

Article

Climate Resilient Low-Income Tropical Housing

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Abstract: Located in East Africa, Uganda is one of the most economically deprived countries that is likely to be dramatically affected by climate change. Over 50% of Ugandan families live in single-roomed overcrowded properties and over 60% of the country's urban population live in slums. Moreover, the gradual shift towards relatively modern and low thermal resistance building materials, in addition to imminent thermal discomfort due to global warming, may considerably affect the health and wellbeing of low-income people, the majority of whom live in low quality homes with very little or no access to basic amenities. This paper evaluates the effects of various construction methods as well as refurbishment strategies on thermal comfort in low-income houses in Uganda. It is aimed at helping low-income populations adapt to climate changes by developing simple, effective and affordable refurbishment strategies that could easily be applied to existing buildings. Dynamic thermal simulations are conducted in EnergyPlus. The adaptive model defined in BS EN 15251 and CIBSE TM52 is used to evaluate the risk and extent of thermal discomfort. Roofing methods/materials are found to be the key factor in reducing/increasing the risk of overheating. According to the results, roof insulation, painting the roof with low solar absorptance materials and inclusion of false ceilings are, respectively, the most effective and practical refurbishment strategies in terms of improving thermal comfort in low-income houses in Uganda. All refurbishment strategies helped to pass Criterion 3 of CIBSE TM52, as an indicator of "future climate scenarios", making low-income houses/populations more climate resilient.

Keywords: thermal comfort; climate change; resilience; refurbishment; low-income; tropical; housing; Uganda; Africa

1. Introduction

Located in East Africa, Uganda occupies an area of 241,038 square kilometres [1] and has an estimated population of 39 million [2]. In 2014, Uganda was ranked 163 out of 188 countries on the Human Development Index (HDI) that "assesses human wellbeing from a broad perspective", including the "ability to achieve a decent standard of living, measured by gross national income per capita" [3]. Around 38% of Uganda's population live below the international income poverty line with a daily income of \$1.25 or less [3]. Moreover, around 60% of the country's urban population live in slums [4,5]; over 50% live in single-roomed properties [6] and only 18% have access to electricity. The situation is more critical in rural areas as only 8% of rural households have access to electricity [3] compared to 55% in urban areas [7]. The rural population accounts for around 85% of the total population in Uganda [8].

The climatic conditions in Uganda vary from hot arid climate in the north to tropical equatorial climate in the south. The local climatic conditions are greatly affected by the altitude and rainfall [9]. Overall, Uganda has a tropical climate moderated by an average altitude of 1100 m above sea level [10].

The mean annual rainfall in different parts of the country varies between 750 and 2000 mm [1,11], and the mean annual temperature varies between 16 °C and 30 °C [11] with the hottest periods between December and February [10].

Currently, the embodied energy of construction methods and materials is the key factor in evaluating the environmental impacts of low-income houses in Uganda [12,13]; however, global warming is expected to increase the average air temperature by 3–4 °C during the next 70 years [9], which may transform operational energy into a major issue in the near future. Moreover, the gradual replacement of sustainable materials, such as adobe and thatched roofs, with environmentally damaging low thermal resistance materials, such as concrete and iron sheet roofs, may deteriorate thermal comfort conditions leading to an increased use of air conditioning, more energy demand and increased CO₂ emissions of the housing sector, which, in turn, contribute to even more climate changes and their associated problems.

Defective design, poor workmanship and low quality construction methods/materials in addition to overcrowding and imminent thermal discomfort due to global warming may considerably affect the health and wellbeing of low-income people, the majority of whom live in substandard houses with limited or no access to basic amenities. Indeed, “climate-proofing” of existing infrastructure is the major strategy of many developing countries in response to the increasing risks posed by climate changes. However, due to limited resources, climate adaptation in the poorest countries is left to individuals as a matter of “self-help” [14]. This situation puts low-income populations in an even more vulnerable position, as they generally have less access to resources to adapt to climate changes.

To this end, this paper intends to evaluate the effects of various construction methods and materials on the risk and extent of thermal discomfort in low-income naturally ventilated houses in Uganda (Figure 1). The ultimate aim is to help low-income populations adapt to climate changes, making them more climate resilient by developing simple, effective and affordable refurbishment strategies to improve thermal comfort and reduce the risk of overheating in their homes. This document is an extended version of a conference paper on thermal comfort conditions in Uganda [15].



Figure 1. Low-income housing and slums.

Housing Conditions and Construction Methods

Detached houses (58%) followed by huts (21.5%) and tenements (18.4%) are the most common housing types in Uganda [16]. Overcrowding is a major issue in Uganda, particularly in the low-income housing sector. The average number of people sleeping in one room in over 50% of Ugandan households is four or more [15]. The low construction quality along with limited access to good quality materials are some of the other major problems of the Ugandan housing industry. Table 1 summarises the most common construction methods and materials used in housing projects in Uganda.

Table 1. Construction methods and materials in Uganda (%) [16].

Building Component	Material	Rural	Urban	Uganda
Roof	Iron sheet	56.7	84.1	61.8
	Thatch	42.6	12	36.9
	Other	0.7	4	1.3
	Total *	100	100	100
Wall	Brick	50.9	83.9	57.1
	Mud and Poles	45.7	12.4	39.4
	Other	3.4	3.8	3.5
	Total *	100	100	100
Floor	Earth/Soil	82.1	25.2	71.4
	Cement/Concrete	16.9	70.8	27
	Other	1	4	1.5
	Total *	100	100	100

* There may be 0.1% discrepancies.

Around 62% of homes in Uganda are covered with iron sheets (Figure 2) and 37% have thatched roofs. Brick walling is the most common walling material (57%) followed by mud and poles (39%). With a share of over 70%, cement/concerc flooring is the most common flooring method/material in urban areas of the country [6,16]. The available data indicate that there is a growing shift away from traditional materials (such as adobe and thatch) towards relatively modern methods and materials (such as bricks and iron sheets) [12,13].



Figure 2. A low-income house with clay walls and an iron sheet roof.

2. Research Methodology

Dynamic thermal simulations are conducted in EnergyPlus to evaluate the effects of various construction materials and refurbishment strategies on thermal comfort in low-income houses. The study is divided into two sections as follows:

- A Section A: Prevailing roofing systems (*i.e.*, iron sheet and thatched) are simulated in combination with the common walling materials (*i.e.*, adobe, burned/fired bricks, stabilised soil blocks, solid concrete blocks and hollow concrete blocks) for a fixed wall thickness of 200 mm. Ten combination scenarios are therefore simulated in total (five walling materials and two roofing systems). The most critical factors on thermal comfort are identified in the first section as the basis for refurbishment strategies investigated in Section B of this study.
- B Section B: Refurbishment strategies are investigated for the most common construction methods in low-income houses in Uganda. The aim is to develop relatively simple and effective refurbishment strategies for low-income people to improve the conditions. The following refurbishment

strategies are considered for improving thermal performance of the most critical building elements identified in Section A of the study:

- Inclusion of false ceiling
- Insulated ceiling (50 mm insulation): “cold roof”
- Insulated roof (50 mm insulation): “warm roof”
- Painted roof: white painted roof with low solar absorptance
- Double skin roofing: an additional layer of iron sheet spaced 100 mm above the existing roof

The tested scenarios in sections A and B are summarised in Table 2. The materials’ properties were defined based on the available information in CIBSE Guide A [17,18] (Table 3).

Table 2. Tested scenarios for prevailing methods of construction and refurbishment strategies.

Tested Scenarios	
Current Conditions	Refurbishment Strategies
Adobe & Iron Sheet/Thatched Roof	Insulated iron sheet roof (warm roof)
Brick & Iron Sheet/Thatched Roof	Painted iron sheet roof
Hollow Concrete Blocks & Iron Sheet/Thatched Roof	Iron sheet roof with ceiling
Solid Concrete Blocks & Iron Sheet/Thatched Roof	Iron sheet roof with insulated ceiling (cold roof)
Stabilised Soil Blocks & Iron Sheet/Thatched Roof	Double skin iron sheet roof

Table 3. Material properties used in the simulations.

Material	Thermal Conductivity (W/m·K)	Thickness (m)	Density (Kg/m ³)
Adobe	0.60	0.200	1450
Brick	1.00	0.200	1900
Hollow Concrete Block	0.86	0.200	875
Solid Concrete Block	1.31	0.200	2240
Stabilised Soil Block	1.10	0.200	1950
Iron sheet roof (0.7 solar absorptance value)	37.00	0.003 *	7800
White iron sheet roof (0.2 solar absorptance value)	37.00	0.003 *	7800
Thatched roof	0.07	0.150	240
Concrete floor	1.31	0.100	2240
Insulation	0.04	0.050	240
Plasterboard	0.20	0.012	850
Glass	0.90	0.006	-
Window frame	5.00	0.050	-

* Limiting thickness of materials according to EnergyPlus.

The initial simulations on the effects of flooring on thermal comfort revealed that refurbishment strategies would either deteriorate or very marginally improve thermal comfort conditions. Flooring refurbishment strategies were therefore excluded from this study.

A 3 m × 3 m × 3 m single-roomed property with four occupants was modelled as the representative of low-income housing in urban areas of Uganda, according to the statistical information described above. A 2 m × 1 m door and a 1 m × 1 m single glazed window with effective opening areas of 80% were also considered. For the refurbishment scenarios, where a ceiling was considered, the height of the ceiling was specified as 2.5 m above the finished floor level. The areas below and above the ceiling were modelled as separate zones to increase the accuracy of the simulations. A similar strategy (2 Zones) was also considered for the double-skin roofing, explained above.

The occupancy pattern was defined as fully occupied (four occupants) from 6 p.m. to 8 a.m. and one occupant from 8 a.m. to 6 p.m. An internal heat gain of 100 W and 70 W per person was assumed for seated and sleeping occupants, respectively. The occupants’ behaviours in terms of opening and

closing the windows and doors were also defined as: windows open 6:30 a.m.–6:30 p.m.; doors open 7 a.m.–8 p.m. [19]. Considering there are not any available weather data for dynamic simulations in Uganda, Kisumu in Kenya was used as the closest city to Kampala. Similar to Kampala, Kisumu is located on the shore of Lake Victoria and its altitude is almost the same as Kampala.

Adaptive model Category II (normal expectation for new buildings and renovations), defined in BS EN 15251 [20] along with the flowing overheating criteria, defined in CIBSE TM52 [21], are used to evaluate the risk of thermal discomfort (Table 4).

Table 4. Overheating assessment criteria.

	Assessment Criteria *	Acceptable Deviation
Criterion 1	Percentage of occupied hours during which ΔT ($\Delta T = T_{op} - T_{max}$ rounded to the nearest whole degree) is greater than or equal to 1 °C	Up to 3% of occupied hours
Criterion 2	“Daily weighted exceedance” (W_e) in any one day >6 °C·h (degree hours)	0 day
Criterion 3	Maximum temperature level (T_{upp}) $\Delta T > 4$ °C	0 h

* Refer to Abbreviations for more information.

3. Results of Simulations

Simulations are divided into two sections of A and B. The first section evaluates the current conditions in terms of thermal comfort in low-income houses built with different construction methods/materials. The second section assesses the effects of refurbishment strategies on thermal comfort conditions.

3.1. Section A: Thermal Comfort Conditions for Prevailing Methods of Construction

3.1.1. Adobe Walls with Iron Sheet/Thatched Roof

Adobe walls with an iron sheet roof failed all three thermal comfort criteria. According to the results, for Criterion 1, ΔT was over 1 °C for over 8% of occupied periods, which is considerably higher than the 3% acceptable level. The building also failed Criterion 2 as W_e (the daily weighted exceedance) exceeded the limit of six degree-hours for 65 days, which is around 18% of occupied days. The results also revealed that ΔT exceeded the “upper limit temperature” (T_{upp}) for six hours. The situation improved significantly for adobe walls with a thatched roof. The building passed the first and second criteria, but it marginally failed the second Criterion by three days. Overall, the building was considerably more comfortable when the iron sheet roof was replaced with the thatched roof.

3.1.2. Brick Walls with Iron Sheet/Thatched Roof

Brick walls had similar performances to adobe walls; however, compared to adobe walls, brick walls performed slightly better with an iron sheet roof and slightly worse with a thatched roof. Similar to the above scenario, brick walls with iron sheet roof failed all three thermal comfort criteria. According to the results, the operative temperature in the building was in nearly 8% of occupied periods above the acceptable levels. The building also failed Criterion 2, as W_e was above the limit for 56 days. There were also two incidents during which ΔT exceeded the upper limit temperature. The conditions improved for brick walls with thatched roof. Although the building failed Criterion 2 by five days, it passed Criterion 1 and Criterion 3 meaning that the buildings were overall thermally comfortable.

3.1.3. Hollow Concrete Block Walls with Iron Sheet/Thatched Roof

Hollow concrete blocks had an extremely poor performance despite their lower thermal conductivity (0.86 W/m·K) compared to bricks (1 W/m·K). Indeed, hollow concrete block walls

failed the requirements regardless of roofing materials. The risk of overheating and thermal discomfort was, however, considerably higher for the iron sheet roof. According to the results, for the iron sheet roof, the building was thermally uncomfortable for 13.7% of occupied periods. Moreover, W_e was above the acceptable limit for 148 days (41% of the entire year) with the maximum value of 35 °C·h (degree-hours) on the 24th of January. There were 39 incidents during which ΔT exceeded the upper limit temperature (T_{upp}), which means that the building also failed Criterion 3. Replacing iron sheets with thatch helped to pass Criterion 3, although the building still failed Criterion 1 and Criterion 2.

3.1.4. Solid Concrete Block Walls with Iron Sheet/Thatched Roof

Solid concrete block walls performed slightly better than brick and adobe walls with an iron sheet roof and slightly worse than adobe walls with a thatched roof. For the iron sheet roof, Criterion 1 was not met as ΔT exceeded 1 °C for around 7% of occupied periods. W_e also was over the acceptable limit of six degree hours for 45 days or 12% of occupied days. As for Criterion 3, ΔT exceeded the 4 °C limit in two hours/incidents. Thatched roof construction improved thermal comfort conditions as the building passed Criteria 1 and 3, although it still failed Criterion 2 by five days.

3.1.5. Stabilised Soil Block Walls with Iron Sheet/Thatched Roof

Stabilised soil blocks had a comparable performance to all other walls except hollow concrete block walls. Similar to all other walling methods/materials, covering the roof with iron sheets deteriorated the conditions. According to the results, the building was thermally uncomfortable for 7.5% of occupied periods and therefore failed Criterion 1. Stabilised soil block walls with iron sheets also failed Criterion 2 and Criterion 3 as W_e exceeded the acceptable limit for 49 days and ΔT was over the 4 °C limit in two incidents. For the thatched roof construction, Criteria 1, 2 and 3 were reduced to 0.8%, five days and 0 incidents, respectively. Therefore, the building passed thermal comfort criteria with a thatched roof but failed the requirements with an iron sheet roof.

3.1.6. Section A: Summary of the Findings

Figure 3 compares the performance of the tested scenarios over a hot summer week during the 24th to 31st of January. According to the results, the most critical factor affecting occupants' thermal comfort in the studied scenarios is the roof construction method/material. Apart from hollow concrete blocks, all walling methods with thatched roofs passed the thermal comfort requirements (passed at least two criteria out of three). For iron sheet roofing, buildings failed all three thermal comfort criteria regardless of walling method/material.

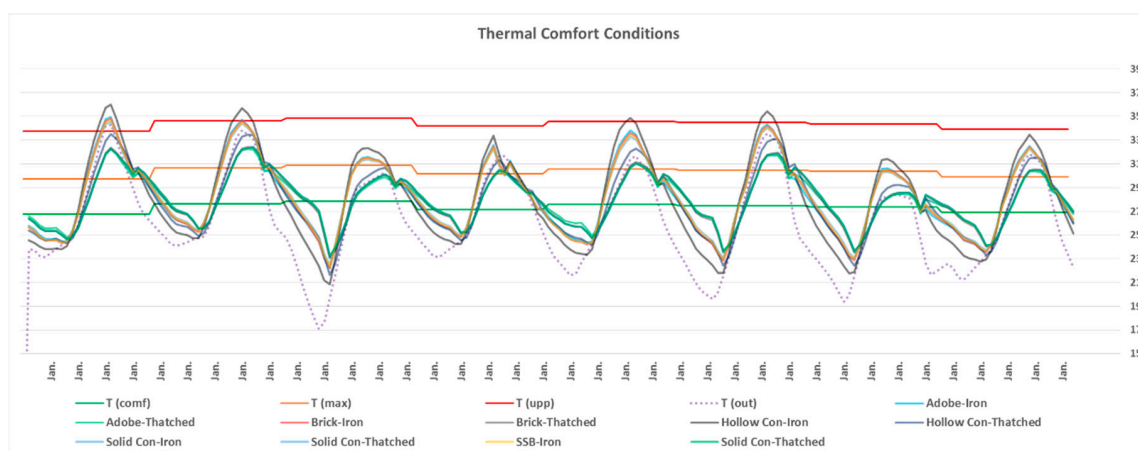


Figure 3. Thermal comfort conditions for tested construction methods during a hot summer week in January.

Overall, the results of Section A reveal that the best conditions in terms of thermal comfort were achieved for adobe walls with a thatched roof and the worst conditions occurred for hollow concrete walls with an iron sheet roof, which dramatically failed all TM52 thermal comfort criteria. A possible explanation for the poor performance of hollow concrete blocks is the lower thermal mass of the blocks compared to other tested materials. High thermal mass acts as a buffer reducing sharp temperature fluctuations in buildings. Unlike the other walling materials, the low thermal mass of hollow concrete blocks resulted in relatively sharp indoor temperature swings and thermal discomfort. Indeed, the operative temperature for hollow concrete walls significantly exceeded the maximum comfortable temperature (T_{\max}) during the day (Figure 3). Moreover, during hot summer days, the operative temperature was occasionally above the absolute maximum temperature level (T_{upp}) meaning extreme thermal discomfort (Figures 3 and 4). Figure 4 compares the performance of the best and worst performing methods over the entire year.

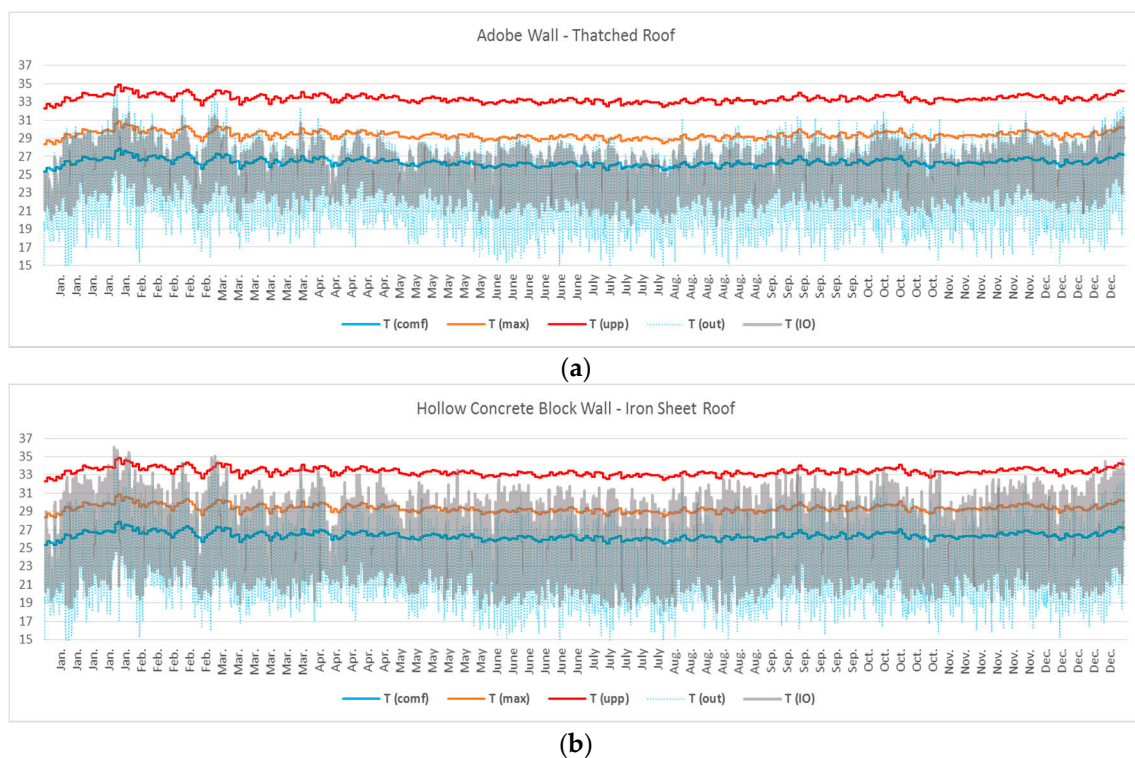


Figure 4. The best (a) Adobe Walls and Thatched Roof; and the worst (b) Hollow Concrete Walls and Iron Sheet Roof conditions in terms of thermal comfort.

3.2. Section B: Refurbishment Strategies

The aim of Section B is to identify simple and effective refurbishment strategies to improve thermal comfort conditions in the existing naturally ventilated low-income houses in Kampala. Although, according to the results of Section A, hollow concrete block walls with an iron sheet roof had the worst performance, all other walling materials combined with iron sheet roofing resulted in critical conditions and failed to provide acceptable thermal comfort conditions. Considering the share of brick walling (57%) and iron sheet roofs (62%) in Uganda [16], arguably the majority of low-income houses in Uganda are made from brick walls and iron sheet roofs (Figure 5). The refurbishment strategies are therefore investigated for brick walls and iron sheet roofs as the most common method of construction in Uganda.



Figure 5. Brick walling and iron sheet roofing is the prevailing construction method in Uganda.

It should be noted that, to avoid complexity and potential high costs, only simple refurbishment strategies are being investigated; however, obviously a combination of the following strategies could further enhance the thermal comfort conditions. The results of simulations for the following refurbishment strategies are explained in this section:

- Inclusion of plasterboard ceiling (12 mm)
- Insulated ceiling (50 mm insulation; 12 mm plasterboard): cold roof
- Insulated roof (50 mm insulation): warm roof
- Painted roof: white painted roof with low solar absorptance
- Double skin roofing: an additional layer of iron sheet spaced 100 mm above the existing roof

Figure 6 shows the thermal performance of brick walls with iron sheet roofing (explained in Section A) as the base case for comparison in Section B.

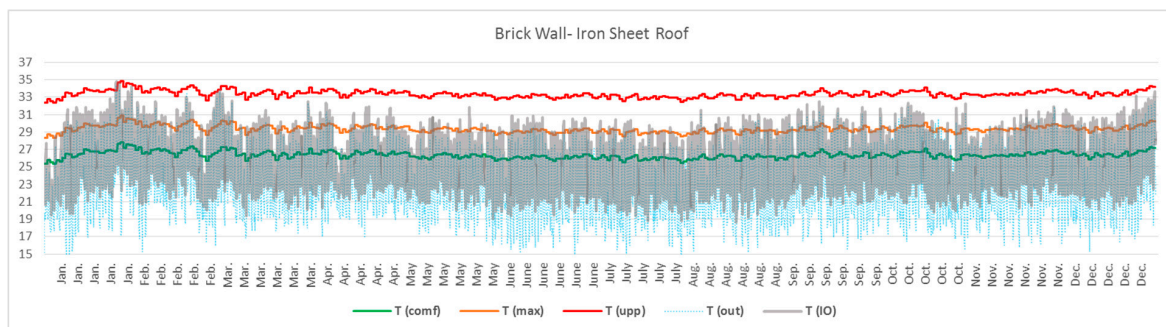


Figure 6. Thermal comfort condition for the base case (Brick Walls & Iron Sheet Roof).

3.2.1. Brick Walls with Iron Sheet Roof and Plasterboard Ceiling

Inclusion of false ceiling significantly improved the conditions and helped to pass two out of the three thermal comfort criteria. The indoor operative temperature was for 2.57% of occupied periods by 1 K or more above the limiting maximum acceptable temperature, meaning that it passed the first Criterion. The building, however, failed Criterion 2, as W_e exceeded the limiting six degree hours for ten days (2.7% of occupied periods). As for Criterion 3 (ΔT exceeding 4 K), there were zero hours during which ΔT exceeded the “upper limit temperature” (T_{upp}). Overall, the building proved to be more thermally comfortable compared to the base case (brick walls and iron sheet roof). Figure 7 shows thermal comfort conditions during the entire year for brick walls with iron sheet roof and plasterboard ceiling.

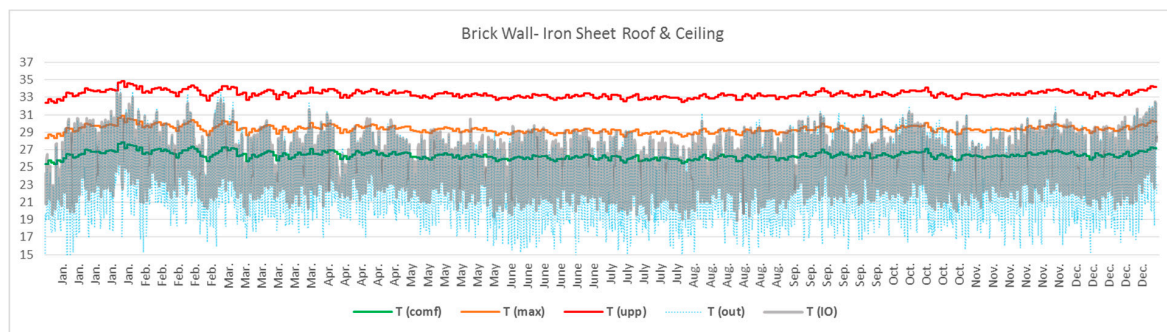


Figure 7. Thermal comfort condition for brick walls with iron sheet roof and plasterboard ceiling.

3.2.2. Brick Walls with Iron Sheet Roof and Insulated Ceiling

As expected, including 50 mm of insulation above the ceiling further improved the conditions, although the improvement was marginal. The results of simulations revealed that brick walls with iron sheet roof and insulated ceiling passed Criterion 1 and 3, but, similar to the above, failed Criterion 2 with seven days exceeding the acceptable conditions. The indoor operative temperature was for 1.02% of occupied periods by 1 K or more above the limiting maximum acceptable temperature; however, ΔT never exceeded the maximum temperature by more than 4 K. Figure 8 shows the results of simulations for brick walls with iron sheet roof and insulated ceiling construction.

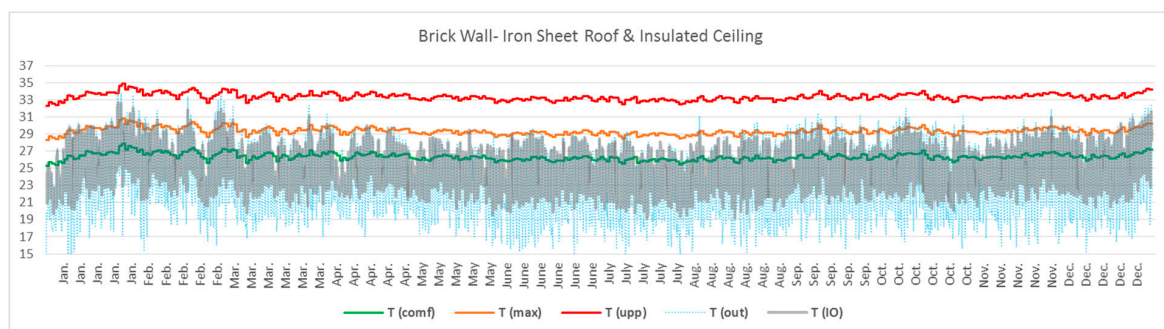


Figure 8. Thermal comfort condition for brick walls with iron sheet roof and insulated ceiling.

3.2.3. Brick Walls with Insulated Iron Sheet Roof

Roof insulation also improved the conditions. Both insulated ceiling and insulated roof achieved almost the same results. According to the results, for insulated iron sheet roof, the building was thermally uncomfortable for 0.97% of occupied periods, and W_e exceeded the acceptable limit for seven days. The building passed Criterion 3 as ΔT never exceeded the upper limit temperature (T_{upp}). Figure 9 illustrates the results of simulations for brick walls with an insulated iron sheet roof.

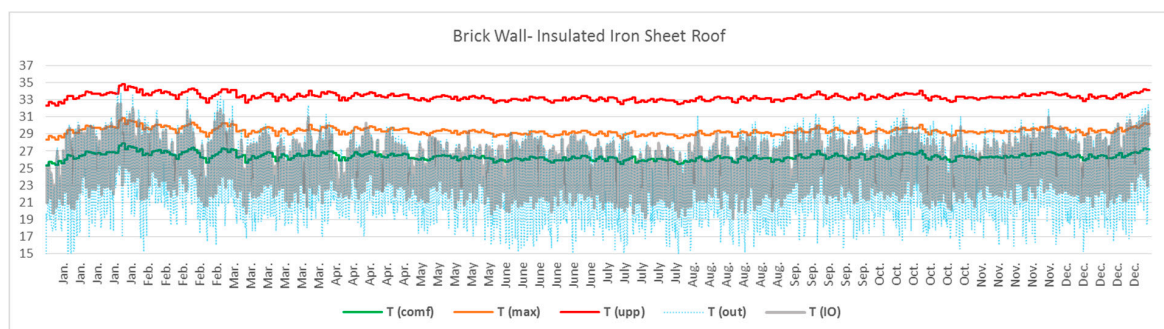


Figure 9. Thermal comfort condition for brick walls with insulated iron sheet roof.

3.2.4. Brick Walls and White Painted Iron Sheet Roof

White iron sheet roof, with low solar absorptance of 0.2, achieved a considerably good performance in terms of thermal comfort compared to other refurbishment strategies. According to the results, the thermal performance of the painted iron sheet roof was significantly better than the base case with an ordinary iron sheet roof. However, similar to other refurbishment methods, white iron sheet roof failed Criterion 2 of TM52 comfort criteria. The results indicate that the building was thermally uncomfortable only for 1.11% of occupied periods, and W_e exceeded the acceptable limit for six days. Moreover, similar to other refurbishment strategies, ΔT never exceeded the 4 °C limit. Figure 10 shows the results of simulations for brick walls with painted iron sheet roof.

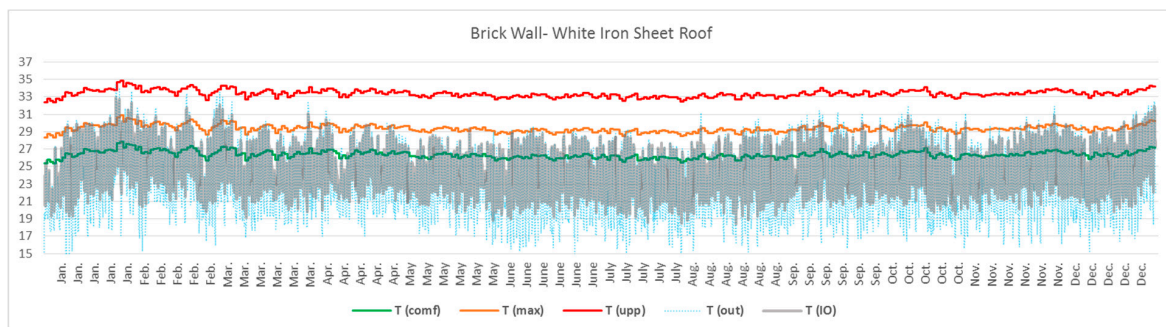


Figure 10. Thermal comfort condition for brick walls with painted iron sheet roof.

3.2.5. Brick Walls and Double-Skin Iron Sheet Roof

An additional layer of iron sheet above the existing roof (double-skin iron sheet roofing) achieved similar performance to the false plasterboard ceiling, explained above. For the double-skin roof, the building was found to be for 2.37% of occupied periods uncomfortable (Criterion 1). W_e was also above the acceptable limit for nine days (Criterion 2). As for Criterion 3, ΔT did not exceed the limiting temperature. Overall, similar to all other refurbishment strategies, double skin roofing passed the thermal comfort requirements, as it failed in only one Criterion out of three. Figure 11 illustrates the thermal comfort conditions for a double-skin iron sheet roof.

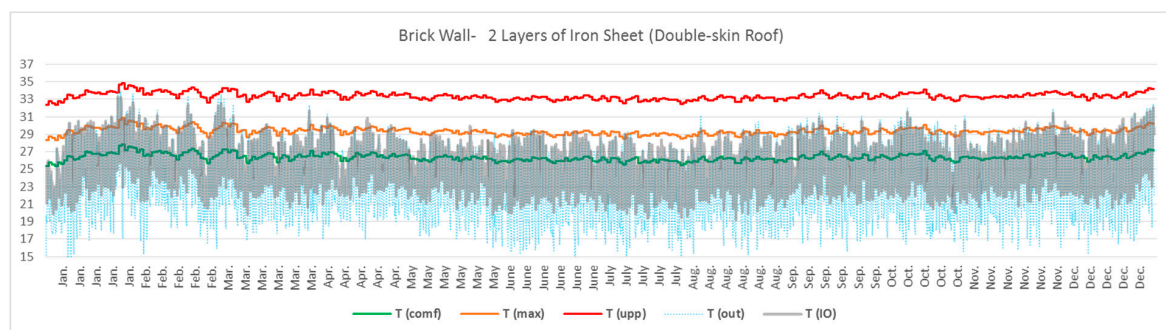


Figure 11. Thermal comfort condition for double-skin iron sheet roof.

4. Discussion

According to the results of this study, average indoor operative temperatures of 26 °C and 29 °C are, respectively, the ideal comfortable and maximum acceptable indoor temperature in naturally ventilated buildings in Kampala. However, a maximum indoor temperature of up to 31 °C was also found to be acceptable in hotter months of the year. It should be noted that the comfortable temperature does not fluctuate dramatically throughout the year thanks to the consistent tropical

weather conditions in Kampala. Therefore, arguably, an average indoor operative temperature of 26 °C can be used as the comfortable temperature for thermal comfort evaluations in Kampala.

Table 5 summarises the results of the simulations in Section A where the current conditions were studied. According to the results, only four out of 10 construction methods passed TM52 thermal comfort criteria. Iron sheet roofing failed the requirements regardless of walling method. The results reveal that the most critical factor affecting occupants' thermal comfort in low-rise naturally ventilated low-income homes in Kampala is the roof construction method/material.

Table 5. Summary of thermal comfort conditions for prevailing construction methods/materials.

TM52 Criteria Construction Method	Criterion 1 *	Criterion 2 *	Criterion 3 *	Overall Pass/Fail
Adobe & Iron Sheet Roof	8.41%	65	6	Fail
Adobe & Thatched Roof	0.57%	3	0	Pass
Brick & Iron Sheet Roof	7.96%	56	2	Fail
Brick & Thatched Roof	0.84%	5	0	Pass
Hollow Concrete Blocks & Iron Sheet Roof	13.69%	148	39	Fail
Hollow Concrete Blocks & Thatched Roof	3.24%	15	0	Fail
Solid Concrete Blocks & Iron Sheet Roof	7.02%	45	2	Fail
Solid Concrete Blocks & Thatched Roof	0.75%	5	0	Pass
Stabilised Soil Blocks & Iron Sheet Roof	7.51%	49	2	Fail
Stabilised Soil Blocks & Thatched Roof	0.83%	5	0	Pass

* Refer to Table 4 for more information.

Figure 12 shows the sun path diagram in Kampala. According to the figure, the sun falls on south facing walls during December and on north facing walls during June. Higher solar transmittance is therefore expected during the hottest periods of the year from south facing windows. Table 6 confirms this finding. According to Table 6, transmitted solar radiation through the window in January and December is over 100% more than the periods between March and September. However, due to the relatively small size of the window in this study, transmitted solar radiation through the window is not a major issue. Solar transmittance could, however, become a major issue for large windows/openings in Kampala.

Table 6. Monthly average transmitted solar radiation rate through the window (W).

Month	Transmitted Solar Radiation
January	93.2
February	69.5
March	44.3
April	41.2
May	40.1
June	39.4
July	40.4
August	41.3
September	41.8
October	56.2
November	78.8
December	98.3

Moreover, according to Figure 12, the sun has a very high altitude during the entire year, which indicates considerably higher solar heat gain through the roof compared to other building elements. This is supported by Figure 13, which shows the average monthly and annual solar radiation rates per area for the walls and roofs.

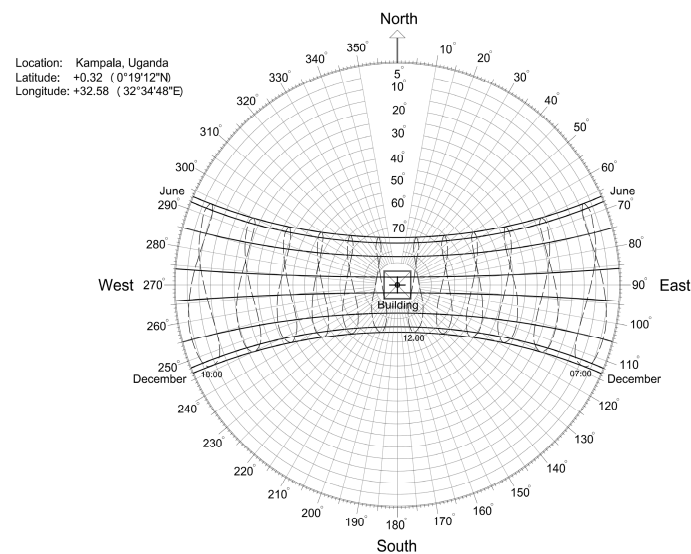


Figure 12. Sun path diagram for Kampala.

According to Figure 13, the average annual heat gain of the roof is over 2.6 times higher than other elements of the buildings. The average monthly heat gain from the roof has, in some cases (e.g., during February), been over four times more than from the walls. This supports the findings of Section A, which highlighted the roof as the key element affecting thermal comfort in Kampala.

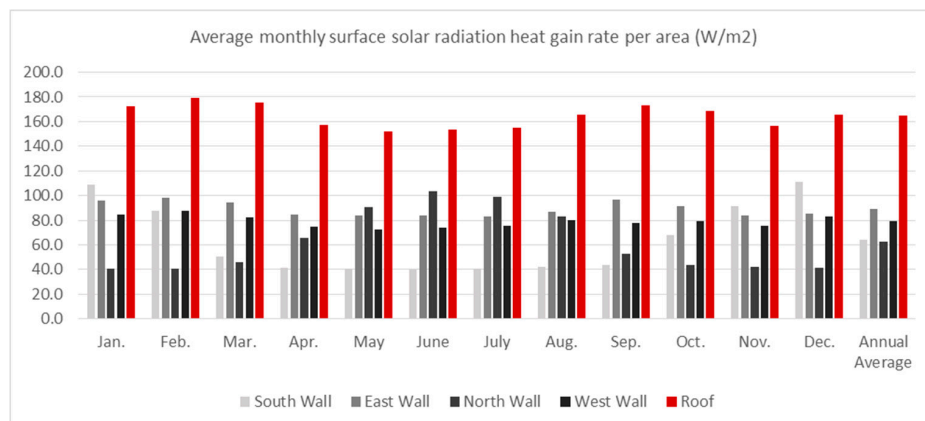


Figure 13. Average monthly and annual surface solar radiation heat gain rate per area (W/m^2).

Table 7 summarises the results of simulations for the refurbishment strategies in comparison to the base case (brick wall–iron sheet roof). According to the results, considering any of the refurbishment strategies would significantly improve thermal comfort conditions. In fact, all refurbishment strategies passed TM52 thermal comfort criteria; however, some performed better than others. The results reveal that the insulated roof is the most effective method that can be considered to improve thermal comfort conditions in low-income houses. The results also reveal that insulated roof, insulated ceiling and painted roof had almost identical performance. However, it should be noted that painted roofs may require regular maintenance to keep them clean and free of dirt. This is because built-up dirt will considerably increase absorptivity [17] and deteriorate the performance of the roof. According to the results, although there have been significant improvements of over 560%, reducing the risk of overheating compared to the base case (for Criterion 2), all refurbishment strategies failed Criterion 2, which indicates the severity of overheating within a day as a function of temperature rise and its duration [21]. Although this could be a concern in the context of low-income housing in

Uganda, considering significant improvements and given the fact that Criterion 3 (as the indication of extreme overheating beyond which “normal adaptive actions will be insufficient to restore personal comfort” [21]) has been met in all cases, such concerns are arguably negligible. Moreover, according to CIBSE TM52, Criterion 3 could also be considered as an indicator of “hot weather conditions and future climate scenarios”. Therefore, all refurbishment strategies would help low-income populations become more climate resilient with respect to global warming during the next 70 years.

Table 7. Summary of thermal comfort conditions for refurbishment strategies.

TM52 Criteria Construction Method	Criterion 1 *	Criterion 2 *	Criterion 3 *	Pass/Fail
Brick wall–Iron sheet roof (Base case)	7.96%	56	2	Fail
Brick wall–Insulated iron sheet roof	0.97%	7	0	Pass
Brick wall–Painted iron sheet roof	1.11%	6	0	Pass
Brick wall–Iron sheet roof with ceiling	2.57%	10	0	Pass
Brick wall–Iron sheet roof with insulated ceiling	1.02%	7	0	Pass
Brick wall–Double skin iron sheet roof	2.37%	9	0	Pass

* Refer to Table 4 for more information.

A sensitivity analysis was carried out to investigate the effects of various thermal insulation thickness on the performance of the roof and ceiling. Table 8 shows the results of simulations for two additional thicknesses of 15 mm and 25 mm. According to the results, reducing insulation thickness to 15 mm deteriorated the conditions for Criterion 1, increasing the risk of thermal discomfort (frequency of overheating) by around 78% and 54% for insulated roof and insulated ceiling, respectively; however, Criterion 1 remained below the acceptable level of 3%. The reduced thickness, however, did not greatly affect Criterion 2 and Criterion 3, and all tested scenarios passed thermal comfort requirements (Table 8). A thinner thermal insulation could therefore be considered to reduce the costs of refurbishment for low-income populations.

Table 8. Sensitivity analysis for two additional thermal insulation thicknesses.

TM52 Criteria Construction Method	Criterion 1 *	Criterion 2 *	Criterion 3 *	Pass/Fail
Insulated iron sheet roof 50 mm	0.97%	7	0	Pass
Insulated iron sheet roof 25 mm	1.18%	7	0	Pass
Insulated iron sheet roof 15 mm	1.73%	8	0	Pass
Iron sheet roof with insulated ceiling 50 mm	1.02%	7	0	Pass
Iron sheet roof with insulated ceiling 25 mm	1.24%	8	0	Pass
Iron sheet roof with insulated ceiling 15 mm	1.57%	7	0	Pass

* Refer to Table 4 for more information.

Double skin roofing and false ceilings also significantly improved the thermal comfort conditions. Although less effective than paints with low solar absorptance, it could be argued that inclusion of false ceiling and/or double-skin roofing would probably be more practical in the long-term, as these options require less maintenance compared to painted roofs. Indeed, one of the major reasons for moving away from thatched roofs in Uganda is their high maintenance requirements compared to iron sheet roofs. Moreover, although insulated ceilings and roofs improved thermal comfort conditions, considering affordability issues and limited access of low-income populations to such materials, insulation should be considered as the next priority and only if financially viable. Obviously, a combination of the above refurbishment strategies would further improve thermal comfort conditions, although the feasibility of such strategies for low-income people with a daily income of \$1.25 [3] is open to serious questions.

5. Conclusions

This paper evaluated the effects of various construction methods on thermal comfort in low-income houses in Uganda. Dynamic thermal simulations (DTS) were conducted with EnergyPlus

to evaluate the risk and extent of overheating in single storey naturally ventilated houses. According to the results, roofing methods/materials greatly affected thermal comfort conditions in the studied buildings. The risk of overheating and thermal discomfort in buildings with iron sheet roofs was up to 15 times higher than in buildings with thatched roofs. Walling methods/materials were found to be less critical compared to the roofs; however, some materials such as hollow-concrete blocks significantly deteriorated thermal comfort conditions. Overall, low thermal conductivity and solar absorptance of roofs followed by a high thermal mass of walls were found to be the key factors in reducing the risks of overheating and thermal discomfort in low-income free-running houses in the tropical climate of Kampala.

Refurbishment strategies were also investigated using DTS. All refurbishment strategies considerably improved the conditions; however, insulated roofs and ceilings followed by painted roofs were found to be the most effective methods. Nevertheless, considering the close performance of all refurbishment strategies in addition to practicality (e.g., maintenance requirements), affordability and availability issues surrounding some of the investigated materials, particularly for low-income people, the prioritised refurbishment strategies are recommended as follows:

1. Inclusion of false ceiling
2. Double-skin roofing
3. White painting roofs with low-solar absorptance
4. Insulated roof (warm roof)
5. Insulated ceiling (cold roof)

It should be noted that all refurbishment strategies helped to pass Criterion 3 of CIBSE TM52, as an indicator of “future climate scenarios”, making low-income houses/populations more climate resilient in respect of global warming during the next 70 years.

This paper intended to evaluate the current conditions and develop simple, effective and practical refurbishment strategies to improve thermal comfort conditions for low-income populations in Uganda. Further research is required to evaluate the actual performance of construction methods and materials as well as the suggested refurbishment strategies using physical measurements on site. More research is also required to evaluate the effects of future climate scenarios and other parameters such as shadings, occupancy patterns/behaviours and ventilation rates and strategies on thermal comfort in low-income houses in Uganda. The cost implications of the abovementioned refurbishment strategies should also be investigated.

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Abbreviations

Operative temperature (T_{OP}): “the operative temperature combines the air temperature and the mean radiant temperature into a single value to express their joint effect”. The operative temperature can be calculated from the following equation when the indoor air speeds is below 0.1 m/s [21]:

$$T_{op} = \frac{1}{2} T_i + \frac{1}{2} T_r, \text{ where } T_i \text{ is the indoor air temperature } (^{\circ}\text{C}) \text{ and } T_r \text{ is the mean radiant temperature } (^{\circ}\text{C}).$$

Comfortable temperature (T_{comf}): the acceptable range of operative temperatures as a function of weighted running mean of the daily mean outdoor air temperature (T_{rm}). Comfortable temperature can be calculated from the following equation:

$$T_{comf} = 0.33 T_{rm} + 18.8, \text{ where } T_{rm} \text{ is } = (1 - \alpha) (T_d - 1 + \alpha T_d - 2 + \alpha^2 T_d - 3 \dots) \text{ and } \alpha \text{ is a constant } (\alpha < 1) \text{ and } T_d - 1, T_d - 2 \dots \text{ are the daily mean temperatures for the previous days [21].}$$

Maximum temperature (T_{max}): is the maximum acceptable operative temperature in free-running buildings. T_{max} can be calculated from the following equation: $T_{max} = 0.33 T_{rm} + 21.8$ [20]. In other words, $T_{max} = T_{comf} + 3$

Daily weighted exceedance (W_e): shows the severity of overheating in any single day in degree hours based on Annex F, “Method B Degree hours criteria” of BS EN 15251 [20]. W_e is the number of occupied hours during which the operative temperature exceeds the acceptable range multiplied by a factor that is a function of exceeded degrees over the acceptable range [21]

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