TRANSITION IN HOUSING DESIGN AND THERMAL COMFORT IN RURAL TANZANIA

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Abstract: This study evaluates the performance of three low-income passive housing designs at providing thermal comfort for their inhabitants in temperate tropical rural Tanzania. Severe climatic conditions in these upland regions include large daily oscillations in air temperature (14℃-36℃) and high levels of solar radiation, causing overheating which affects inhabitant health and wellbeing. Inadequate shelter in these difficult climatic conditions is a widespread problem with 71% of Tanzanians living in rural areas, of which 28% of are below the national poverty line. Over the last 10 years an increasing number of houses are using modern building materials (brick or concrete walls and iron roof) rather than traditional vernacular design (mud-pole walls and thatch roof). Three designs were chosen to describe this transition. The performances of the three houses were simulated across a study year using IES and then compared against five chosen criteria to assess thermal comfort. Detailed analyses of critical times of day and specific areas of the building envelope were used to identify critical areas of design. The traditional house overheated significantly less often with smaller diurnal indoor temperature swings than the modern houses (due to its higher roof insulation and wall thermal mass). It also experienced uncomfortably low temperatures least often but maintained higher temperatures for longer during hot evenings. The modern houses outperformed the traditional house in ventilation gains with constant heat rejection *throughout the day and night. The traditional house's open structure resulted in high daytime* ventilation gains and night-time heat rejection. Consideration of the position and internal gains of each room was found to be an important design factor. Across the study year the traditional design provided greater thermal comfort. However, as durability and social pressures are important factors in the choice of building materials, the design of modern materials that can mimic and improve on traditional material performance is critical to improving the health of inhabitants.

Keywords: Low Income, Housing, Passive Design, Thermal Comfort, Rural Tanzania.

1 Introduction

This research was taken 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 (Tanzania Bureau of Statistics 2012). As a high proportion of these homes are situated in regions with a temperate tropical climate this project only considers the specific case of rural temperate tropical regions in Tanzania. Only the low-income case was studied as 28% of the rural population is currently living below the national poverty line (World Bank 2014). 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℃. This, combined with heat gains from high levels of solar radiation, as well as limited access to electricity and air conditioning facilities, can result in excessively high indoor temperatures that seriously affect the quality of life of inhabitants. Effects of thermal discomfort also include heat stroke, confusion, low sleep quality, confusion, behavioural disorders and exacerbation of health problems in susceptible groups (CIBSE 2008). 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 important for provision of 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 (Kalabamu 1985). This was supported by a survey of 19 mud-pole houses from the visit to a region outside Dar es Salaam. Average temperatures in this region were 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). 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. This is supported by other studies in East Africa identifying roof construction as the key element affecting thermal comfort in low-income houses (Hashemi 2016).

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 (Nguluma 2003). 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.

2 Methodology

Data for this project was collected in a literature review, site visits and surveys of three communities in rural Tanzania. 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 (VE) were then used to compare the thermal comfort performance of three house designs (selected to illustrate the transition in house design) and to identify reasons for the differences. The thermal performance of Houses 1-3 across a study year was assessed against five thermal comfort performance criteria before they were analysed over smaller timescales.

2.1 Weather Data

Tabora (Figure 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 Tanzanian temperate tropical upland climate. 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 was Meteonorm.

Figure 1: Tabora, Tanzania (Open Street Map)

3 Housing

Literature about low-income housing design in rural regions of Tanzania with a temperate tropical upland climate (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 (Nguluma 2003; Kalabamu 1985). 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 (Kalabamu 1985; Mattsson 2009; Mwakyusa 2006). This study concentrates on the more recent development of housing design, which has been largely focused on different building materials used in construction.

Housing designs chosen for analysis in this project are based on the houses described in relevant literature (Kalabamu 1985; Mattsson 2009; Mwakyusa 2006; Kalabamu 1989) and are supported by the 2002 and 2012 Tanzanian Government Housing and Population Censuses, 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 (2006) which has an extremely comprehensive set of information on housing design across Tanzania.

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 2. 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%) and roofing material has seen the most dramatic change, with thatch being replaced by corrugated iron.

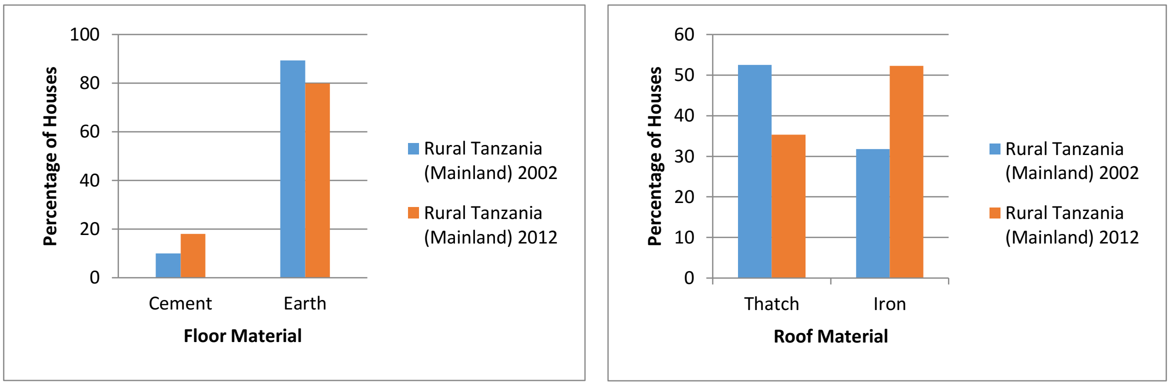

Figure 2: Construction materials used in rural Tanzanian housing for floor (a) and roofing (b) by proportion of houses

The proportion of wall materials used in 2002 and 2012 (Figure 3) shows that mud and pole was the most commonly used wall material in 2002 but its use has fallen while baked brick use has grown. Exactly the same trends were seen in Tabora (Figure 4).

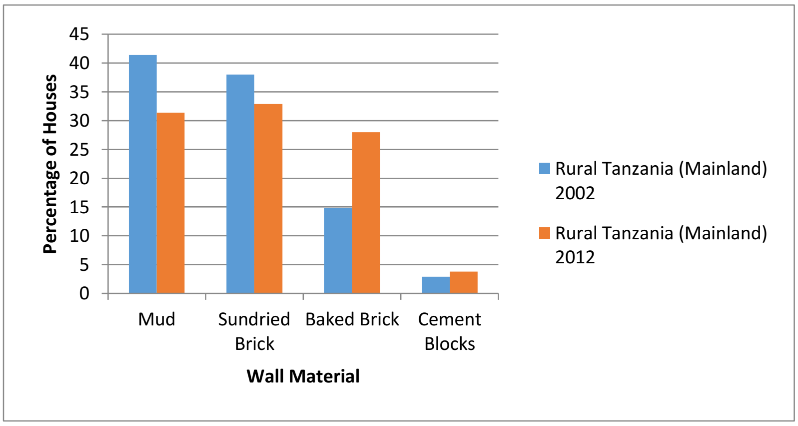

Figure 3: Construction materials used in rural Tanzanian housing for walls by proportion of houses

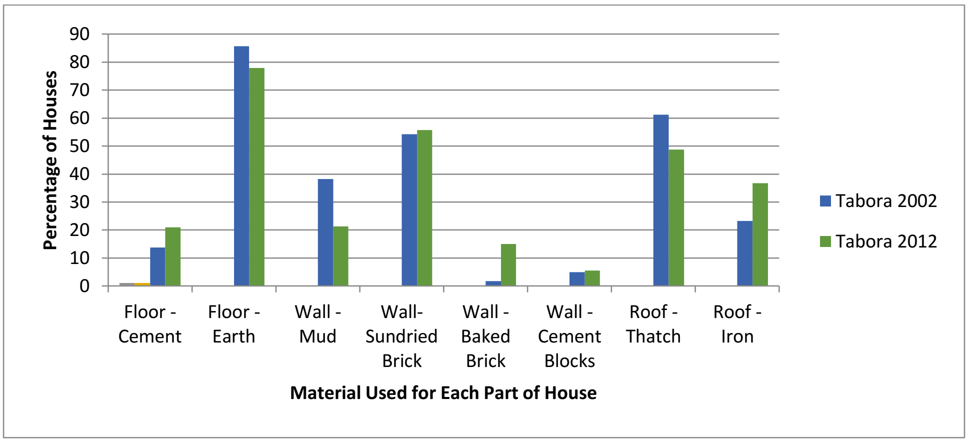

Figure 4: Proportion of houses with each construction material for floor, wall and roof in rural houses in Tabora in 2002 and 2012

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.

3.1 Three Study Houses (current, transition and future)

All three houses follow the same floor plan (Figure 5), are designed for 5 occupants (Tanzania Bureau of Statistics 2012) and have an indoor kitchen (Nguluma 2003). The windows are simply holes in the wall and the roof has a hipped shaped and 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 walls between each room that stop at a height of 2.4m. There are no partitions between the rooms and the roof zone above this height.

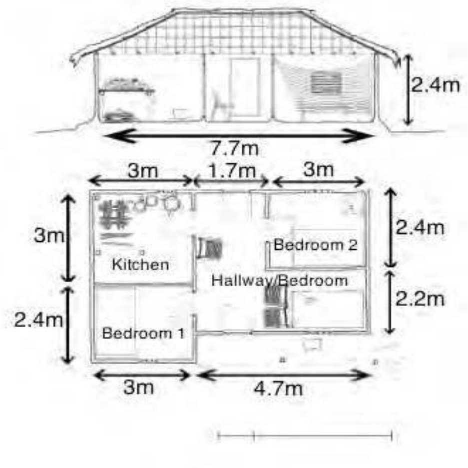

Figure 5: Floor plan for all houses and photograph of House 1 design

House 1's construction materials were most commonly used in 2002, but are still widely in use today. The walls are mud and pole (made from mud stuck onto a wooden pole structure, see Figure 5). 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's construction form the floor and the roof is made from thatched leaves.

House 2 (the transition house shown in Figure 6) describes the main changes in rural low-income housing design over the last decade. The exterior and interior walls of the house are made from baked bricks (also known as burnt bricks). 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 6: House 2 Design

Figure 7: House 3 Design (Mattsson 2009)

House 3, the 'future house' (shown in Figure 7) is identical to House 2, except for the use of concrete blocks for all of its walls.

The key design features can be compared in Table 1 below.

Table 1: Comparison of Key Design Features of Houses

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

3.2 Material Properties

The properties of the materials used in construction for Houses 1-3 can be seen in Table 2. The most representative properties for a low-income context were selected using data collected during visit, CIBSE A and the available literature on construction in Tanzania.

Table 2: Construction material properties (wall U values are external wall/internal)

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

4 IES (VE) Model Details

IES inputs will be discussed in this section to define the details of the model and explain the choices and assumptions made. Each room (and its associated roof area) was modelled as an individual thermal zone to allow comparisons to be made between the performances of rooms in each house, as well as between the houses. The model can be seen in Figure 8, with the three houses located in the middle of the 'village' used to simulate the effects of adjacent buildings.

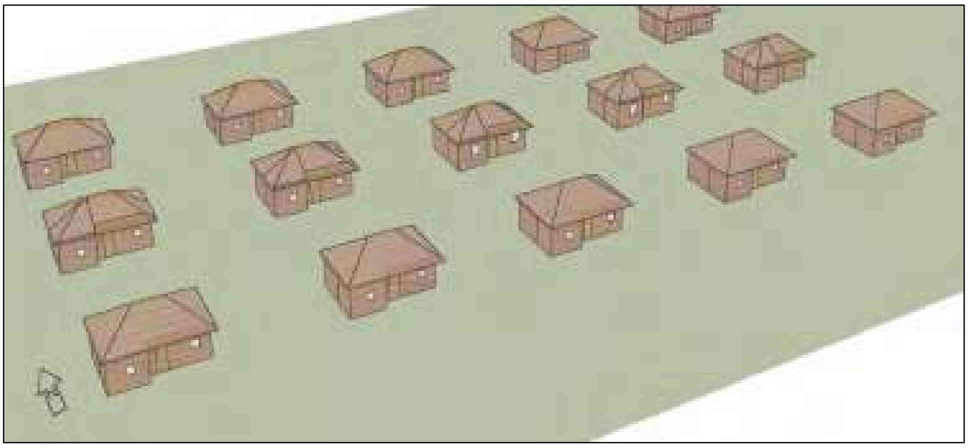

Figure 8: 'Village' arrangement of houses in IES simulation

Internal gains depend on occupant behavior with 90W/person for a relatively stationary human body (CIBSE 2006). Occupancy patterns were assigned to each room based on the times of sunrise, sunset and as well as daily routine of households in rural Tanzania which was based on visit information and other sources (Raleigh International 2013; IFAD

2015). 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 (Tanzania Bureau of Statistics 2012) and a peak heat output was calculated to be 1.275kW (Biomass Energy Centre 2015).

Doors are left open during the day and are shut at night (for security). 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 area to 64.5%, according to data collected during site visits. The openings into the roof overhang are 60% open in House 1, compared to 10% in Houses 2 and 3 due to poor connections between mud walls and thatch roofing. 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 as cracks and gaps are common in mud and pole walls. The better construction quality and materials of Houses 2 and 3, give these houses an infiltration of 5ac/h.

One week of internal/external temperature 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 week. The same month in the simulation predicted similar results and similar differences between the two houses. The IES model will only be used to demonstrate trends and the effect of various aspects building design on thermal performance rather than giving exact results.

5 Performance Criteria

The chosen criteria for thermal comfort analysis were:

- Criterion 1: Percentage of hours above 33℃
- Criterion 2: Percentage of hours above 35℃
- Criterion 3: Percentage of hours below 18℃
- 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 and percentages of hours are taken as the percentage of hours out of total hours in a year (not just for occupied hours as exact information on occupancy patterns was difficult to find and non-working family members are more likely to spend the afternoon inside). Assessment of all hours is therefore based on the perspective that a house should provide thermal comfort for all times of day.

The temperatures 33℃ and 35℃ used to assess overheating were derived from the CIBSE A criteria for overheating in the UK which gives maximum values of 5% and 1% for temperatures of 25℃ and 28℃ respectively (CIBSE 2006) which 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 the two equivalent temperatures for Tabora.

The sensation of temperature and its effect on health are dependent on the acclimatisation of a person to their environment. Adaptive thermal comfort model CIBSE TM52 was selected to take this into consideration and 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 (IES 2013).

The three criteria are:

- 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."
- 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℃hr resulting in failure in this criterion.
- 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:

$$T_{\max} = 0.33T_{rm} + 18.8 + S.A.R$$

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

6 Results and Discussion

6.1 Comparison of Houses

6.1.1 Criteria 1 and 2

Figure 9 and Figure 10 show the performance of each room of Houses 1-3 in Criteria 1 and 2 with House 1 outperforming the other houses. It maintains indoor temperatures below 35℃ in all rooms for the entire study year and only exceeds 33℃ in less than 0.5% of hours. The highest proportion of overheating occurred in the kitchen (0.5%) while Houses 2 and 3 experienced overheating for 6-7% hours in all rooms except for the hallway/bedroom (3.5%). All rooms in House 1 stayed below the maximum of 1% and 5% hours/year in Criteria 1 and 2 but only the hallway/bedroom passed these criteria in Houses 2 and 3. This shows that a significant proportion of the year will be extremely uncomfortable for inhabitants. The results for Houses 2 and 3 were very similar for each room, with House 3 performing marginally better.

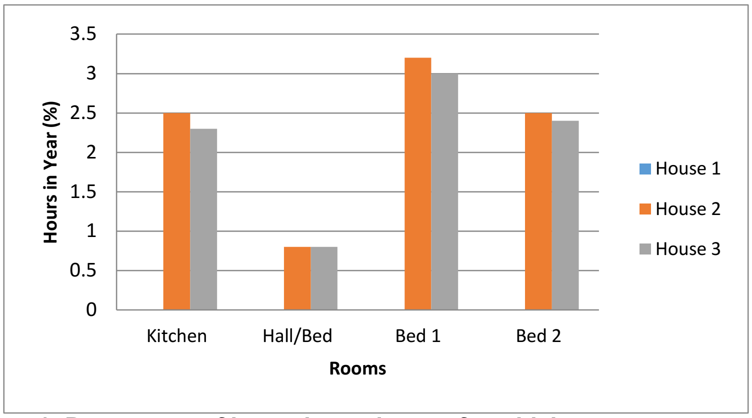

Figure 9: Criterion 1: Percentage of hours in study year for which room temperature is greater than 35℃

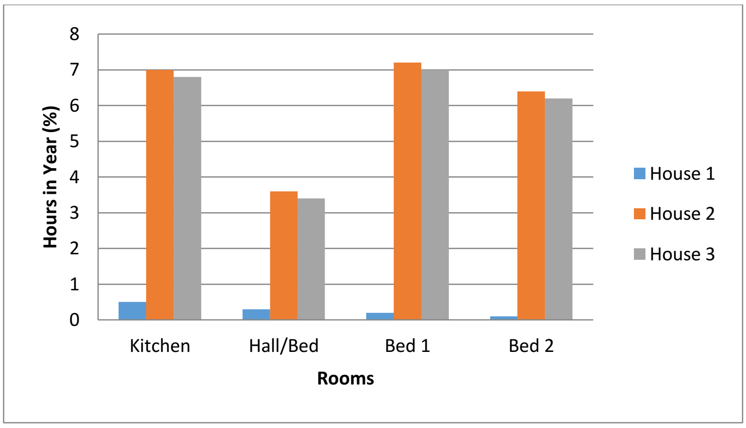

Figure 10: Criterion 2: Percentage of hours in study year for which room temperature is greater than 33℃

6.1.2 Criterion 3

House 1 outperformed the other two houses across all rooms (see Figure 11). The hallway/bedroom had the highest proportion of hours spent below 18℃ in all three houses, and the kitchen in all three houses had the lowest proportion of hours of thermal discomfort. Again, House 3 marginally outperformed House 2 in all of the rooms.

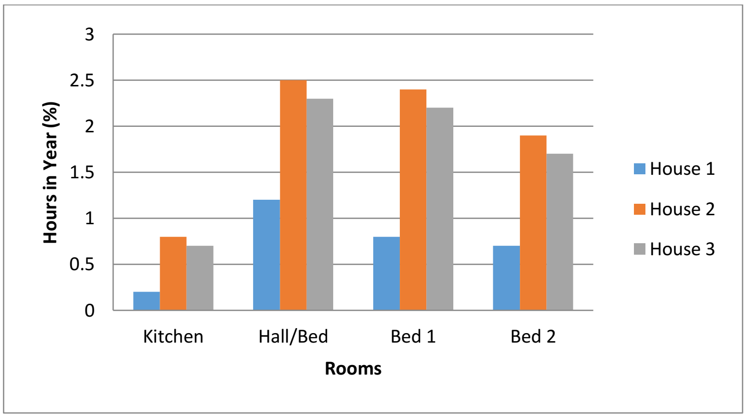

Figure 11: Criterion 3: Percentage of hours in study year for which room temperature is less than 18℃

6.1.3 Criterion 4

TM52 Criteria I (Figure 12) follows the same trend of House 1 outperforming the other houses with all rooms in it spending less than 0.5% of the year with temperatures 1℃ or greater than the calculated real time maximum adaptive temperature. Houses 2 and 3 exceed the maximum allowable proportion of the year (3%), with the kitchen and bedrooms 1 and 2 exceeding it considerably (7-8%). Therefore all rooms in House 1 pass TM52 Criteria I, while Houses 2 and 3 fail this criteria in every room. The highest proportion of overheating occurred in the kitchen and bedroom 1, less in bedroom 2 and significantly less in the hallway/bedroom.

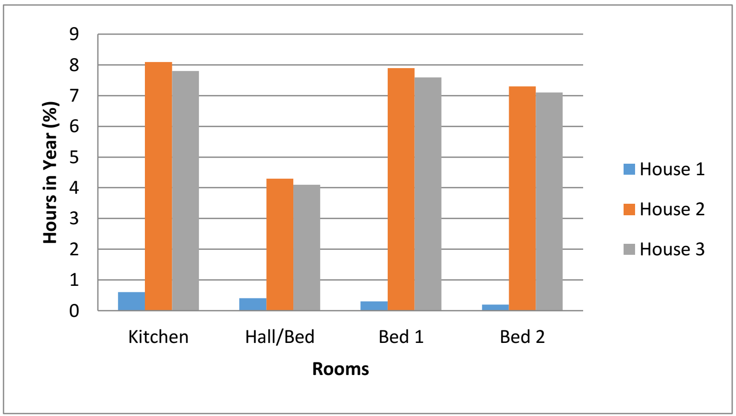

Figure 12: Criterion 4: TM52 Criteria I Percentage of hours in study year for which room temperature is over 1℃ higher than maximum adaptive temperature

The results for TM52 Criteria II (Table 3) confirm that providing thermal comfort in terms of both temperature and duration of overheating is a difficult challenge with all three houses all failing. House 1 results follow the same trends that have been seen in all of the previous criteria: far outperforming the other two houses (although it still exceeds the maximum value by over 300%) with the kitchen subjected to the highest level of overheating. 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.

Table 3: Results for TM52 criteria II and III for study year (ΔT is room temp. minus maximum adaptive temperature)

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

For TM52 Criteria III (Table 3) the highest values of ΔT are shown, with all rooms in House 1 passing 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 TM52 Criteria I and III and therefore passed Criterion 4.

6.1.4 Criterion 5

In House 1 indoor temperatures of all rooms were greater than the outside temperature for 60% of the year, apart from the kitchen which was 67%. Houses 2 and 3 performed badly in all rooms (hallway/bedroom 84%, kitchen 93% and bedroom 2 97%). These proportions are extremely high and would suggest a high level of thermal discomfort.

6.2 Performance Over Time

The variation of room temperature with time follows a similar diurnal cycle throughout the year for all cases (limited seasonal change). Figure 13 plots the temperatures of bedroom 1 (representative of all rooms) in all three houses over a hot five-day period. The large swings in ambient temperature are mimicked by the indoor room temperatures, with Houses 2 and 3 exhibiting almost identical results.

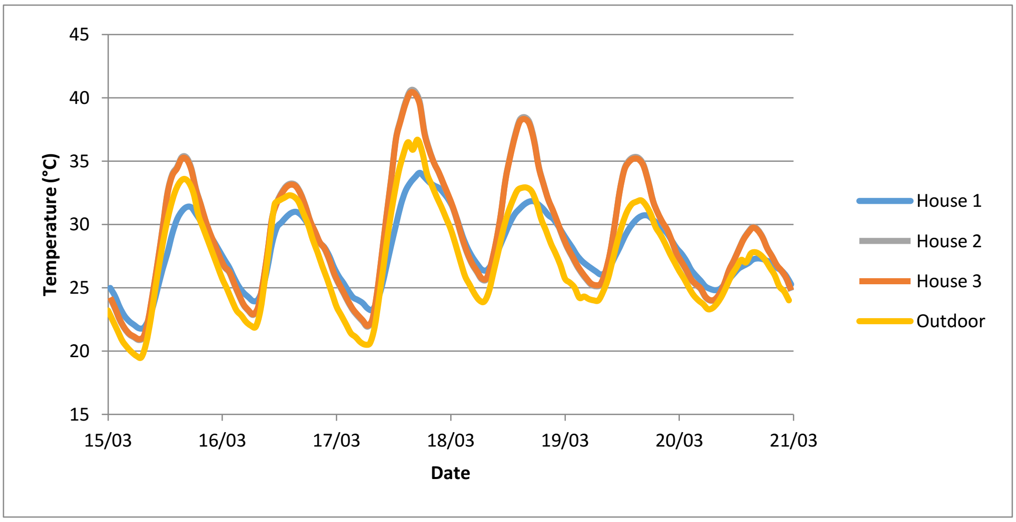

Figure 13: Comparison of indoor dry-resultant temperatures for bedroom 1 in Houses 1-3 and outdoor temperature over five day period 15/03 to 21/03

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.

A 'typical warm day' was used to analyse performance across a day. Results for bedroom 1 (Figure 14) show temperature moderation in House 1 and a small time lag between external and internal temperature rise. The performance of the kitchen in each house (Figure 15) 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.

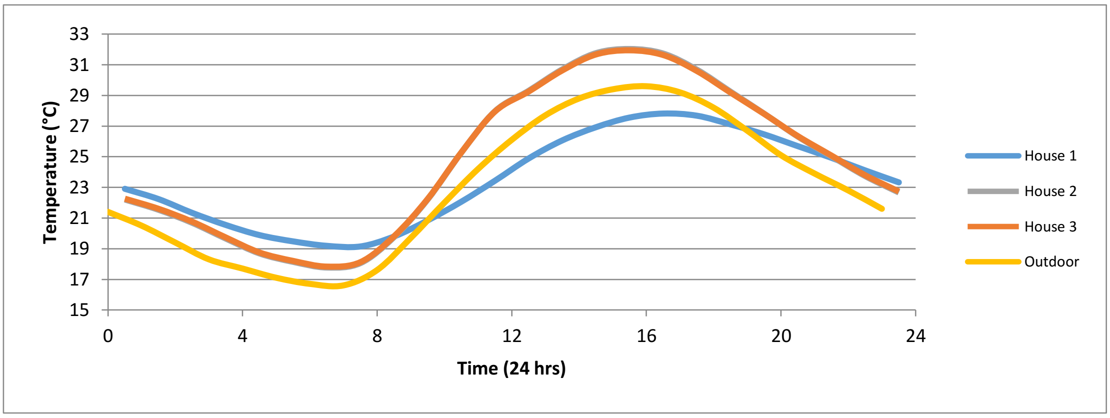

Figure 14: Comparison of performance in bedroom 1 on typical warm day (09/03)

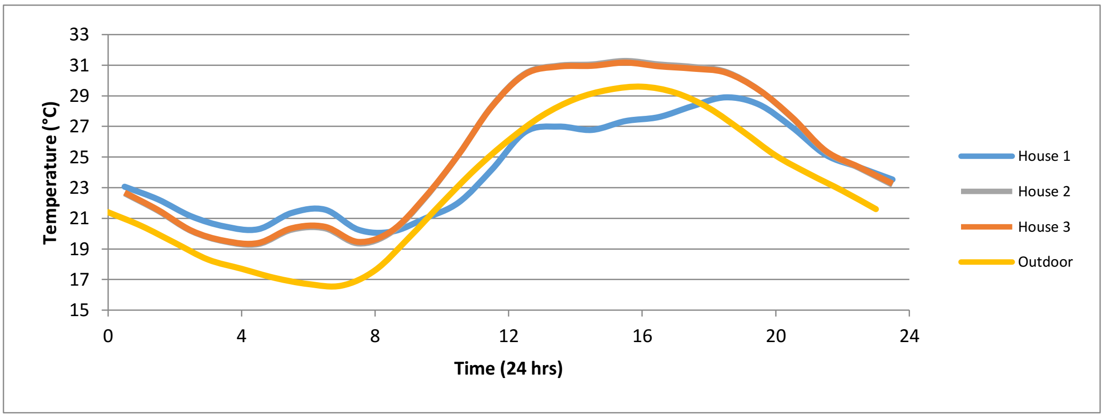

Figure 15: Comparison of performance in kitchen on typical warm day (09/03)

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 16. The temperatures for each room are denoted by colour with reference to the key. Figures 16(a-d) show that Houses 2 and 3 heat up faster than House 1, with a temperature difference of ~2℃.

At 10pm (Figure 16(e)) this temperature difference becomes negligible as all rooms in each house fall to 24℃. The outdoor temperature is 22℃ and there are no external gains. The temperatures in all houses continue falling (Figure 16(f)) and by 3am Houses 2 and 3 are cooler than House 1. The heating and cooling rates in House 1 are therefore lower than in House 2 and 3. House 1 is slower to overheat during the day (reducing daytime thermal discomfort) but on hotter nights House 1 will maintain higher temperatures than the other two houses. This may result in thermal discomfort during the earlier part of the night, at a point when occupants will be sleeping indoors.

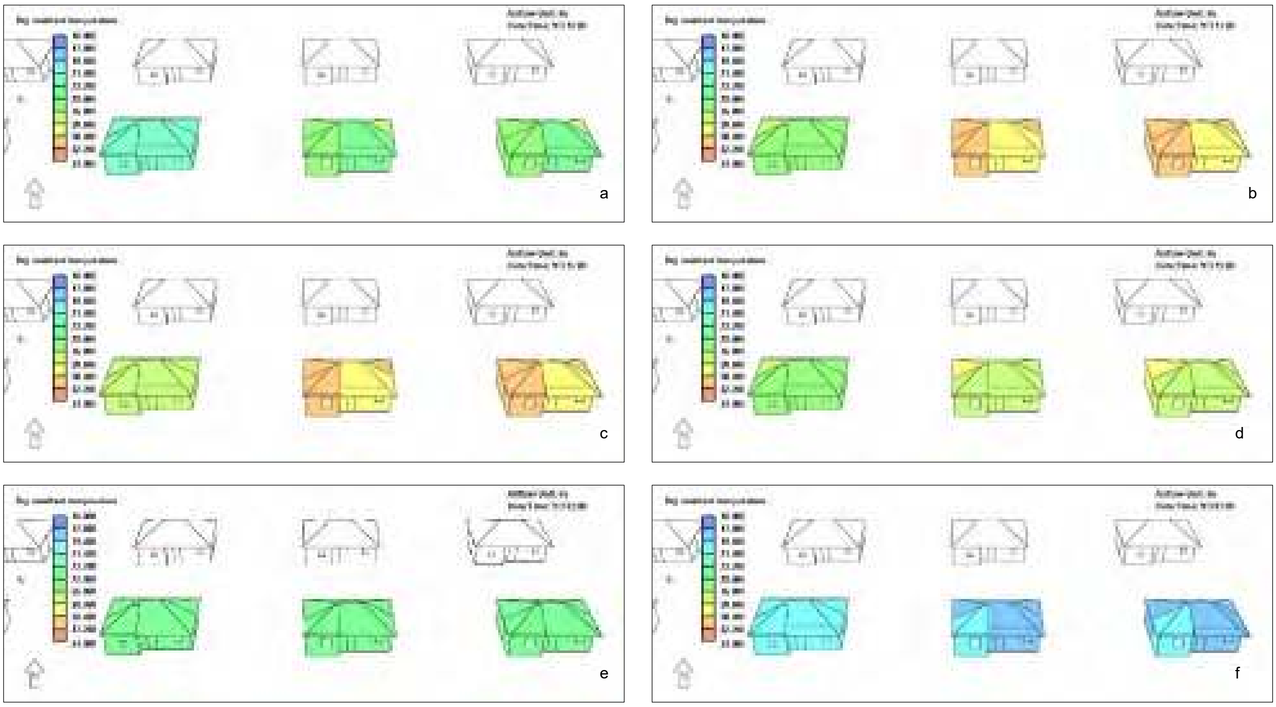

Figure 16(a-f): Room temperatures for Houses 1-3 (left to right) throughout a typical warm day. (a-f correspond to times 10am, 1pm, 4pm, 7pm, 10pm and 3am)

6.3 Summary of Observations

1. Across the entire year House 1 overheats and experiences uncomfortably low temperatures significantly less often than Houses 2 and 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 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 and 3 occurs most often in the kitchen and bedroom 1.
5. Overheating in Houses 2 and 3 occurs the least in the hallway/bedroom but the daily weighted exceedence is highest in bedroom 2.

6.4 Analysis of Key Areas

Observations 1-5 will be explained by further analysis of the house performances in the followings sections.

6.4.1 Roof

Conduction gain through the roof for the 'typical warm day' (Figure 17) shows that daytime conduction gains through House 2 and 3's roofs are far higher than House 1. The conduction gain increases from sunrise until it reaches a very high peak value of 2kW 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 negative gains indicate heat emission from the house. 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/m2K) allows a much higher heat flux through the roof than House 1's thatched roofing (U-value of just 0.54W/m2K). This results in higher heat transmission into the house when external temperatures and solar radiation are high and a high transmission of heat out of the house when internal temperatures are higher than external temperatures.

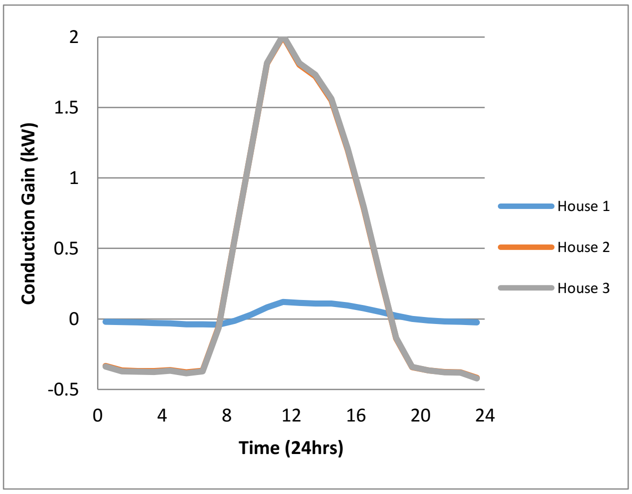

Figure 17: Roof conduction gains

These results explain the behaviour described in Observation 1, with iron roofing a key contributor to daytime overheating. 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.

6.4.2 Walls

The conduction gain through external walls is plotted for the hallway/bedroom on the 'typical warm day' (Figure 18), showing 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. The thick mud and pole walls in House 1 provide the greatest thermal storage capacity and the largest time lag for emission of heat energy (see ρCλ values in Table 4). This can be seen in Figure 18, 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. This timing is good for moderating internal temperatures and is a key factor in explaining the behaviour described in Observation 1. However, 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 during the early evening.

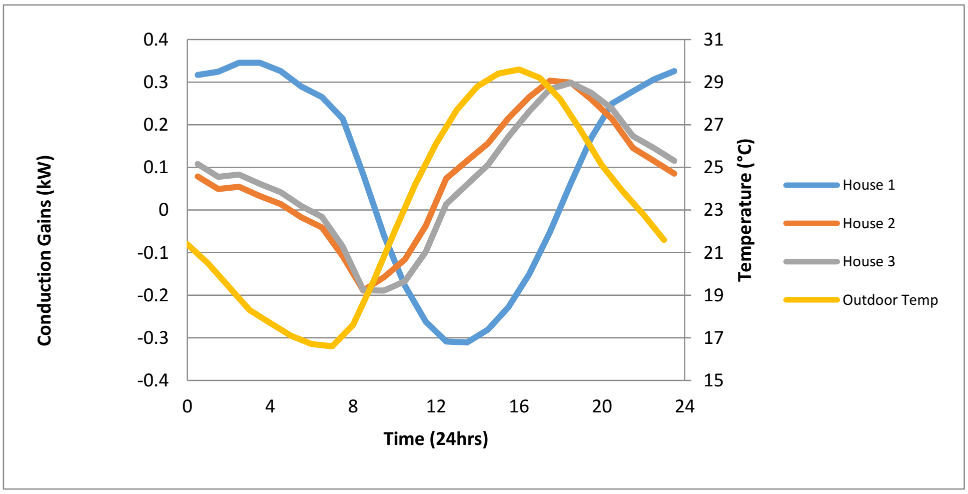

Figure 18: Wall conduction gains

Table 4: Values for wall material thermal storage capacity term ρCλ for Houses 1-3

Mud and Pole	Baked Bricks	Concrete Blocks
1411	1428	1100

The thermal storage of the baked brick and concrete walls of House 2 and 3 is considerably less effective at internal temperature regulation as their walls absorb heat during the night- time/early morning (when temperatures are lowest) and emit/conduct heat energy into the house from midday until 6am the next morning. This heat flux into the room occurs during the hottest period of the day and increases overheating in these two houses. The U-values of these external walls (see Table 2) are higher than mud-pole walls, resulting in a faster heat wave reaching the inside surface faster. This is an important factor for Observation 1.

Figure 18 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 is due to concrete having lower U-value than baked bricks (slower waves delay heat gains making House 3's graph the same as House 2's but shifted to the right). This slightly improved thermal moderation behaviour is a contributing factor for Observation 3 which states that House 3 has more moderate temperature swings than House 2.

6.4.3 External Ventilation and Infiltration

House 1's large roof overhang openings and gaps and cracks give it greater infiltration and external ventilation than Houses 2 and 3. Its higher airflow increases gains (peak value 1.2kW) during the daytime and negative gains (heat removal) during the night-time (Figure 19). 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.

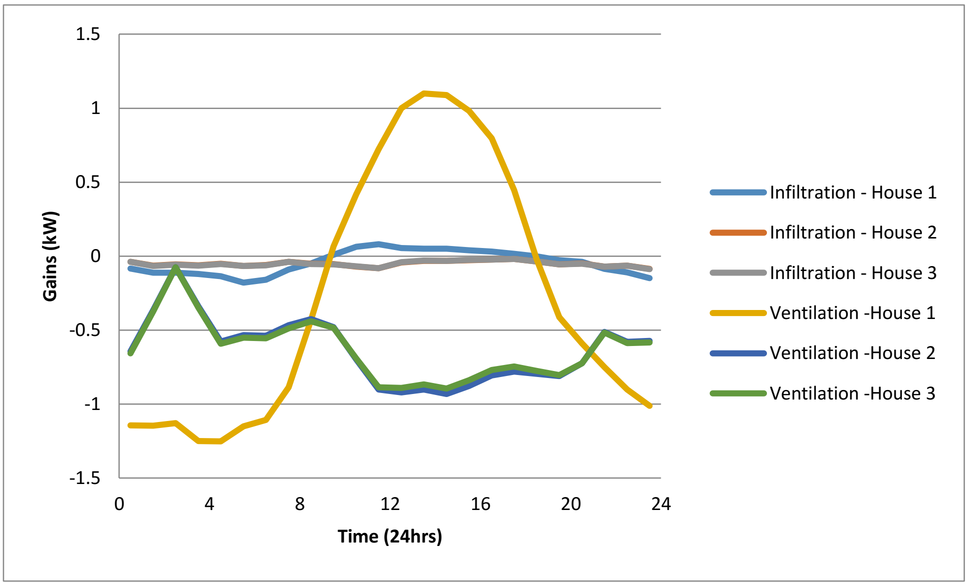

Figure 19: External ventilation and infiltration gain

Houses 2 and 3 exhibit similar results because they have the same openings and level of workmanship. Their 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 constant rejection of heat by ventilation in these two houses is beneficial for thermal comfort during hot days.

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 for cross-ventilation. 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.

6.4.4 Solar Gain

Table 5 shows the maximum gains, when they occur and the mean values for each room in Houses 1 and 2. The sun path for Tabora (computed in IES-VE) showed that the angle of the sun varies throughout the year affecting the solar gain at two periods of the year. North-facing rooms (bedroom 2 and kitchen) receive highest solar gains in June and the southern-facing rooms (bedroom 1 and hallway/bedroom) do so in December. The lower gains in House 1 are due to its smaller windows.

Table 5: Internal solar gains for Houses 1 and 2 across study year

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

Radiation flux reaches a maximum value of 1.3kW/m2 during the year. There will be relatively high absorption of this 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 (thatch has 0.6). There will be periods of very high external solar gain during the year, with House 1 absorbing the least through the roof. 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.

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 because of the position of the sun. 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. The direct east-west movement of the sun affects bedroom 2 for Houses 2 and 3 because, as an east-facing room, it is the first to heat up in the morning and then has its high indoor temperature sustained throughout the day 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.

The afternoon solar radiation falls more on the western side of the house, increasing the solar gains in the kitchen and bedroom 1 at the time of highest ambient temperature, resulting in these rooms overheating more often than others (Observation 4). 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 cooking gains (occupancy gains have minimal effect) have more of an effect on House 1 than the other two houses.

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 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, security and disease vectors), the key design principles which make them effective at providing thermal comfort should be considered and applied to improving modern house designs.

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