Note: This paper was presented at ZEMCH 2015 international conference. Please use the following to cite this publication:

Hashemi, A., Cruickshank, H., Cheshmehzangi, A. (2015). Improving Thermal Comfort in Low-income Tropical Housing: The Case of Uganda, ZEMCH 2015 International Conference, 22-25 September 2015, Lecce, Italy.

Improving Thermal Comfort in Low-income Tropical Housing: The Case of Uganda

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Abstract
The average temperature in East African countries is estimated to rise by 3-4 °C during the next 70 years due the global warming. Uganda is one of the East African countries which will be greatly affected by the global warming. Due to their vulnerable living conditions, low-income people will be hit the worst by the consequences of climate changes. Around 38% of Uganda's population live below the international poverty line of $1.25 a day and more than 60% of the country's urban population live in slums. On the other hand, due to various social and practical reasons, sustainable locally available construction methods and materials, such as adobe and thatched roofs are being gradually replaced with environmentally harmful materials such as concrete and iron sheet roofs. This situation in addition to imminent thermal discomfort caused by the global warming as well as defective design and inappropriate construction methods may considerably affect the health and wellbeing of low-income people the majority of whom live in substandard overcrowded homes. This paper intends to evaluate the effects of different construction methods and materials on the risk of thermal discomfort in low-income houses in Uganda. Dynamic thermal simulations are conducted in EnergyPlus and adaptive model Category II, defined in BS EN 15251, is used for the thermal comfort evaluations. The results reveal that roof construction methods/materials are the key factor in reducing or increasing the risk of thermal discomfort in naturally ventilated buildings in tropical climates. Compared to iron sheet roof, thatched roof provided up to 15 times better conditions by reducing the number of hours during which internal operative temperature exceeded the "limiting maximum acceptable temperature". Hollow concrete block walls with iron sheet roof was found to be the worst construction method which dramatically failed all three thermal comfort criteria defined by CIBSE TM52.

Keywords: *Thermal Comfort, Natural Ventilation, Low-income Housing, Tropical Housing, Uganda.*

1. Introduction
Located in East Africa, Uganda occupies an area of 241,038 square kilometres (Byakola 2007) and has an estimated population of around 39 million (UNDESA 2014). The climatic conditions in Uganda vary greatly from hot arid climate to tropical equatorial uplands. Local climates also vary greatly depending on the altitude and rainfall (EMI 2012). Overall, Uganda has a tropical climate, moderated by an average altitude of 1100 meters above the sea level (ACTwatch Group &

PACE/Uganda 2013), with two rainy seasons and mean annual rainfall of 750-2000mm (Byakola 2007; UBOS 2006).

The mean annual temperature of the most parts of the country varies between 16 °C and 30 °C; however, Northern and Eastern parts of the country may experience temperatures higher than 30 °C and the temperature in South Western part may get below 16 °C (UBOS 2006). The average temperature in East African countries is estimated to increase by 3-4 °C during the next 70 years due the global warming (EMI 2012). The current situation has raised concerns over thermal comfort conditions of Ugandan low-income populations the majority of whom live in overcrowded and poor quality houses with very limited or no access to basic facilities. In fact, due to their vulnerable living conditions, low-income people will be hit the worst by the consequences of climate changes.

Around 38% of Uganda's population live below the international poverty line of $1.25 a day and more than 60% of the country's urban population live in slums (Malik 2014; EPRC 2013). Furthermore, only less than 15% of Ugandan households have access to electricity. The situation is much more critical in rural areas as only around 5% of rural households have access to electricity compared with around 55% in urban areas (UBOS 2012). This is while around 85% of the population lives in rural areas (UN-HABITAT 2009).

In fact, considering the negligible operational energy (space heating and cooling) of low-income housing sector, embodied energy is currently the key factor in evaluating the environmental impacts of low-income houses (Hashemi et al. 2015). However, the gradual replacement of sustainable locally available construction methods and materials, such as adobe, mud and poles (wattle and daub) and thatched roofs with environmentally harmful and low thermally resistant materials such as concrete and iron sheet roofs may not only increase the embodied energy but also deteriorate thermal comfort conditions in low-income housing sector.

This situation in addition to imminent thermal discomfort caused by the global warming as well as defective design, inappropriate construction methods and poor workmanship may considerably affect the health and wellbeing of low-income people. To this end, this paper intends to assess the effects of various construction methods and materials on the risk and the extent of thermal discomfort in low-income naturally ventilated tropical housing in Uganda.

2. Housing types, conditions and construction methods

Detached houses are the most common housing type in Uganda (58%) followed by huts (21.5%) and tenements (18.4%) (Table 1). According to the national surveys in 2002, 27% for Ugandan families lived in "room/rooms" dwelling types. This figure was 62% in urban and 21% in rural areas of the country (UBOS 2006). In 2005/06, over 50% of Ugandan families lived in single-roomed houses (NPA 2010).

Table 1: Share of dwelling types in Uganda (UBOS 2010).

Dwelling Types	Year 2009/10		
	Urban	Rural	Uganda
Detached	30.2	64.4	57.9
Huts	6.2	25.1	21.5
Tenements	58	9.2	18.4
Others	5.7	1.4	2.2

Moreover, in 2010, around 62% of urban and 42% of rural families used only one room for sleeping (UBOS 2012). Considering the average household size of 5 people (3.9 people in urban and 5.2 persons in rural areas) (UBOS 2010), it could be argued that the number of sleeping people in almost half of Ugandan households is 4 or more people which is considerably more than the international standards. Such conditions could greatly affect the health and wellbeing of the occupants contributing to issues such as poor indoor air quality and increased risk of infectious and transmissible diseases (UBOS 2012). Table 2 below shows the average household size and the number of rooms used for sleeping in urban and rural areas of Uganda. According to these data, it could be argued that there is a tangible transition of material use in Ugandan rural and urban housing, where the growing demand is towards iron sheet roofs and brick walls for construction of houses.

Table 2: Household size and the number of rooms used for sleeping (UBOS 2010; UBOS 2012).

Indicator	Year 2009/10		
	Urban	Rural	Uganda
Average household size	3.9	5.2	5
Rooms used for sleeping			
One	62.3	42.0	45.8
Two	21.9	30.2	28.7
Three or more	15.1	27.2	24.9
Missing	0.7	0.6	0.6

Figure 1 below also summarises the most common construction methods and materials used in housing projects during 2002-2010. In 2010, around 62% of homes in Uganda (84% in urban areas and 57% in rural areas) were roofed with iron sheets (Figure 2) followed by thatched roof which took a share of 37%. Around 57% (84% urban and 51% rural) of all dwellings had brick walls and 39% (12% urban and 46% rural) were made out of mud and poles. More than 71% of floors were made from earth (25% urban and 82% rural) and 27% (71% urban and 17% rural) were covered with cement (NPA 2010; UBOS 2010).

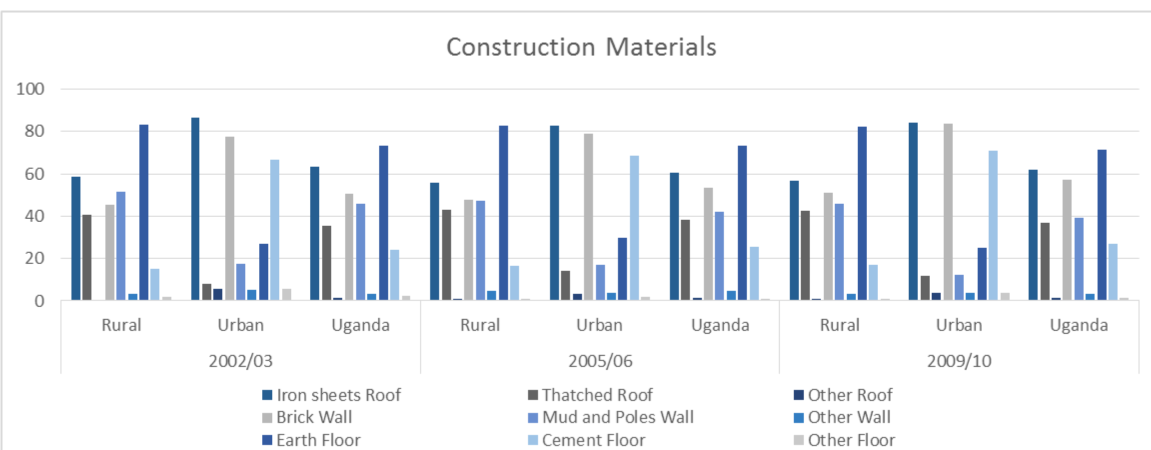


Figure 1: Construction methods and materials (%) (NPA 2010; UBOS 2010).

Figure 1: low-income housing with iron sheet roofing.

3. Research Methodology

Dynamic thermal simulations are conducted in EnergyPlus software programme to assess the current conditions as well as the effects of material alternations on thermal comfort conditions. Prevailing walling methods and materials including adobe, burned bricks, stabilised soil blocks, solid concrete and hollow concrete blocks are simulated for a fixed wall thickness of 200mm. Simulations are also carried out for common roofing types (i.e. iron sheet and thatched). Ten combination scenarios are therefore simulated in total (five walling materials and two roofing systems). Available information in CIBSE Guide A (CIBSE 2015) and Perez (2009) are used to define the materials' properties shown in Table 3. A design air change rate of 10 ACH is considered as the maximum air infiltration in the building.

Table 3: Material properties used in the simulations.

Material	Thermal Conductivity (W/m.K)	Thickness (m)
Adobe	0.6	0.200
Brick	1	0.200
Hollow Concrete Block	0.86	0.200
Solid Concrete Block	1.31	0.200
Stabilised Soil Block	1.1	0.200
Iron sheet roof	37	0.003
Thatched roof	0.07	0.150
Concrete floor	1.31	0.100

Based on the statistical information described above, a 3x3x3m single-roomed house with four occupants was modelled as the representative of low-income housing in urban areas of Uganda. A 2x1m door and a 1x1m single glazed window with effective opening area of 80% were also considered. The occupancy pattern was defined as fully occupied during 6pm-8am and 1 occupant during 8am-6pm. The occupants' behaviours in terms of opening and closing the windows and doors were also defined as: windows open 6:30am-6:30pm; doors open 7am-8pm (Olweny 1996).

For the weather data, Kisumu in Kenya was used as the closest city to Kampala and as there are no available weather data for thermal simulations in Uganda. 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, defined in BS EN 15251 (BSI 2007) was considered for thermal comfort evaluations in the case study building. The following overheating criteria defined in CIBSE TM52 (CIBSE 2013) were also used to evaluate the risk of thermal discomfort:

1) Criterion 1: maximum 3% of occupied hours during which indoor operative temperature can exceed the maximum acceptable temperature by 1 K or more ($\Delta T = T_{op} - T_{max}$ rounded to the nearest number).
2) Criterion 2: daily "weighted exceedance" (W_e) in any one day should not be more than 6 (degree-hours).
3) Criterion 3: this criterion set the absolute maximum temperature level (T_{upp}) where the indoor operative temperature should not at any time exceed 4 K above the maximum acceptable adaptive temperature ($\Delta T <= 4$ K).

4. Results of Simulations

According to the results, an average indoor operative temperature of around 26 °C would be the ideal comfort temperature in free-running, naturally ventilated buildings in Uganda. It should be noted that due to the rather consistent weather conditions, comfort temperature does not change dramatically throughout the year. The average maximum acceptable indoor temperature was also defined as around 29 °C. In hotter months of the year, however, a maximum indoor temperature of up to 30.8 °C was also found to be acceptable.
Table 4 summarises the results of the simulations. The results reveal that the most critical factor affecting occupants' thermal comfort in naturally ventilated homes in Kampala is the roof construction method/material. The thermal performance of different walling and roofing methods are explained in detail in the following sections.

Table 4: Summary of thermal comfort conditions for different construction methods and materials.

TM 52 Criteria	Criterion 1 (ΔT over 1 K)	Criterion 2 (Daily degree-hours over 6)	Criterion 3 (times ΔT over 4 K)
Adobe & Iron Sheet Roof	8.41%	65	6
Adobe & Thatched Roof	0.57%	3	0
Brick & Iron Sheet Roof	7.95%	56	2
Brick & Thatched Roof	0.84%	5	0
Hollow Concrete Blocks & Iron Sheet Roof	13.69%	148	39
Hollow Concrete Blocks & Thatched Roof	3.24%	15	0
Solid Concrete Blocks & Iron Sheet Roof	7.02%	45	2
Solid Concrete Blocks & Thatched Roof	0.75%	5	0
Stabilised Soil Blocks & Iron Sheet Roof	7.51%	49	2
Stabilised Soil Blocks & Thatched Roof	0.83%	5	0

4.1 Adobe walls with iron sheet/thatched roof

Adobe walls with iron sheet roof failed all three TM52 thermal comfort criteria. Regarding the first criterion, the indoor operative temperature was for 8.4% of the occupied periods by 1 K or more above the limiting maximum acceptable temperature. The building also failed criterion 2 (the daily weighted exceedance W_e) as for 65 days (17.8% of occupied days) W_e exceeded the limit of 6 degree-hours. As to criterion 3 (ΔT exceeding 4 K), the results reveal that there were six hours during which ΔT exceeded the “upper limit temperature” (T_{upp}). The situation considerably improved for adobe walls with thatched roof. The building passed both criterion 1 (0.6%, 1 K or more above the maximum acceptable temperature) and criterion 3 (ΔT, 0 hours exceeding T_{upp}) but marginally failed criterion 2 by only 3 days during which W_e exceeded the limit. Overall, the building seemed to be much more thermally comfortable compared to the previous roofing method (iron sheet roof). Figure 3 shows the thermal performance of the building during the entire year for thatched and iron sheet roofs with adobe walls.

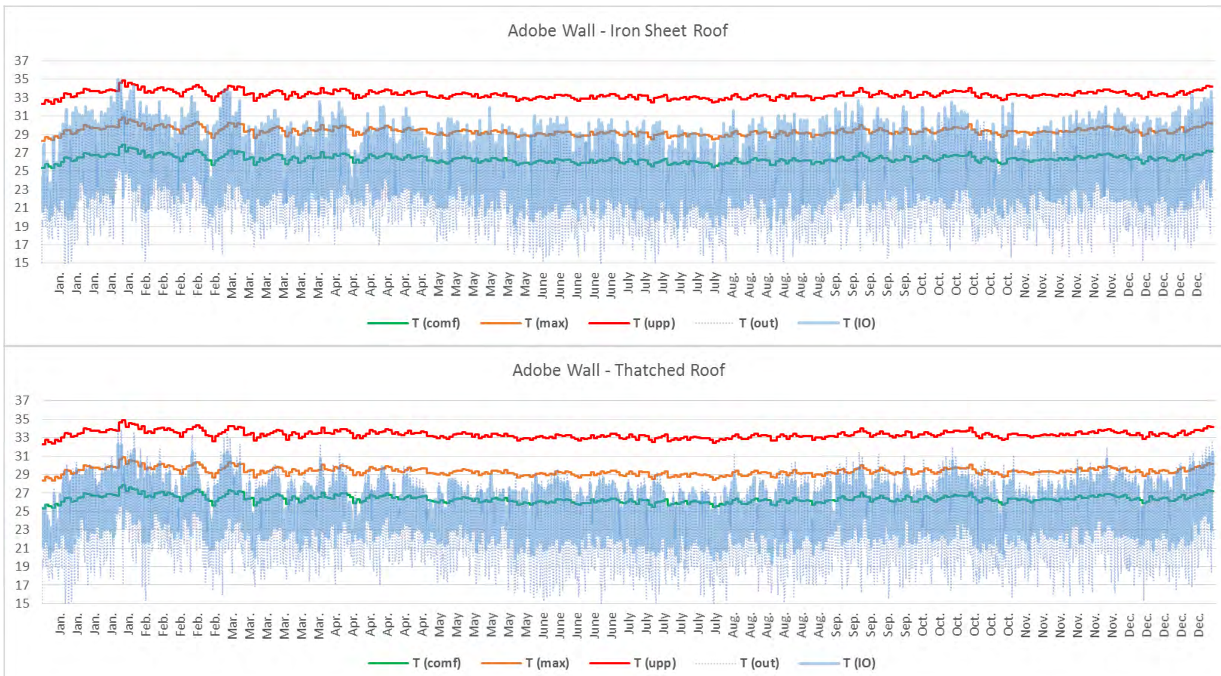


Figure 3: Thermal comfort condition for adobe walls with iron sheet (top) and thatched roofs (bottom).

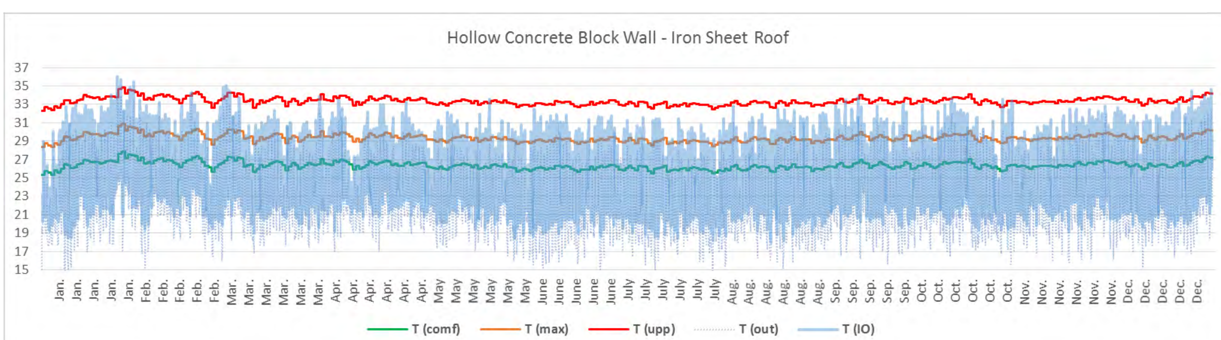
4.2 Brick walls with iron sheet/thatched roof

The results of simulations revealed that adobe and brick walls had similar performances although brick walls performed marginally better than adobe walls with iron sheet roof and slightly worse than adobe walls with thatched roof. Similar to adobe, brick walls with iron sheet roof failed in all three thermal comfort criteria. The building was thermally uncomfortable as the indoor operative temperature was in 8% of the occupied periods above the maximum acceptable levels. Moreover, for 56 days, W_e exceeded the acceptable limit. Regarding the third criterion, there were two days during which ΔT exceeded the maximum acceptable temperature by more than the 4 K. Similar to adobe construction, the situation considerably improved for the thatched roof. The building passed criterion 1 and criterion 3 but failed in criterion 2 as there were 5 days during which W_e exceeded the acceptable limit. Figure 4 summarises the results of simulations for brick walls with iron sheet and thatched roof constructions.

Figure 4: Thermal comfort condition for brick walls with iron sheet (top) and thatched roofs (bottom).

4.3 Hollow concrete block walls with iron sheet/thatched roof

Hollow concrete block walls had a very poor performance in terms of thermal comfort. This was despite the fact that the thermal conductivity of hollow concrete blocks (0.86 W/m.K) was lower than brick walls (1 W/m.K). The results indicated that hollow concrete block walls failed to satisfy thermal comfort criteria regardless of roofing types. The situation, however, was considerably worse for the iron sheet roof. According to the results, for hollow concrete block walls with iron sheet roof, the building was thermally uncomfortable for 13.7% of the occupied periods which is significantly higher than the 3% acceptable level. Moreover, W_e exceeded the acceptable limit in 148 days which is around 41% of the entire year. The maximum value for W_e was reported on the 24th of January with a value of 35 °C.hr (degree-hours). The building also failed criterion 3 as there were 39 hours/incidents during which ΔT exceeded the upper limit temperature (T_{upp}). Figure 5 summarises the results of simulations for hollow concrete block walls with iron sheet and thatched roof construction methods.



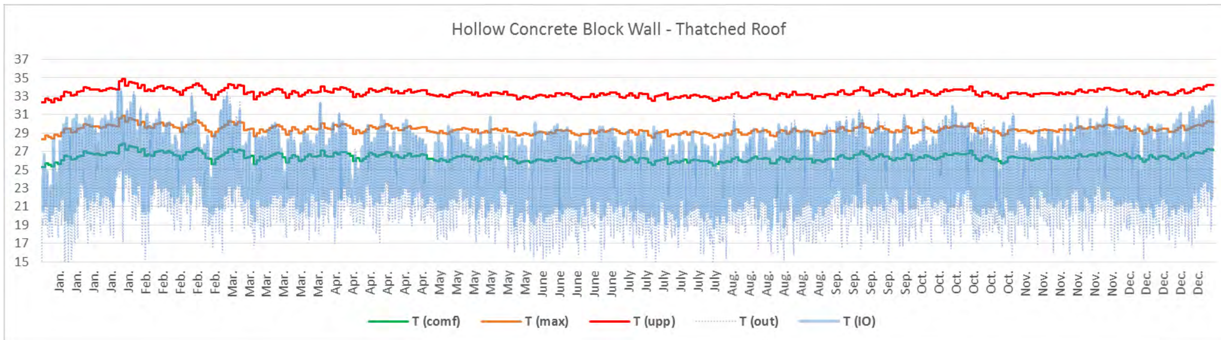


Figure 5: Thermal comfort condition for hollow concrete block walls with iron sheet (top) and thatched roofs (bottom).

4.4 Solid concrete block walls with iron sheet/thatched roof

Solid concrete block walls had a comparable performance with adobe and brick walls. According to the results, the thermal performance of solid concrete block walls was slightly better than adobe and brick walls with iron sheet roofing system and slightly worse than adobe walls with thatched roof. Similar to other walling methods, solid concrete block walls with iron sheet roof failed in all three TM52 thermal comfort criteria; however, thermal performance of the building improved considerably with the thatched roof. For the iron sheet roof, the building was thermally uncomfortable during 7% of the occupied periods and W_e exceeded the acceptable limit for 45 days. Moreover, there were two hours during which ΔT exceeded the 4 K limit. For the thatched roof construction, the building passed criteria 1 and 3 but failed criterion 2 by five days during which W_e exceeded the acceptable limit. Figure 6 summarises the results of simulations for solid concrete block walls with iron sheet and thatched roofs.

Figure 6: Thermal comfort condition for solid concrete block walls with iron sheet (top) and thatched roofs (bottom).

4.5 Stabilised soil block walls with iron sheet/thatched roof

Stabilised soil blocks had a similar performance to solid concrete blocks, adobe and brick walls. Similar to all other walling methods/materials, thatched roof had a considerably better performance compared to iron sheet roof. For the iron sheet roof, the buildings was found to be for 7.5% of the occupied periods uncomfortable (criterion 1). W_e was also above the acceptable limit of 6 for 45 days. Regarding criterion 3, ΔT also exceeded the 4 K limit for two days. Criteria 1, 2 and 3 were respectively reduced to 0.8%, 5 days and 0 days for stabilised soil block walls with thatched roof meaning that the building passed criteria 1 and 3 but failed to meet the requirements for criterion 2. Figure 7 compares the thermal comfort conditions for stabilised soil block walls with thatched and iron sheet roofs.

Figure 7: Thermal comfort condition for stabilised soil block walls with iron sheet (top) and thatched roofs (bottom).

5. Conclusions

This paper evaluated the effects of various construction methods on thermal comfort in low-income tropical housing in Uganda. Dynamic thermal simulations were conducted in EnergyPlus and the risk of thermal discomfort in naturally ventilated buildings was studied for different walling and roofing methods. According to the results, an average internal operative temperature of 26 °C would be an ideal comfort temperature in free-running buildings in Kampala. The maximum average internal temperature was also defined as 29 °C. The comfort and maximum temperatures could however vary by up to 1.8 °C depending on the running mean outdoor temperature.

According to the results of the simulations, roofing method/material is the most critical factor affecting thermal comfort conditions in free-running buildings in tropical climate of Kampala. The results reveal that, compared to iron sheet roof, thatched roof improved thermal comfort conditions by up to 15 times for criterion 1 of CIBSE TM52 guidelines. In other words, the risk of overheating (frequency of thermal discomfort), was reduced by up to 15 times when iron sheet roof was replaced with thatched roof. The two other criteria defined by CIBSE TM52 were also improved considerably for the thatched roof construction. Therefore, it could be argued that, when it comes to construction materials, improving thermal performance of the roof is key to improving thermal comfort in naturally ventilated buildings in tropical climates.

Although important, walling materials were found to be less critical compared to roofing methods. The results of this study revealed that the thermal performance of different walling materials, with the exception of hollow concrete blocks, were almost identical. Hollow concrete block walls performed the worst in terms of providing thermal comfort. This was despite the fact that the thermal conductivity of hollow concrete blocks was considerably lower than solid concrete blocks, bricks and stabilised soil blocks. A possible reason for this is the much less thermal mass of hollow concrete blocks compared to the rest of the walling materials.

In summary, low thermal conductivity of the roof along with high thermal mass proved to be the key factors in reducing the risk of thermal discomfort. The priority, however, should be given to the roof as it is critical in achieving acceptable thermal performance in tropical climates. This research concentrated on the thermal performance of common construction methods and materials in Uganda. Further research is required to evaluate the effects of ceilings and insulation levels as well as emissivity and solar absorptance rates of the roofs on thermal comfort conditions. A sensitivity analysis is also required to evaluate the effects of various parameters such as occupancy patterns/behaviours, shadings, ventilation rates and strategies and thermal condustivity values on the thermal performance/comfort in low-income houses in Uganda.

Acknowledgements
This work is funded through an EPSRC research programme, Energy and Low Income Tropical Housing, grant number: EP/L002604/1.

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