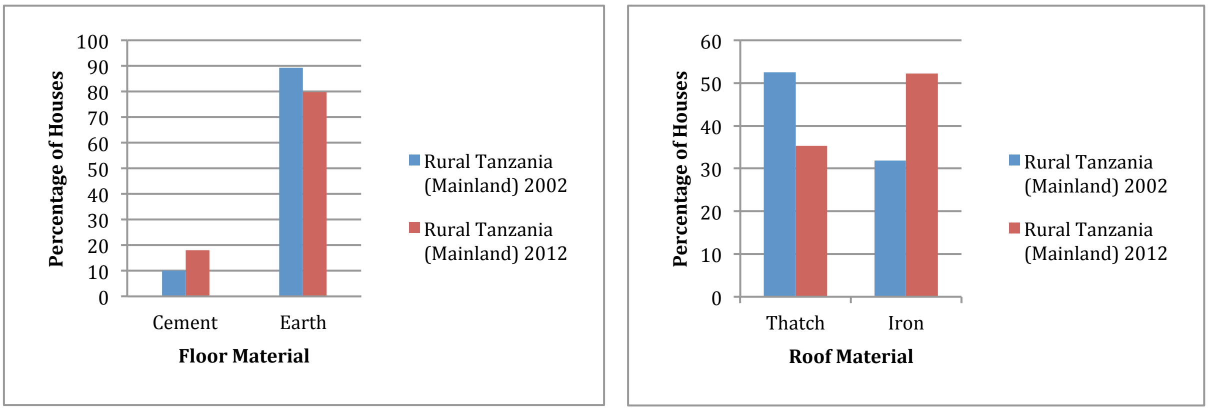


Figure 3.3 Construction materials used in rural Tanzanian housing for floor (a) and roofing (b) by proportion of houses[2,14]

The change in the main materials used for floor and roof house construction in mainland rural Tanzania between 2002 and 2012 can be seen in Figure 3.3. It shows that there has been a significant increase in the use of cement as a floor material, although earth is still widely used (80% in 2012 compared with 89% in 2002). Roofing material has seen the most dramatic change, with thatch use falling by 17% and corrugated iron use increasing by 21%. In 2012 corrugated iron was used by 52% of houses covered in the census, while thatch roofing was used in 35% of houses.

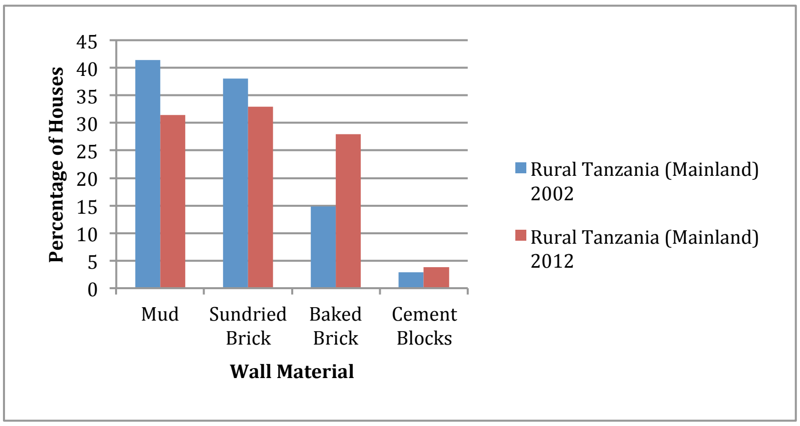


Figure 3.4 Construction materials used in rural Tanzanian housing for walls by proportion of houses[2,14]

Figure 3.4 shows the proportion of use of materials used for walls in 2002 and 2012. It can be seen that mud and pole was the most commonly used wall material in 2002 but its use has fallen from 41% to 31% of houses. Baked brick use has grown considerably (an increase from 15% to 28%) and there has also been a small increase in cement block use (3% to 4% of houses).

Exactly the same trends can be seen in Tabora, with Figure 3.5 also highlighting the transition away from earth floors, mud and pole walls and thatch roofs.

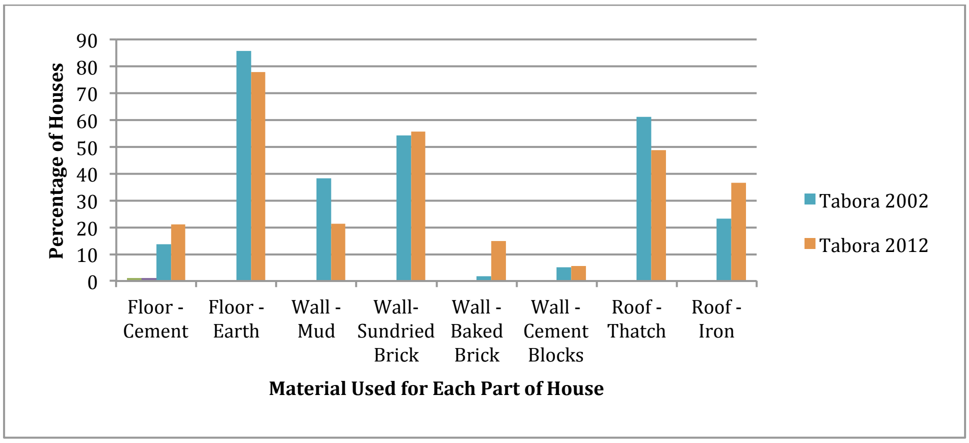


Figure 3.5 Proportion of houses with each construction material for floor, wall and roof in rural houses in Tabora in 2002 and 2012[2,14]

This census data and other literature on housing design has led to the selection of three houses for further discussion and thermal performance analysis. Together they illustrate the change in house design in rural Tanzania, starting many decades ago and finishing with the most desirable ‘future’ house that is likely to become more common in rural areas when a sufficient level of economic development is achieved. All three houses follow the basic Swahili house design which, as discussed earlier, has become the dominant design across the country.

3.2.1 House 1

The first house in this timeline of development is the ‘current house’, which is made from the most commonly used construction materials in 2002, which are still widely in use today. The walls are mud and pole (made from mud stuck onto a wooden pole structure) with both the wood and mud collected for free from the local area. House 1 is the only house with different indoor and outdoor wall thicknesses (120mm and 200mm respectively). The naturally compressed sand and earth on the site before the house construction forms the floor and the roof is made of thatched leaves.

The house is rectangular and contains two bedrooms, one hallway (which also acts as a bedroom/living space) and a kitchen. The kitchen is located inside the house as this was found to be a common arrangement in Tanzanian housing.[5] The size and number of rooms were chosen to represent a typical house with average household size and number of sleeping rooms in rural Tanzania found to be 5 and 2.5 respectively.[2] There is one door and two small windows (measuring 0.4m by 0.4m) placed on the longer sides of the house. The windows are holes in the wall as glass is prohibitively expensive.

The roof has a hipped shaped because this was the most common roof design. It overhangs the walls by 25cm on all sides, except for the extra shading provided on half of the front side of the house. The overlap area is completely open to air movement inside. There is no inner ceiling and there are internal mud and pole walls between each room that stop at a height of 2.4m. This means that there are no partitions between the rooms and the roof zone above this height.

A picture of this type of house and its floor plan can be seen in Figure 3.6 below.

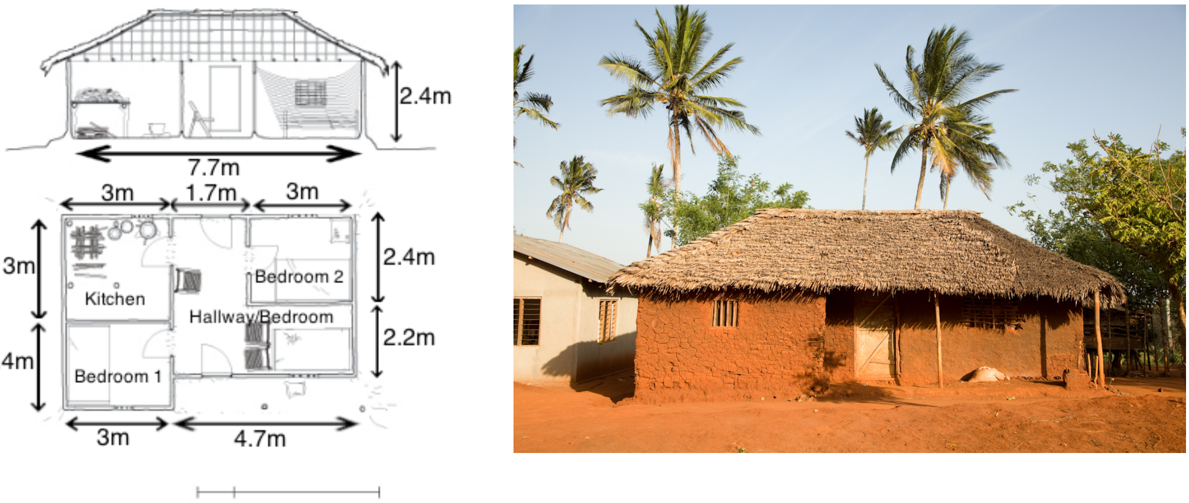


Figure 3.6 Floor plan and photograph of House 1 design[16]

The choice of this design as the ‘current house’ is supported by a literature review of low-income house designs in Tanzania[12,13,15,17] and by the site visit which found that a large number of houses were of this design (with some variation in size and layout).

3.2.2 House 2

The second house is the ‘transition house’ (shown in Figure 3.9) which describes the main changes in rural low-income housing design over the last decade. The design is the same has House 1, apart from changes in construction materials, window sizes and roof overhang openings.

The construction materials used in the house are those that the census data has shown to have increased in use significantly over the last ten years (see Figure 3.3 and Figure 3.4). The exterior and interior walls of the house are made from baked bricks (also known as burnt bricks) which are formed from locally sourced clay and sand. The roof is made from corrugated iron and the floor is a layer of cement.

The windows are larger (measuring 1m by 0.8m) and have a wooden louvre to give some occupant control over ventilation. The gap between the roof overhangs and the interior of the house is much smaller than in House 1, giving further control over air inflow.

Figure 3.7 Photo of House 2 design[18]

Figure 3.8 Photo of House 3 design[13]

3.2.3 House 3

The third house is the ‘future house’ (shown in Figure 3.10) which is identical to House 2, except for the use of concrete blocks for all of its walls. Figure 3.4 shows that it is currently very uncommon in rural areas due to its associated high material costs. This type of house is common in urban regions, particularly in Dar es Salaam where earnings are higher.[15] Low-income houses have similar dimensions to houses 1 and 2, because the overall size is limited by its material costs. This choice was supported by the information collected during trip to Tanzania and the literature.[13]

3.2.4 Comparison Table

The layout of all three houses can be seen in Figure 3.6 and the key design features can be compared in Table 3.1 below.

House Number	**1**	**2**	**3**
Wall Material	Mud & pole	Baked bricks	Concrete Blocks
Roof Material	Thatch	Corrugated Iron	Corrugated Iron
Floor Material	Earth	Cement	Cement
Windows	Open (0.4m by 0.4m)	Louvre (1m by 0.8m)	Louvre (1m by 0.8m)
Internal Walls	Mud & pole (up to 2.4m)	Baked bricks (up to 2.4m)	Concrete blocks (up to 2.4m)
Inner Ceiling	None	None	None
Roof Shape	Hipped	Hipped	Hipped

Table 3.1 Comparison of key design features of Houses 1-3

3.2.5 Material Properties

The properties of the materials used in construction for Houses 1-3 can be seen in Table 3.2. The extensive supply of photos from the visit were extremely useful for checking the dimensions and colour (relevant for the solar absorptivity and emissivity terms) of all of the materials considered in this study against the literature. Use of CIBSE A and the available literature on construction in Tanzania gave these properties which were chosen to be the most representative for the low-income context given the limited information available.

Materials	Thickness (mm)	Density (kg/m3)	Thermal Conductivity (W/mK)	U Value (W/m^{2}K)	Spec. Heat Capacity (kJ/kgK)	Absorptivity	Emissivity
Walls							
Mud & Pole	200/120	1700	0.83	2.43/2.47	1	0.65	0.9
Baked Brick	100	1700	1	3.70/2.78	0.84	0.69	0.9
Concrete Block	100	1700	0.77	3.33/2.57	0.84	0.63	0.94
Roofing							
Thatch	120	240	0.07	0.54	0.18	0.5	0.9
Corrugated Iron	0.7	7900	72	7.14	0.53	0.9	0.89
Floor							
Earth	-	1460	1.28	2.25	0.88	0.6	0.9
Cement	300	1860	0.72	1.60	0.84	0.73	0.93

Table 3.2 Construction material properties (wall U values are external wall/internal)[4,15,19,20,21,22,23,24]

The choice of properties for the wall materials was the most difficult as those for mud and baked bricks depend on both the proportion of clay and sand used and the properties of the local soil used. In the case of the baked bricks it was found that although the relatively poor dimensional accuracy of the bricks results in significant use of mortar, the properties of the mortar used are almost identical to the bricks. As a result the walls will be modelled as just bricks. There is a large range of different types of concrete blocks that could be used in Tanzania, but from the photos of rural concrete houses from the trip it could be seen that solid blocks (with no air gaps) were most common. Therefore a similar density to that of known blocks used in Uganda was chosen.[23] It should be noted that there are different U values for internal and external walls because the resistances of both the internal and external surfaces have been taken into consideration in addition to the material resistance.

Colour of the materials is a determining factor for solar absorptivity and emissivity. Although some houses do have outer plastering of a lighter colour than the construction materials, this is relatively uncommon and all analysis will be based on the assumption that any plastering is of the same colour as the material below.

3.3 Thermal Comfort Performance of Current Housing

The environmental conditions discussed in Section 3.1 make the task of providing adequate thermal comfort difficult in this low-income context. It is clear that the house designs must significantly moderate indoor temperatures in order to provide sufficient thermal comfort.

A 1985 report on rural Tanzanian housing concluded that "rural houses fail to satisfy biophysical and psychosocial needs of the rural inhabitants" and describes the failure of houses in protecting inhabitants from excessive heat and cold.[12] This was supported by a survey of 19 mud-pole houses from the visit to a region outside Dar es Salaam. This region is closer to the capital with concrete housing found to be more common here than in rural areas. It also has a more coastal tropical climate without the temperature drops associated with the upland regions. However, average temperatures in the region are comparable to the study area, allowing data collected from the visit to be used to provide background information on the thermal performance of current housing. It was found that 32% of the homeowners interviewed described excessive internal temperatures as the biggest problem with their house (more than this proportion mentioned it as a problem, rather than the main problem). Six of these houses had iron roofing, all of which complained about overheating. Homeowners with thatched roofing mentioned that this was also a problem for them, but that their houses were cooler than concrete houses with iron roofs.

4 Building Physics

Before using the computer software, building physics theory was used to predict critical areas for the house design and to help guide the analysis and check that sensible results were obtained. A brief overview of these areas is given in this section.

Due to the large variation in daily temperature and high solar radiation experienced in the region, house design which is adapted for this climate is not straightforward and requires a balanced approach to satisfying its conflicting needs at different times. The key aim is to provide a relatively constant internal temperature which is inside the comfort range for the occupants, regardless of the temperature changes and radiation outside. Given the low-income constraint on design, strategies used to achieve this use passive cooling techniques to both prevent and modulate heat gains, and natural cooling to remove excess heat from the interior spaces.[25]

Daytime temperatures are high across the whole year, making prevention of overheating the main priority during sunlight hours. As a result solar gain is not required to warm the house at any point in the year and the high solar radiation in the region cannot be directly used to improve thermal comfort at any point. Insulation will be required to reduce heat transmission into the house during the daytime and minimise heat losses out of the house at night. Heat storage is important for absorbing daytime heat (from solar radiation and air temperature) and balancing cooler night-time conditions.

4.1 Solar Gain

Solar gain can affect the heating of the house in two ways. These are the external gains through the building materials and internal gains from radiation heating internal surfaces through openings. Both of these cases must be addressed to reduce gains.

As the sun's path in this region is a direct route from east to west (Figure 3.2), there will be minimum solar gain on north and south facing walls and high solar gain will occur on east and west facing walls. Solar heat gain on the west side of the house will be particularly problematic for overheating as it coincide with the hottest part of the day. As a result, orientation of the buildings to minimise the surface area of the house on east and west sides, placement of windows on the north and south sides (or use of smaller windows) and use of shading will be important in limiting the heat gain from the region's intense solar radiation. In all three house designs the windows are placed on the two longer sides which is a good design for minimising heat gain if it is orientated as previously discussed. If the house is not oriented in this way the internal and external solar gain will not be at a minimum. House 1's windows are smaller than in Houses 2 & 3, despite all three houses having the same amount of shading from the roof overhang. As a result it is expected that House 1 will receive a lower amount of internal solar gain.

The degree to which solar heat energy is transmitted through the building envelope depends on the absorptivity of the outer surface (the fraction of the incident radiation energy that is absorbed by a surface), the insulation of the envelope and the thermal mass of the envelope. Insulation and thermal mass will be discussed in the following sections. Absorptivity and emissivity of the house surfaces are important factors for solar gain as a high absorptivity will result in high radiation absorption and therefore higher solar heat gain, while emissivity will dictate the level of radiation emitted by the surface. The thatched roofing has a significantly lower absorptivity than corrugated iron (0.5 compared to 0.9) and will absorb less solar radiation and House 1 will experience lower solar gain through the roof. The absorptivity of the wall surfaces are very similar (0.63-0.69) and therefore there will be little difference in the solar gain in the walls for the houses. The values of emissivity for both roof materials and all the wall materials are about 0.9 indicating a relatively high level of radiation emission from all of the surfaces. This is important for night-time emission of heat.

4.2 Thermal Insulation

The aim of thermal insulation is to reduce heat transmittance through the building envelope. As materials are used in homogenous form in the houses studied, the insulation can simply be measured by their calculated U-values (a measure of heat loss). From a comparison of these U-values (Table 3.2) we can see that all three of the wall materials will exhibit similar heat transfer, although the thick mud walls do have a lower value and therefore insulate the house more. Thatch roof provides a high level of insulation with a U-value of 0.54W/m^{2}K whereas then iron roof will allow heat to be conducted easily due to its high U-value of 7.14W/m^{2}K. This is expected to contribute to the heat gains in Houses 2 and 3 significantly.

Use of thermal insulation in wall or roof materials is important for reducing the transmission of heat from solar gain and external ambient temperature into the house during the daytime. It will also reduce heat loss during cooler nights. Conversely, during hot periods the insulation will restrict heat loss from the interior space, making the evenings uncomfortably hot. For this reason a moderate amount of insulation is optimal and ventilation will be important for accelerating heat loss during these periods (this will be discussed later).

4.3 Heat Storage

The use of thermal mass is important because it regulates the size of indoor temperature swings relative to the region's large outdoor temperature swings. Peak indoor temperatures can be reduced by thermal mass because it allows heat from high daytime air temperatures and solar radiation to be stored, rather than entering the house and causing overheating. This stored heat is then radiated and conducted from the building envelope back to the external environment and into the interior space later in the day when ambient temperatures are lower.[26]

There is a time lag between the time at which heat energy is absorbed and emitted, which is dependent on the amount of thermal mass used. As a result, for the climate in this study a moderate amount of thermal storage should be used to give a diurnal time lag, allowing the heat stored during the day to be emitted in the night-time when temperatures drop below a comfortable level. The time at which temperatures drop below this level tends to be after 12am, requiring a relatively large time lag.

However, as throughout much of the year the night-time air temperature does not fall below 15°C the amount of heat to be emitted during the night should not be too high or it will result in overheating during the night. Clearly it is important to strike a balance between using high thermal mass to keep the internal space cooler during the day and lower thermal mass to ensure that at night-time the space is not heated too much. This is particularly important given that the occupants sleep inside the house at night-time.

When designing the thermal mass it is also important to consider the time lag required for different parts of the house as the western wall will receive a large amount of radiation during the afternoon, whereas the eastern wall will have done so in the morning. Houses 1-3 use a single material with a constant thickness for all exterior walls and are therefore not designed to accommodate for this.

In the three house designs considered only the wall materials are used for heat storage. Their performance is dictated by thickness and thermophysical properties, the latter of which is given by the term $\rho C \lambda$ where ρ is density, C is the thermal capacity and λ is conductivity. A low value of this term indicates that the material has a low heat storage capacity.[25] We can see that in the case of this study (where a single homogenous material is used for wall materials), there will need to be a trade off between having a higher conductivity to increase thermal storage capacity while trying to limit heat conduction from the external to internal surfaces. The values for this term can be seen in Table 4.1 for each of the wall materials. The lower value for concrete indicates that, unlike mud-pole and baked bricks, House 3's concrete walls have low thermal storage capacity and will be poor at thermal mass regulation of internal temperatures during the daytime and night time by energy absorption. The thickness of the walls affects the amount of energy which can be stored, with the thick mud and pole walls (200mm) giving House 1 a significantly larger thermal mass, time lag and therefore improved temperature regulation.

Mud and Pole	Baked Bricks	Concrete Blocks
1411	1428	1100

Table 4.1 Values for wall material thermal storage capacity term ρCλ for Houses 1-3

4.4 Ventilation

As the night-time temperatures do not fall so low as to require a large amount of heating the amount of re-emitted stored heat should be relatively low. As a result night-time ventilation is important for the removal of heat emitted by the thermal storage material. This will regulate the indoor temperature at night and help to reset the material's heat storage capability for the next day. Control over the ventilation will allow the occupants to control the amount that night-time heat storage emission heats the inside of the house.

Airflow into the house is driven by pressure differences due to the stack effect and wind. It will occur as 'natural ventilation' i.e. through openings and windows, as well as infiltration through cracks and unintentional openings. Stack effect will be less significant for these house designs due to their limited height and the fact that the temperature inside the house will generally be cooler than outside. However, at night there will be some inflow of cooler air from outside. Section 3.1.4 showed that wind speed is high enough to be a driving force throughout the year (as long as the house is orientated accordingly) and therefore wind will contribute to the ventilation of the house more than stack effect. In reality local geography will affect the wind patterns, but for this study the wind direction and speed in the weather data will be taken as being the conditions affecting the houses which are modelled. Although the houses are unlikely to be oriented for the prevailing wind (and cannot be for the whole year as it changes significantly between the two seasons), the house design does give significant scope for wind ventilation, with windows and doors all positioned on two parallel sides and all rooms opening into a single zone above a height of 2m. If these sides are placed on the windward and leeward side, cross-ventilation will occur with the majority of the airflow moving through the hallway. If the door on the leeward side is left closed, it is expected that more ventilation will reach the kitchen and two bedrooms as more airflow will be forced to move sideways and leave through the windows in these rooms.[25] Ventilation of the kitchen will be particularly important to remove the high internal gains and health-damaging air pollutants.

The key difference between House 1 and Houses 2 & 3 is that House 1 is more poorly constructed and has a higher level of infiltration and large gaps between the walls and the roof. Although House 1 has smaller windows than Houses 2 & 3, they are louvre windows and will restrict airflow. As was discussed in Section 4.3, night-time ventilation will be important for removing stored heat on warmer nights to prevent thermal mass from causing discomfort.

5 IES Analysis: House Comparison

5.1 IES Model Details

For accurate simulations IES models require a large amount of inputs to be defined. These will be covered in this section to define the details of the model and explain the choices and assumptions made.

In this study four of IES's computation 'modules' were used to create a model which could simulate the interaction between the three selected houses and their environmental conditions to an appropriate level of accuracy. These modules are

- ModelIT which was used to 'build' the house designs in IES and define the thermal zones.
- SunCast which was used to calculate the incidence of solar radiation on the house.
- MacroFlo which was used to model the effect of airflow into (and out of) the house. It also models air movement between different thermal zones in the

house, although this is calculated by computing each zone as a node in its centre which has the zone's average conditions. Greater precision is available through the CFD analysis of the MicroFlo module, but this was deemed unnecessary given that IES is to be used for a general comparison and proof of principles rather than exact results.

- ApacheSim which was used to compute the behaviour of the houses when subjected to the year of weather data. It uses the assigned construction materials and outputs from the other three modules to provide a large range of output data which can be used to analyse performance in many areas.

5.1.1 House Position & Materials

The model can be seen in Figure 5.1, with the three houses located in the middle of the 'village' which is used to simulate the effects of adjacent buildings. The spacing of the houses is 10m from wall to wall, which was estimated from the photographs of the three villages visited by a team member. The houses are identical in shape and dimensions to the house design shown in Figure 3.6. The construction materials assigned to each house are as detailed in Table 3.1 and Table 3.2 with the same thickness for interior and exterior walls in Houses 2 & 3 but different thicknesses in House 1.

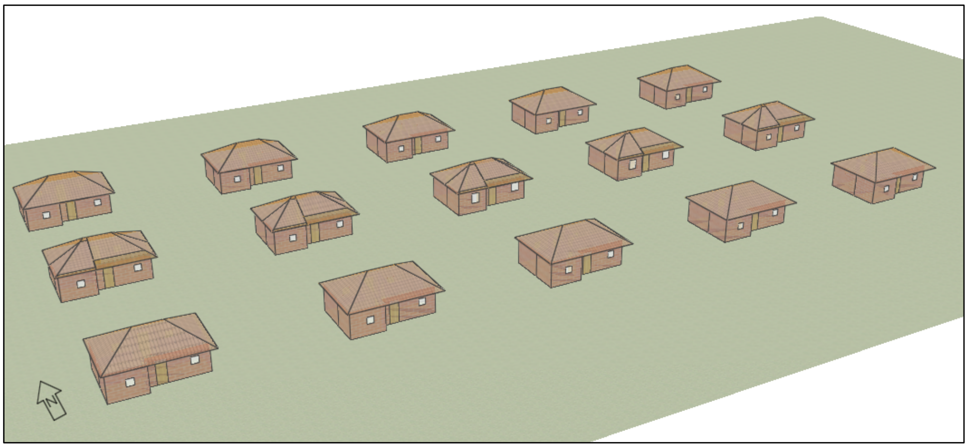
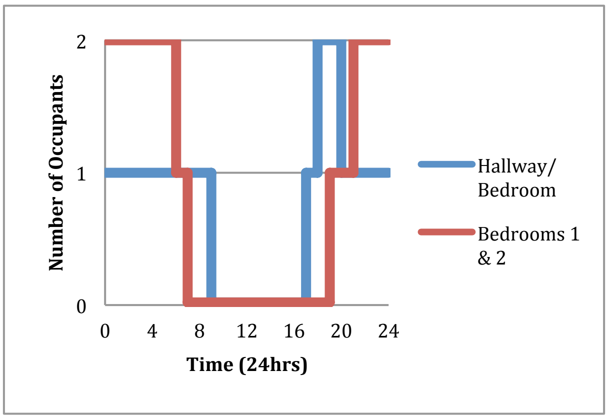


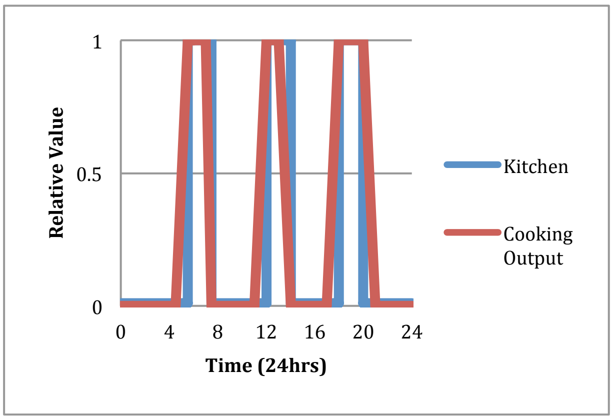
Figure 5.1 'Village' arrangement of houses in IES simulation

5.1.2 Heat Gains & Occupancy

IES calculates the external gains using the weather file and assigned materials values but the internal gains depend on the occupant behaviour. There is an internal gain of 90W/person associated with the heat output of a relatively stationary human body (a standard IES value which is consistent with CIBSE A values). It is therefore important to define when each room is occupied throughout a typical day and by how many members of the 5-person household. The occupancy patterns seen in Graphs 5.2 and 5.3 were then assigned to each room using the times for sunrise, sunset and periods of high external temperature as well as three sources[27,28,29] which detail the daily routine of households in rural Tanzania. As the kitchen is positioned inside the house, internal heat gains from the cooking source are also included in the model with cooking times derived from the same sources. Firewood is used for cooking fuel by 90.2% of households in rural Tanzania[2] and a rough calculation gave its peak heat output to be 1.275kW (using the quantity of wood used, its calorific content and burning efficiency[30]). The amount of heat given out by the fire is not constant, as the stove will take a while to heat up initially and cool down after use.



Graph 5.1 Daily occupancy patterns for hallway/bedroom and bedrooms 1 & 2



Graph 5.3 Daily occupancy pattern for kitchen (maximum of 1 person) and relative cooking output (proportion of 1.275kW)

5.1.3 Openings

The doors are left open during the day and shut at night (because of security concerns). The windows are left open at all times with House 1's windows fully open and House 2 and 3's louvre windows restricting openable are to 64.5%. This decision was made from looking at the photographs from the site visit and from details of a conversation with inhabitants during the visit, which both suggested that openings were left open during the day in many houses. Given that high solar gains are likely through openings this does not seem to be the optimal configuration, but it may be due to the need to remove smoke from cooking. The openings into the roof overhang are 60% open in House 1, compared to 10% in Houses 2 and 3. This is because the site photos showed that the connection between mud walls and thatch roofing is much more poorly constructed than that of baked bricks/concrete and iron roofing, leading to larger gaps for airflow. As was mentioned in the house descriptions, there is no partitioning of rooms above 2.4m and there is no inner ceiling, allowing air to flow freely into and out of the common roof area.

House 1 is leaky with a high infiltration of 10ac/h (air changes per hour) as cracks and gaps are common in mud and pole walls (this was seen in photographs from the site visit). The better construction quality of Houses 2 & 3, and the stronger and more durable materials used (baked bricks/concrete walls and iron roofing) give these houses a lower infiltration of 5ac/h. This is still high by UK house levels (0.65ach/h[31]) because the houses considered in this study are from a low-income context that has a comparably worse construction process and lower expectations for quality (confirmed by the gaps seen in walls and around windows in the photos of houses from the visit).

5.2 IES Model Limitations

At least six months of data for indoor and outdoor thermal conditions in a house in the region would be required to have accurate data with which the simulation's results could be compared (advice from Max Fordham Engineering Consultancy). As this was unfeasible only a small sample of data was collected during the visit by a team member. This cannot be used to validate the accuracy of the model but it does give some indication of the conditions in both mud and concrete houses across a day. Reassuringly, during the same month of the year the simulation predicted similar results and differences between the two houses. Nonetheless, the IES model will be used to demonstrate trends and the effect of various aspects building design on thermal performance rather than giving exact results.

5.3 Performance Criteria

The choice of criteria for measuring house performance is a key part of the study as it is effectively a statement of the definition of thermal comfort used. The chosen criteria are:

- Criterion 1: Percentage of hours above 33°C
- Criterion 2: Percentage of hours above 35°C
- Criterion 3: Percentage of hours below 18°C
- Criterion 4: TM52 Adaptive Thermal Comfort
- Criterion 5: Percentage of hours where internal dry resultant temperature > external temperature (and peak difference)

Criteria 1-3 and 5 all use indoor dry resultant temperature as it is weighted average of air temperature and mean radiant temperature, therefore accounting for the effect of surface radiation. All percentages of hours are taken as the percentage of hours out of the total hours in a year rather than just for occupied hours. This decision was made because exact information on occupancy patterns was difficult to find and non-working family members may be more likely to spend the afternoon inside. The assessment of all hours is therefore based on the perspective that a house should provide thermal comfort for all times of day.

5.3.1 Criteria 1 & 2: Overheating

Criteria 1 and 2 assess the overheating of each house in terms of the proportion of hours across the study year which are spent with indoor dry resultant temperatures above 33°C and 35°C. These temperatures were derived from the CIBSE A criteria for overheating in the UK which gives maximum values of 5% and 1% for temperatures of 25°C and 28°C respectively.[4] These temperatures are clearly unsuitable for Tanzania's hot climate and the low-income context of this study. A simple comparison of the percentage of hours exceeding these temperatures in London was used to select two equivalent temperatures (in terms of percentage of hours exceeded in a year), which are 33°C and 35°C in Tabora.

5.3.2 Criterion 3: Thermal Discomfort from Low Temperatures

Criterion 3 assesses the ability of each house to prevent indoor temperatures from falling below comfortable values, by comparing the percentage of hours across the study year spent below 18°C. The choice of a temperature of 18°C was based on a WHO paper[32] which gives a basic range for comfort of 18-24°C. Despite the simplicity of this range, it is acceptable, as the criterion will only be used for a comparison of the houses, rather than an exact judgement on their suitability for inhabitants.

5.3.3 Criterion 4: TM52 Adaptive Thermal Comfort

The sensation of temperature and its effect on health are dependent on the acclimatisation of a person to their environment. For this reason an adaptive thermal comfort model was selected because it allows this to be taken into consideration (in contrast to PMV thermal comfort methods). The model is based on three key ideas: firstly, people become accustomed to their thermal environment and adapt to it, with more recent thermal experience being more important (hence it uses an exponentially weighted running mean of the daily mean outdoor air temperature). Secondly, people notice gradual changes less than sudden changes and thirdly, the acceptable indoor temperature is related to the outdoor temperature, as people will find moving indoors a relief if it is hotter outside regardless of how high the temperature actually is.[4] Additionally, the adaptive model has been shown to be the most accurate way to model how people adapt to their thermal environment in naturally ventilated buildings.[33]

CIBSE TM52 assesses performance against three criteria, giving a classification of overheating if a room fails any two of the three criteria. A summary of the key details of the TM52 method will be given here but a more detailed explanation of the method can be found in IES's TM52 explanation[34]. The three criteria are:

I. Hours of exceedence: "The number of hours during which ΔT is greater than or equal to one degree (°K) shall not be more than 3% of occupied hours. ΔT is defined as operative temperature [dry resultant temperature] less the maximum acceptable temperature."

II. Maximum daily weighted overheating exceedence: Assesses the severity of overheating across a day in terms of both duration and magnitude of temperature (its units are degree hours). It is weighted to account for both of these terms, with a value greater than 6 resulting in failure in this criterion.

III. Upper limit on temperature: Sets an absolute maximum value for indoor operative temperature where the maximum ΔT is set to 4°C.

The maximum acceptable temperature is the upper limit of the thermal comfort threshold and is calculated from:

$$T_{max} = 0.33T_{rm} + 18.8 + suggested\ acceptable\ range$$

where T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature, and the suggested acceptable range is 4°C (the maximum range suggested by CIBSE as performance expectations are lower for the context of this study).

5.3.4 Criterion 5: Comparison of Indoor and Outdoor Temperatures

Criterion 5 is similar to Criterion 4 as it is also based on the logic that humans adapt to their climate. The relationship between indoor and outdoor temperature is important for thermal comfort. If the indoor temperature exceeds the outdoor temperature during a hot period this would suggest poor performance in providing thermal comfort. Consequently, this criteria will assess the percentage of hours for which indoor temperature exceeds outdoor temperature, and the peak difference.

5.3.5 Perceived Temperature

The five criteria chosen all use dry resultant temperature and do not take relative humidity into consideration. This is common for thermal comfort measurements but, given that relative humidity does affect how the ambient temperature feels to a person, future studies would benefit from using a ‘perceived temperature’ criteria which takes this into account. There is no IES plug-in to calculate perceived temperature and it is complicated to calculate across the thermal zones of a house, as wind speed must also be taken into consideration. An estimation of the effect of relative humidity can be seen in Figure 5.2. It shows that for the low wind speeds expected inside the study houses (in this case 1m/s), relative humidity in the range 40-60% causes a small deviation (±2°C) in perceived temperature relative to dry-bulb temperature. This shows that the omission of relative humidity from the criteria is acceptable as relative humidity (described in Section 3.1.2) usually sits within this range during the hottest part of each day (when the criteria are most likely to be exceeded).

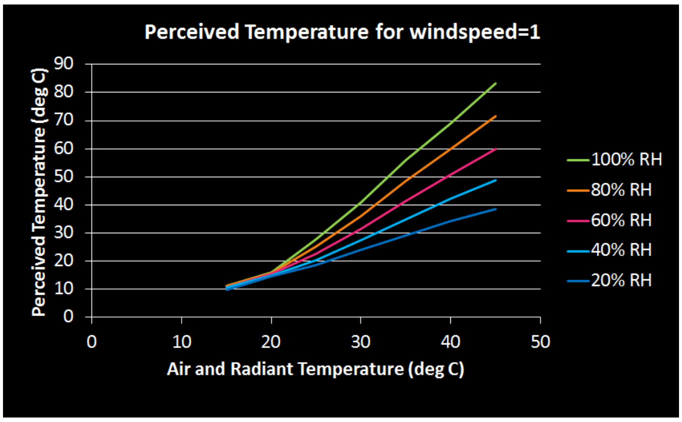


Figure 5.2 Example of effect of relative humidity on perceived temperature

6 Results and Discussion

The thermal performance of Houses 1-3 across the entire study year will initially be compared in terms of each of the five performance criteria. As these criteria assess performance over the whole year a comparison over smaller timescales will then be undertaken to give more detailed results. Following this, further analysis and discussion of building physics principles will be used to explain the trends found in this section. The fact that each room (and its associated roof area) is modelled as an individual thermal zone allows comparisons to be made between the performances of rooms in each house, as well as between the houses.

6.1 Comparison of Houses

6.1.1 Criteria 1 & 2

Figure 6.1 and Figure 6.3 show the performance of each room of Houses 1-3 in Criteria 1 and 2 respectively. House 1 performs much better than the other two houses in Criterion 1 with it maintaining indoor temperatures below 35°C in all rooms for the entire study year. Similarly, Criterion 2 shows that overheating (dry resultant temperature above 33°C) is significantly less of a problem in House 1, with it occurring in less than 0.5% of hours. The highest proportion of overheating occurred in the kitchen (0.5%), with mid-range values in the hallway/bedroom (0.3%) and bedroom 1 (0.2%), and the lowest values in bedroom 2 (0.1%). In comparison, Houses 2 and 3 experienced overheating for 6-7% hours in all rooms except for the hallway/bedroom where the occurrence of overheating is lower at around 3.5%. All rooms in House 1 stayed below the maximum of 1% and 5% hours/year in Criteria 1 and 2 (see derivation in Section 5.3.1), while it is only the hallway/bedroom which passed these criteria in Houses 2 and 3, with the rest of the rooms exceeding these levels. Although these maxima are derived from a simple comparison, when exceeded they show that a significant proportion of the year will be extremely uncomfortable for inhabitants. It was found that the results for Houses 2 & 3 were very similar when each room is compared, although House 3 performs marginally better.

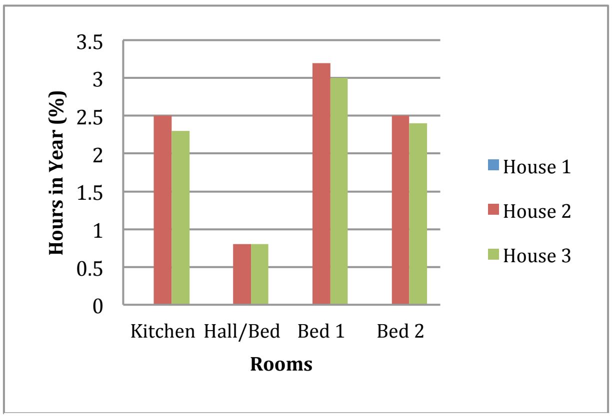


Figure 6.1 Criterion 1: Percentage of hours in study year for which room temperature is greater than 35°C

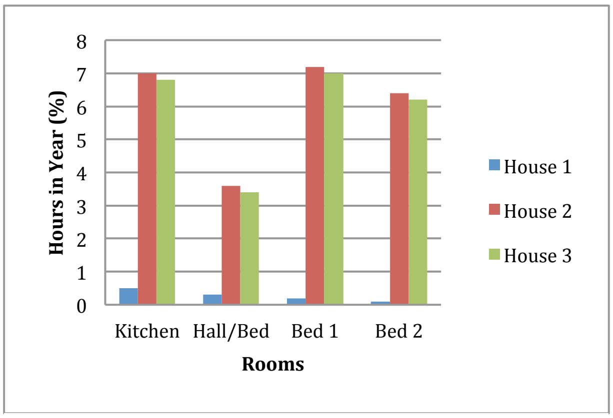


Figure 6.3 Criterion 2: Percentage of hours in study year for which room temperature is greater than 33°C

6.1.2 Criterion 3

The performance of the houses in preventing low indoor temperatures were assessed and can be seen in Figure 6.2, with House 1 outperforming the other two houses in all of the rooms. The hallway/bedroom had the highest proportion of hours spent below 18°C in all three houses, with its result of 1.2% in House 1 significantly lower than the results of House 2 and House 3 (2.5% and 2.3% respectively). Again, House 3 marginally outperformed House 2 in all of the rooms. The kitchen in all three houses had the lowest proportion of hours of thermal discomfort from low temperatures.

6.1.3 Criterion 4

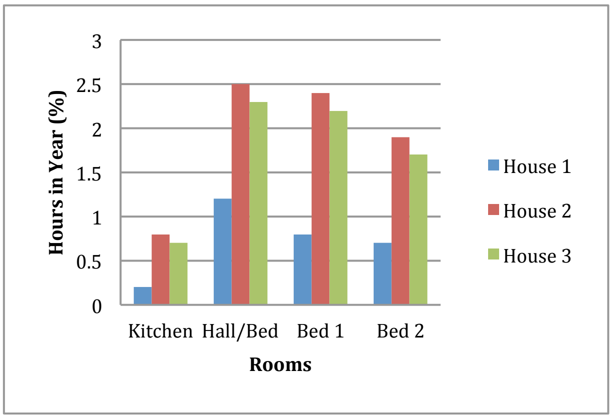


Figure 6.2 Criterion 3: Percentage of hours in study year for which room temperature is less than 18°C

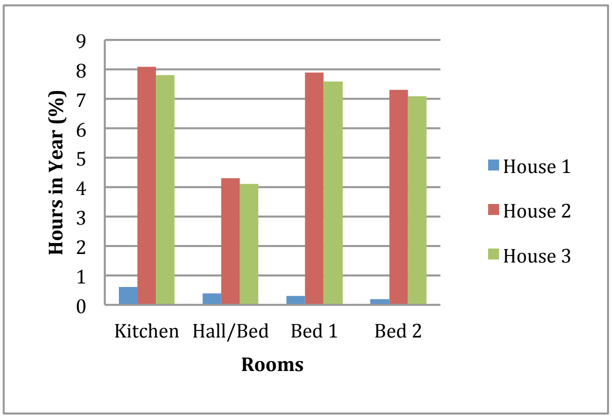


Figure 6.5 Criterion 4: TM52 Criteria I Percentage of hours in study year for which room temperature is over 1°C higher than maximum adaptive temperature

The TM52 Adaptive Comfort analysis is assessed using three of its own criteria. The first of these, TM52 Criteria I, can be seen in Figure 6.5 and follows the same trend of House 1 performing better than Houses 2 and 3 with all of the rooms in House 1 spending less than 0.5% of the year with temperatures 1°C or greater than the calculated real time maximum adaptive temperature. The relationship between the performances of the four rooms in House 1 is the same as was seen in Criterion 2. Houses 2 and 3 exceed the maximum allowable proportion of the year (3%) which is specified for the criteria, with the kitchen and bedrooms 1 and 2 in the range 7-8% which is far in excess of this maximum. As a result all of the rooms in House 1 pass TM52 Criteria I, while all of the rooms in Houses 2 and 3 fail this criteria. Noticeably, Houses 2 and 3 exhibit a similar relationship between the performances of their rooms as in Criterion 2: the highest proportion of overheating occurs in the kitchen and bedroom 1, a slightly lower proportion occurs in bedroom 2 and it is significantly lower in the hallway/bedroom.

House Number	Kitchen	Hallway/Bedroom	Bedroom 1	Bedroom 2
TM52 Criteria II Daily weighted exceedence (°Chr)				
1	28	25	21	20
2	60	48	62	69
3	60	47	61	69
TM52 Criteria III Max. ΔT (°C)				
1	4	4	3	3
2	8	7	10	8
3	7	7	10	8

Table 6.1 Results for TM52 criteria II and III for study year (ΔT is room temp. minus maximum adaptive temperature)

TM52 Criteria II allows the maximum value of daily weighted overheating exceedence to be just 6°Chr (degree-hours) at any point during the year. The results for this are shown in Table 6.1 and confirm that, when both the temperature and duration of overheating are taken into consideration, providing thermal comfort is a difficult challenge for these three houses as they all fail this criterion. For House 1 these results show the same trends that have been seen in all of the previous criteria: it far outperforms the other two houses (although it still exceeds the maximum value by over 300%) and the kitchen is subjected to the highest level of overheating, followed by the hallway/bedroom and then the two bedrooms. Again the results for Houses 2 and 3 are close in value and show that the lowest level of exceedence occurs in the hallway/bedroom. However, in this case bedroom 2 is subjected to the highest level of overheating (with a value of 69°Chr for both houses) in contrast with the results of previous criteria.

In TM52 Criteria III (also shown in Table 6.1) the maximum amount by which room temperature can exceed the maximum adaptive temperature (ΔT) at any point in the year is 4°C. The highest values of ΔT are shown in the graph, with all rooms in House 1 passing this criteria and all rooms in Houses 2 and 3 failing. In both of these houses bedroom 1 exhibits the highest peak ΔT with a value of 10°C.

Overall, all rooms in Houses 2 and 3 failed Criterion 4 because they failed TM52 Criteria I, II and III. All of the rooms in House 1 passed Criteria I and III and therefore passed Criterion 4's TM52 thermal comfort analysis.

6.1.4 Criterion 5

In House 1 it was found that for 67% of the year the temperature of the kitchen was greater than the outside temperature, while values for the other three rooms were in the range 60-61%. Results for Houses 2 and 3 were within 0.4% of each other and showed that for large periods of the year the indoor temperatures of these two houses were greater than those outside. Again, the hallway/bedroom had the least overheating (84%) while the kitchen (93%) and bedroom 2 (97%) had the highest. These proportions are extremely high and would suggest a high level of thermal discomfort with these two house designs providing limited relief from overheating in periods with high external temperatures. The peak differences between internal and external temperatures followed a similar trend with House 1's rooms in the range 4.7-7°C compared to 4.5-9.3°C in Houses 2 and 3.

6.1.5 Performance Over Time

Due to the lack of significant seasonal changes, the variation of room temperature with time follows a similar diurnal cycle throughout the year for all cases. An example of this cycle can be seen in Figure 6.3, which plots the temperatures of bedroom 1 in all three houses over a hot five-day period that includes the hottest outdoor temperature of the year (17th March). All of the rooms in each house displayed a similar cycle, so bedroom 1 was simply chosen as an example case. The large swings in ambient temperature are mimicked by the room temperatures shown for all three of the houses, with Houses 2 and 3 showing almost identical results (hence why only one of them can be seen plotted in this graph).

Overheating in Houses 2 and 3 is again confirmed to be significantly worse than in House 1 with the temperature above the outdoor temperature for the duration of this sample period. Daily temperature swings in Houses 2 and 3 are often greater than the diurnal outdoor variation, while House 1 can be seen to have reduced these swings significantly with lower daytime temperatures and higher night-time temperatures.

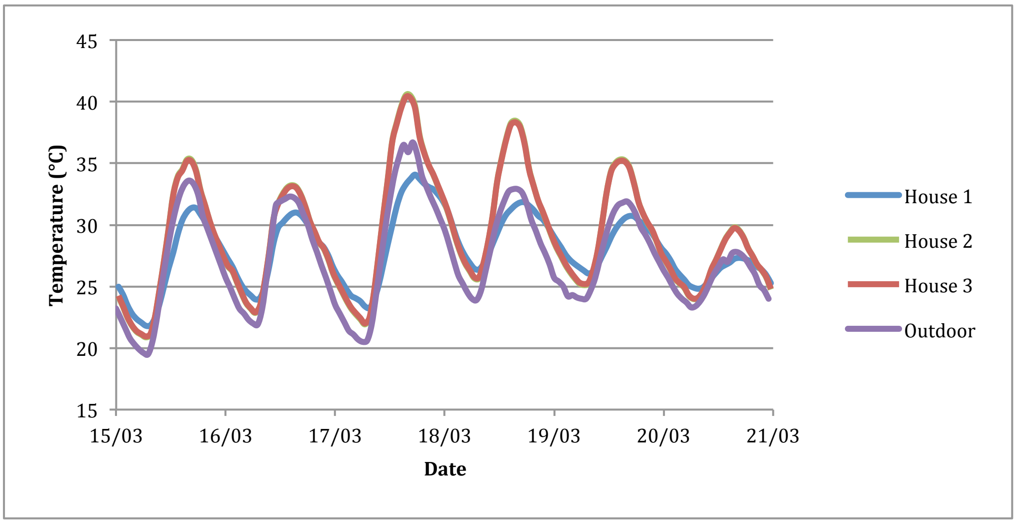


Figure 6.3 Comparison of indoor dry-resultant temperatures for bedroom 1 in Houses 1-3 and outdoor temperature over five day period 15/03 to 21/03

A 'typical warm day' (9th March) with commonly occurring weather conditions (selected by consideration of outdoor temperature, global radiation, wind speed and direction) was selected to enable an analysis of performance across a day. The results for bedroom 1 can be seen in Figure 6.4, which clearly shows both the temperature

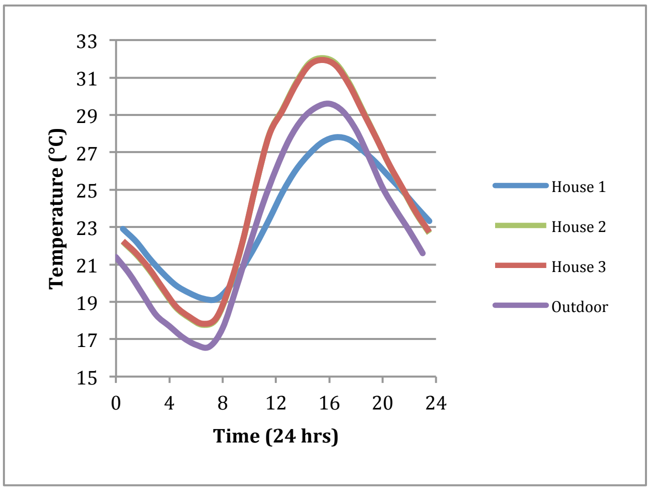


Figure 6.4 Comparison of performance in bedroom 1 on typical warm day (09/03)

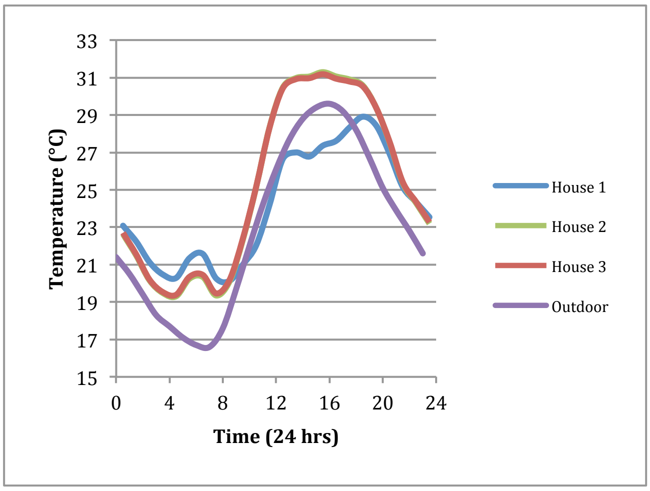


Figure 6.8 Comparison of performance in kitchen on typical warm day (09/03)

moderation effect in House 1 and a small time lag between external and internal temperature rise. Outdoor and indoor temperatures are at a minimum around 7am (sunrise) and reach a maximum temperature between 3pm and 5pm. The performance of the kitchen in each house is shown in Figure 6.8. This presents a different curve shape to that seen for the other rooms with three small peaks which are due to the high internal cooking gains in the morning, afternoon and evening. These peaks are more noticeable during the morning for Houses 2 and 3 but affect House 1 throughout the day.

The changes in room temperature for all rooms in Houses 1-3 on this day can be seen in snapshots at four hourly intervals (and at 3am) in Figure 6.9. The temperatures for each room are denoted by colour with reference to the key. Figures 6.9(a-d) show that Houses 2 and 3 heat up faster than House 1, with each snapshot showing a temperature difference of at least 2°C between them.

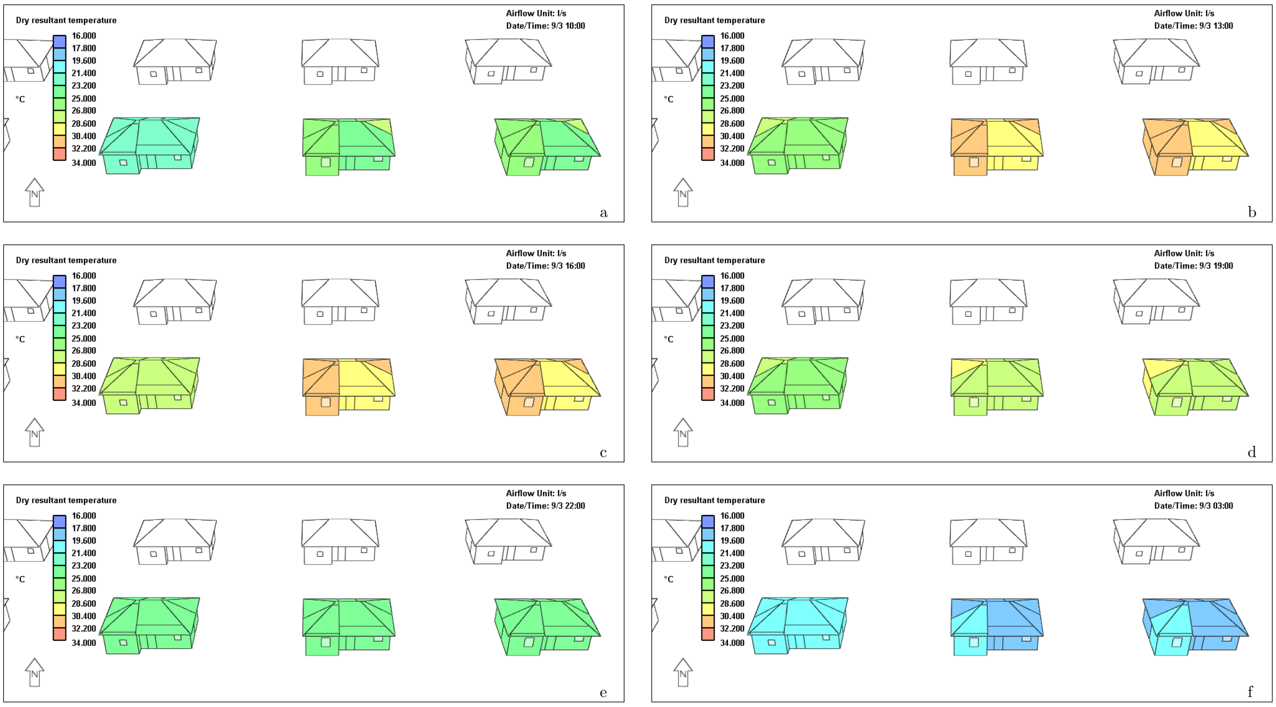


Figure 6.9(a-f) Room temperatures for Houses 1-3 (left to right) throughout a typical warm day. (a-f correspond to times 10am, 1pm, 4pm, 7pm, 10pm and 3am)

At 10pm (Figure 6.9(e)) this temperature difference becomes negligible as all rooms in each house fall to 24°C. This is because the outdoor temperature has fallen to 22°C and therefore there are no external gains (there is no solar gain as the sun has set). After this time the temperatures in all houses keep falling, with Figure 6.9(f) showing that by 3am Houses 2 and 3 are cooler than House 1 (apart from bedroom 1). This shows that the heating and cooling rates in House 1 are considerably less than those for House 2 and 3. The benefits of this for House 1 are that it is slower to overheat during the day which reduces thermal discomfort during this period, and that during cooler evenings the indoor temperatures do not fall as quickly as in Houses 2 and 3.

This means that during hotter nights House 1 will maintain warmer temperatures than the other two houses because of its slower cooling rate. This may result in thermal discomfort during the earlier part of the night, at a point when occupants will be sleeping indoors. As was found in the criteria analysis, Figures 6.9(a-c) also show that the hallway/bedroom is the coolest room during the hottest period of the day in Houses 2 and 3.

6.1.6 Summary of Observations

The following observations summarise the results of the previous sections:

1. Across the entire year House 1 overheats and experiences uncomfortably low temperatures significantly less often than Houses 2 & 3. On a daily basis it is subjected to lower diurnal temperature swings with lower daytime temperatures and marginally higher night-time temperatures when compared to outdoor temperatures and Houses 2 and 3.
2. Overheating in House 1 occurs most often in the kitchen (where the highest temperatures occur) and the least often in bedroom 2.
3. Across the year House 3 both overheats and experiences uncomfortably low temperatures marginally less often than House 2.
4. Overheating in Houses 2 & 3 occurs most often in the kitchen and bedroom 1 (where the highest temperatures occur).

5. Overheating in Houses 2 & 3 occurs the least in the hallway/bedroom, whereas in House 1 this room spends the second highest proportion of time at high temperatures.
6. The daily weighted exceedence in Houses 2 and 3 is highest in bedroom 2.
7. Uncomfortably low night-time temperatures occur least in the kitchen in all three houses.

6.2 Analysis of Key Areas

Observations 1-7 will be explained by further analysis of the house performances in the followings sections.

6.2.1 Roof

Conduction gain through the roof for the ‘typical warm day’ can be seen in Figure 6.10. It was found that in each house all four rooms had similar results, so a single room (hallway/bedroom) has been selected to be shown in this graph for comparison between houses. The graph shows that conduction gain through the roofs in Houses 2 and 3 is far higher than in House 1 during the daytime. The conduction gain increases from sunrise until it reaches a very high peak value of 2kW in the middle of the day (when the sun is directly overhead) before decreasing over the afternoon. In contrast, House 1 maintains a steady level of conduction gain throughout the day with a peak value of just 0.1kW between midday and 2pm.

At night-time House 2 and 3’s roof conduction gains are negative (peak value of -0.4kW) indicating that heat is emitted from the house during this period. The material used for roofing in the three houses can explain these results. Firstly, it should be noted that the corrugated iron and thatch have very low thermal storage capability and therefore conduction gains are due to direct conduction only. The high U-value of House 2 and 3’s corrugated iron (7.14W/m^{2}K) allows a much higher heat flux through the roof than House 1’s thatched roofing (U-value of just 0.54W/m^{2}K). This results in higher heat transmission into the house when external temperatures and solar radiation are high (in the middle of the day) and a high transmission of heat out of the house when internal temperatures are higher than external temperatures (at night-time).

These results explain the behaviour described in Observation 1, showing that the iron roof in houses 2 and 3 is a key contributor to overheating during the daytime.

The limited levels of heat transfer permitted by House 1's thatch roof keep internal temperatures low during the daytime and prevent internally stored heat from being released at night, resulting in higher night-time temperatures.

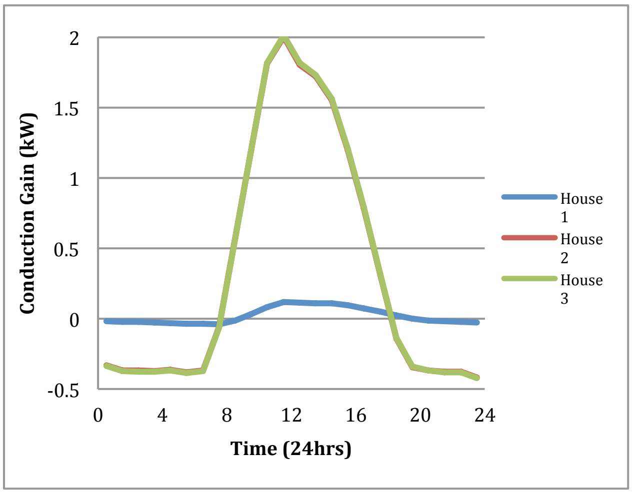


Figure 6.10 Roof Conduction Gain

6.2.2 Walls

The conduction gain through external walls is a measure of the amount of heat energy released into the house and has been plotted for the hallway/bedroom in each house for the 'typical warm day' in Figure 6. (rooms in each house followed similar trends and a single room has been chosen to simplify the comparison again). The graph shows that the conduction gain does not always vary directly with outdoor temperature. This is because, unlike the roof materials, the wall materials have considerable thermal storage capacity, resulting in heat energy being stored in the material during the hottest periods of the day and then released at a later time. In Section 3.4 it was predicted that the thick mud and pole walls in House 1 would provide the greatest thermal storage capacity and the largest time lag for emission of heat energy. This can be seen in Figure 6.11, with the walls emitting heat energy (positive conduction gain) during the night-time when ambient temperatures are lowest, and absorbing heat energy (negative conduction gain) during the hottest part of the day (between 10am and 5pm). This timing is good for moderating internal temperatures and is a key factor in explaining the behaviour described in Observation 1 as the absorption reduces internal temperatures during the hottest period of the day and then emits the heat energy (externally and internally) during the coldest period, allowing the thermal storage to reset for the next day and also increasing the internal temperature. However, it should be noted that the time lag is not perfect, as the walls start to emit heat energy from 6pm onwards (when ambient temperatures are still relatively high at 26°C). This explains House 1's higher temperatures (relative to those in House 2 and 3) during the early evening (see Section 5.1.6). A slightly longer time lag would improve performance by preventing overheating in the evening.

The thermal storage of the baked brick and concrete walls of House 2 and 3 is considerably less effective at internal temperature regulation. This can be seen by the way in which both of these types of walls absorb heat energy during the night-time/early morning (when temperatures are lowest) and emit/conduct heat energy

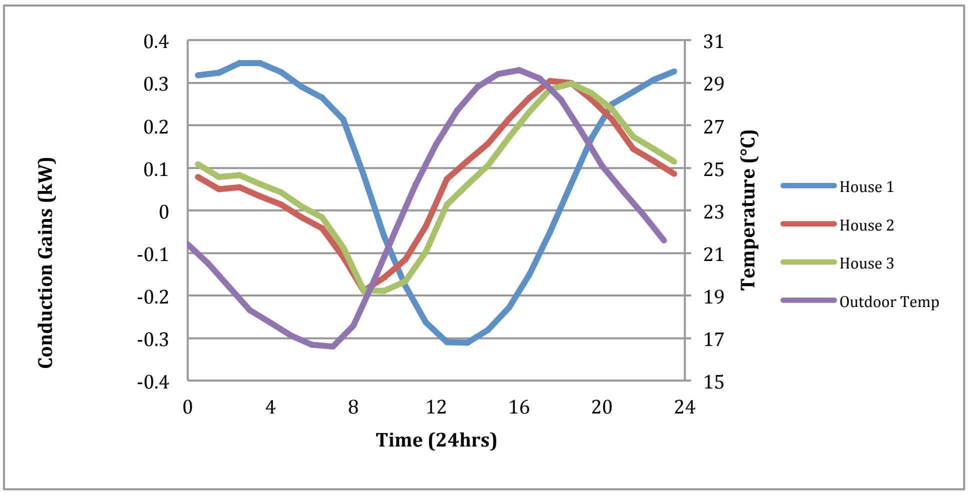


Figure 6.11 Wall Conduction Gain

into the house from midday until 6am the next morning. As this heat flux from the walls into the room occurs during the hottest period of the day it explains why overheating is more of a problem in these two houses. The U-values of these external walls (see Table 3.2) are higher than mud-pole walls, meaning that the speed with which the heat wave reaches the inside surface will be higher, giving rise to this greater correlation between heat gain and outdoor temperature. This contributes to the discrepancy in performance between House 1 and Houses 2 and 3 described in Observation 1.

Figure 6.11 shows that the performance of House 3's concrete walls is slightly closer to that of the mud-pole walls with higher heat emittance than House 2's baked bricks in the cooler night-time/early morning period and lower heat emittance (and conductance into the house) in the hotter period of the day. This can be explained by the fact that the U-value of concrete is lower than for baked bricks, meaning that the heat wave takes longer to reach the inside of House 3. This delays heat gains so that they heat the house slightly later in the day (House 3's graph is the same as House 2's but shifted to the right) when ambient temperatures are lower. This slightly improved thermal moderation behaviour will be a contributing factor for Observation 3 which states that House 3 has more moderate temperature swings than House 2. It should also be noted that the earth floor of House 1 was found to provide more effective thermal moderation than the cement floor in Houses 2 and 3.

6.2.3 External Ventilation & Infiltration

External ventilation and infiltration affect House 1 very differently from Houses 2 and 3. This is because they are both much less controlled in House 1 due to its large roof overhang openings and lower level of workmanship (more gaps and cracks increase infiltration). The effect of higher airflow through House 1 is that it receives high gains (peak value of 1.2kW) during the daytime when external temperatures are higher than those inside and large negative gains (i.e. heat removal) during the night-time, when external temperatures are lower than internal temperatures. This can be seen for the 'typical warm day' in Figure 6.12 where daytime ventilation gain and

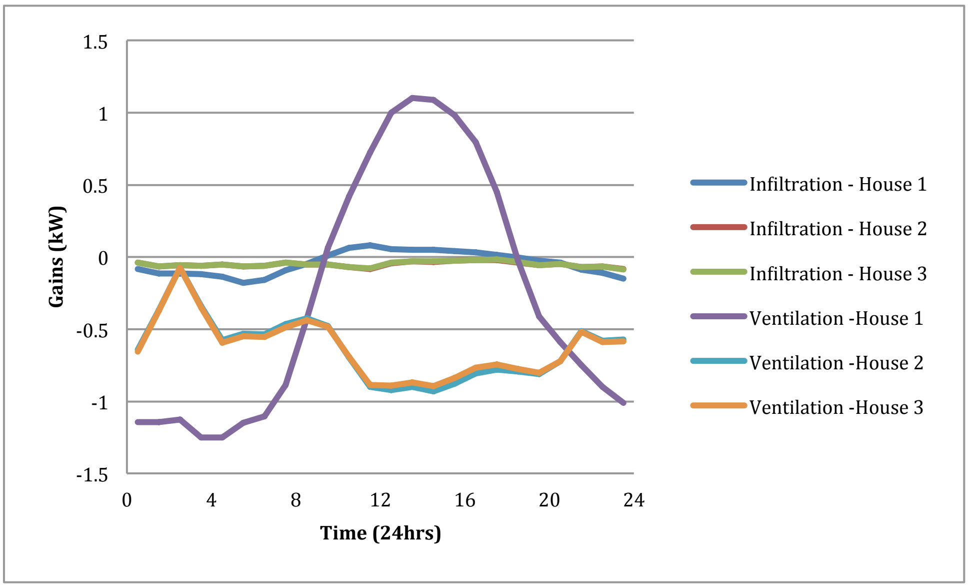


Figure 6.12 External Ventilation and Infiltration Gain

infiltration gain are shown for the hallway/bedroom of Houses 1-3. The benefits of high ventilation during hot nights is clear, with House 1 showing a peak heat rejection of 1.2kW at 4am for this day. This will also be good for removal of heat stored in the mud walls. However, during the daytime this ventilation will contribute significantly to rises in indoor temperature.

Houses 2 and 3 exhibit similar results because they have the same openings and level of workmanship. In both of these houses ventilation gains are negative throughout the entire day and reach a peak heat rejection level of 0.9kW during the hottest period of the day (the afternoon). The constant rejection of heat by ventilation in these two houses is beneficial for thermal comfort during hot days. Infiltration gains follow the same trends as ventilation gains in each house, although the magnitude of these gains are negligible in comparison.

Houses 2 and 3 clearly outperform House 1 in terms of the contribution of ventilation towards preventing overheating, although this is not immediately apparent from the assessment of overheating in this project. However, on closer inspection of the results for Criteria 2-4 it can be seen that the hallway/bedroom in House 1 is the room that spends the second highest proportion of time overheating. This can be attributed to the fact that it is the room with the largest amount of external openings (due to the large roof overhang and two doors which are open in the daytime). This allows cross-ventilation to occur more easily. The hallway/bedroom is the most ventilated room in Houses 2 and 3 and is therefore the coolest room (as they only have negative gains) as was stated in Observation 5. This analysis has shown the impact that controlling ventilation can have on heat gain/rejection for the houses. Clearly high ventilation is can result in overheating during the day and excessive heat loss on cold nights, but it can also be beneficial for high heat removal during hotter nights.

6.2.4 Solar Gain

Unfortunately IES does not allow for specific analysis of external solar gain (this is all contained within the conduction gains discussed in the previous sections) and only offers an analysis of internal solar gains. These internal solar gains were found to be significantly lower than the conduction and ventilation gains analysed in the previous

Location	Peak Value (W)	Time of Peak	Mean (W)
House 1			
Kitchen	67.3	12:30, 23/Jun	9.6
Hallway/Bedroom	32.7	08:30, 03/Jan	5.7
Bedroom 1	45.4	14:30, 24/Dec	7.3
Bedroom 2	67.4	12:30, 23/Jun	9.6
House 2			
Kitchen	136.3	12:30, 23/Jun	20.4
Hallway/Bedroom	62.8	08:30, 03/Jan	11.8
Bedroom 1	84.8	16:30, 20/Dec	15.4
Bedroom 2	136.2	12:30, 23/Jun	20.5

Table 6.2 Internal solar gains for Houses 1 and 2 across study year

sections, but they do offer some indication of when each room will be more affected by solar gains (although they only account for gains through the north and south sides as this is where the windows are situated). Table 6.2 shows the maximum gains, when they occur and the mean values for each room in Houses 1 and 2. House 3 is not included in the table because it had very similar results to House 2 with marginally lower gains due to the slightly lower absorptivity of concrete (0.63) compared to baked bricks (0.69). The sun path for Tabora (**Error! Reference source not found.**) showed that there is some variation in the angle of the sun at different times of the year. The effect of this can be seen in Table 6.2 which shows that there is a variation of solar gain at two periods of the year. Rooms on the northern side (bedroom 2 and the kitchen) receive highest solar gains in June and the southern facing rooms (bedroom 1 and the hallway/bedroom) do so in December. June is in the dry season when cloud cover is lower which explains the higher gains in the north facing rooms. The lower gains in House 1 compared to House 2 are due to its smaller windows. However, these internal solar gains are roughly an order of magnitude less than the conduction gains discussed in Sections 6.2.1 and 6.2.2 which limits their comparative effect on overheating. As conduction gains are due to the combined effect of heat conduction from high ambient temperatures and external solar gain, it is expected that external solar gains will considerably higher than internal gains. This is supported by the fact that radiation flux reaches a maximum value of 1.3kW/m2 during the year. There will be relatively high absorption of this energy by all of the houses as the walls have absorptivities of 0.63-0.69. The corrugated iron roofs will absorb a particularly high level of this radiation in comparison with the thatched roofing due to its absorptivity of 0.9 instead of 0.6. This shows that there will be periods of very high external solar gain during the year, with House 1 absorbing the least through the roof (as shown in Section 6.2.1). Houses 2 and 3 absorb significantly more due to the higher roof absorptivity, and House 3 will absorb marginally less radiative energy through its walls than House 2 because of its lower absorptivity (0.63 compared to 0.69). These key points explain Observations 1 and 3. This is because high radiation gains (combined with low insulation) result in more overheating in Houses 2 and 3 when compared to House 1, as well as House 3 overheating marginally less often than House 2.

The orientation of long walls and windows facing in the north-south direction which was chosen for the simulation was compared with an east-west orientation (rotation by 90 degrees). It found that the mean solar gain in every room in Houses 1-3 was around 30% lower for the north-south orientation. For overheating prevention maximum values of solar gain are more important as days of high solar radiation are the most likely to heat up the houses. It was found that the annual peak value of solar radiation was 50% less for the north-south orientation. This proves that radiation on east and west facing walls is highest throughout the year because of the position of the sun throughout each day, which can be seen in Figure 6.5. The relatively direct movement of the sun from east to west also explains why the daily weighted exceedence was highest in bedroom 2 for Houses 2 and 3 (Observation 6). This is because, as an eastern facing room, it is the first room to heat up in the morning when ambient temperatures are cooler (hallway/bedroom has a larger volume and does not heat up as much). It will then have its high indoor temperature

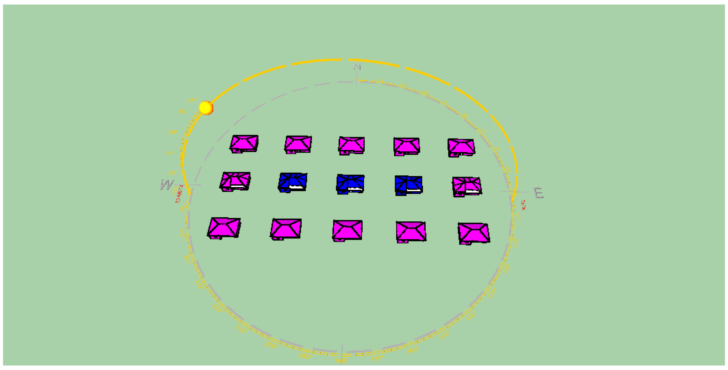


Figure 6.5 Position of sun relative to houses at 16:00hrs in March.

sustained throughout the day (when solar radiation is higher on western facing walls) by high ambient temperatures. As a result it spends the longest time at high temperatures of all the rooms, which results in a high daily weighted exceedence. This is because daily weighted exceedence takes the amount of time spent at high temperatures each day into consideration, unlike the other criteria.

The afternoon solar radiation falls more on the western side of the house, increasing the solar gains in the kitchen and bedroom 1 at this time. This is due to the position of the sun, an example of which is shown in Figure 6.5. As this coincides with the period of highest ambient temperature, the overall gains for these rooms are very high and result in them overheating and reaching the highest temperatures more often than other rooms (Observation 4) in Houses 2 and 3. Although the kitchen was the most susceptible room to overheating in House 1 (Observation 2), this is not entirely due to solar gain because it is less susceptible to conduction gains (due to its lower roof absorptivity and higher levels of insulation and thermal mass). Instead the higher occurrence of overheating in this room (and not bedroom 1) is due to the combined contributions of internal gains and external gains, because internal gains have more of an impact on overheating when external gains are lower. This is also the reason why Section 6.1.5 found that cooking gains have more of an effect on House 1 than the other two houses. The simulation showed that occupancy gains are significantly lower and have a minimal effect in comparison.

Observation 7 observes that the kitchen in all three houses is the least likely room to experience uncomfortably cold temperatures. This is also due to the combined effect of high cooking gains in the evening and high afternoon solar gain on the western side of the house. These gains heat up the kitchen as outdoor temperatures fall, reducing thermal discomfort from low night-time temperatures.

7 Conclusions

The study has shown that the ‘current house’ (House 1) offers a far greater level of thermal comfort than the ‘transition house’ (House 2) and the ‘future house’ (House 3) for the temperate tropical climate of Tanzania. This was shown by its vastly superior performance across all criteria. It does this by moderating diurnal temperatures, therefore reducing the incidence of overheating during the daytime and cold temperatures at night-time. This was found to be due to the thermal mass of the thick mud-poles walls and insulation and lower solar radiation absorption through the thatch roof. The iron roofing in Houses 2 and 3 was found to perform particularly badly due to its very high conduction gains. However, House 1 did not perform the best in all cases, with its more open structure resulting in higher daytime ventilation gains (and night-time heat removal) than the other two houses. The fact that it cools down more slowly than Houses 2 and 3 each night also means it can be more uncomfortable during hotter evenings. The study also found that House 3 performs marginally better than House 2 because of its slightly lower wall conduction gains and internal solar gains. Overall, it must be concluded that the thermal comfort provided by all three houses is not acceptable and can be improved through further analysis of several critical design areas which were identified in the study. These include reducing gains through the roof, controlling ventilation at different times of day and designing thermal mass for optimal time lag and temperature moderation.

The rooms in the houses also had varying levels of thermal comfort, in particular with the kitchen and bedroom 1 on the western side suffering from afternoon solar gains combined with high ambient temperatures. The internal gains from the kitchen in House 1 were also more dominant in dictating thermal comfort in the house. The results show that building design should also take into consideration the position and use of each room, and design them accordingly (using additional thermal mass, ventilation or shading) to reduce the effects of the most dominant gains on thermal comfort for each case.

The results from this study highlight a serious deficiency in appropriate design of modern low-income housing for thermal comfort in the temperate tropical Tanzanian climate. Although traditional housing design may be viewed as no longer being suitable by some people because of non-thermal factors (e.g. durability and security), the key design principles which make them effective at providing thermal comfort should be considered and applied to improving modern house designs.

7.1 Further Work

To provide more accurate and representative results, more information needs to be collected on material properties. Dataloggers should be used to collect at least six months of thermal data from houses similar to those investigated in this study. This will allow the model's results to be validated and allow for more accurate analysis in IES. A more detailed analysis of the effects of specific design improvements for each house should be undertaken. These improvements should be based on the critical areas for performance identified in this study

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