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# Effects of thermal insulation on thermal comfort in low-income tropical housing

Arman Hashemi[a]*

[a] *School of Environment and Technology, University of Brighton, Brighton, BN2 4GJ, UK.*

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**Abstract**

This paper evaluates the effects of thermal insulation on thermal comfort in low-income tropical housing in Uganda. Dynamic thermal simulations are conducted to assess the effects of wall, roof and floor insulation strategies. 96 combination scenarios are simulated for various geometries, insulation and construction methods. Adaptive approach is used to evaluate the conditions within the case study buildings. The results indicate that external wall insulation improves thermal comfort in all conditions whereas internal wall and floor insulation may deteriorate the conditions. Roof insulation is the most effective strategy to reduce the risk of overheating. Due to the effectiveness of roof insulation and marginal improvements of external wall insulation, especially for brick walls, wall insulation may be disregarded when used in conjunction with roof insulation.

*Keywords:* Thermal Comfort; Overheating; Tropical; Low-income; Housing; Uganda

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## 1. Introduction

Uganda is an East African country with a population of around 39 million people and an area of over 241 thousand square kilometres [1,2]. According to UNDP [3], with an HDI score of 0.483 Uganda is ranked 163 out of 188 countries in the Human Development Index. Around 38% of Uganda's population live in poverty [3]. Over 60% of Uganda's

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* Corresponding author. Tel.: +44 (0) 1273 642272.
*E-mail address:* A.Hashemi@brighton.ac.uk

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urban population live in slums [4,5] and over 50% live in single-roomed overcrowded properties [6] built from low quality materials (Figure 1). Moreover, rapid urbanisation and growing housing demand are some of the other current challenges of the country [7]. Currently, embodied energy of construction methods and materials seems to be the major challenge which requires immediate attention to mitigate negative environmental effects of the construction industry [8,9].

Fig.1. Low-income housing.

Adobe, cob, rammed earth, wattle and daub (also known as mud and poles), burned bricks, stabilised earth blocks; and concrete are the most common walling materials used in many developing countries including Uganda [10,11,12,13,14]. Table 1 shows the most common construction methods/materials in urban areas of Uganda. Over 84% of homes in urban areas of Uganda are covered with iron sheet and 12% with thatch. With nearly 84%, brick is also the most common walling material and cement/concert (71%) is the most common flooring material in urban areas of the country.

Table 1. Most common construction methods/materials in urban areas of Uganda (%) [15].

| | | |
|---|---|---|
| Roof Construction* | Iron sheets Roof | 84.1 |
| | Thatched Roof | 12 |
| | Other | 4 |
| Wall Construction* | Brick Wall | 83.9 |
| | Mud and Poles Wall | 12.4 |
| | Other | 3.8 |
| Floor Construction* | Earth Floor | 25.2 |
| | Cement Floor | 70.8 |
| | Other | 4 |

*Up to 0.1% discrepancies.

Despite a moderate tropical climate, , rapid replacement of traditional methods and materials with relatively modern methods and construction such as iron sheet roof and hollow concrete blocks etc., due to various social and practical reasons, along with climate change and global warming have transformed overheating and thermal discomfort into a major issue in Uganda. According to UN-HABITAT [16], the average temperature in Uganda is expected to increase by1.5 ºC in the next 20 years and by up to 4.3 ºC by 2080. The climate change, poverty and inappropriate construction methods along with the very low access to electricity (18% on average [3]), may seriously affect the low-income populations who may not have access to appropriate facilities and knowledge to adapt to climate change.

This paper evaluates the effects of thermal insulation on the risk of overheating in low-income tropical housing in Uganda. It is aimed to provide design and refurbishment recommendations to improve thermal comfort conditions for the low-income publications. The current housing conditions and environmental impacts of construction methods and materials as well as the effects of solar shading and alternative construction methods on thermal comfort have been discussed in other papers [17,18,19].

**Nomenclature**

Operative temperature (Top): "The operative temperature combines the air temperature and the mean radiant temperature into a single value to express their joint effect" [20].

## 2. Methodology

Dynamic thermal simulations were conducted in EnergyPlus to evaluate the effects of internal and external insulation on thermal comfort and risk of overheating. A small village of 12 buildings (thermal zones) with different geometries and construction materials and an average household size of 4 occupants per dwelling [15] was modelled. Table 2 summarises the modelled scenarios.

Table 2. Zone Names and Characteristics.

| Construction Methods & Geometry | Case Studies/Thermal Zones | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Thermal Zone | Z1 | Z2 | Z3 | Z4 | Z5 | Z6 | Z7 | Z8 | Z9 | Z10 | Z11 | Z12 |
| Zone Size | 3x3x3m | | | 3x3x3m | | | 3x3x3m | | | 3x3x3m | | |
| Wall Construction | Brick | | | Hollow Concrete | | | Brick | | | Hollow Concrete | | |
| Insulation | None | Int. | Ext. | None | Int. | Ext. | None | Int. | Ext. | None | Int. | Ext. |
| Windows | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Window size | 1x1m with an effective opening area of 80% | | | | | | | | | | | |
| Door size | 2x1m with an effective opening area of 80% | | | | | | | | | | | |
| TV | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 3 |

According to the available data, nearly 60% of buildings in Uganda have brick walls, over 60% have iron sheet roofs and 27% have cement/concert flooring [15,21]. These figures are considerably higher in the urban areas of Uganda (Table 1). Moreover, according to Hashemi et al. [18], hollow concrete blocks are becoming increasingly common in Uganda. Bare hollow concrete walls provide the worst thermal comfort conditions compared with traditional and other common walling materials [18]. Simulations were therefore conducted for the most common construction methods as well as hollow concrete blocks in urban areas of Uganda. Table 3 summarises the properties of the materials used in simulations.

Table 3. Material properties used in the simulations.

| Material | Thermal Conductivity (W/m.K) | Thickness (m) | Density (Kg/m3) | Solar Transmitance | Solar Absorptance |
|---|---|---|---|---|---|
| Brick | 1.0 | 0.200 | 1900 | - | 0.70 |
| Hollow Concrete | 0.86 | 0.200 | 875 | - | - |

| | | | | | |
|---|---|---|---|---|---|
| Iron sheet roof | 37.0 | 0.003 | 7800 | - | 0.70 |
| White Iron Sheet | 37.0 | 0.003 | 7800 | - | 0.20 |
| Concrete | 1.31 | 0.100 | 2240 | - | 0.70 |
| Glass | 0.90 | 0.006 | - | 0.775 | - |
| Insulation | 0.04 | 0.050 | 240 | - | - |

The occupancy profile in the case study buildings was considered as 1 occupant between 8pm-6pm and fully occupied between 6pm- 8pm. Window were considered to be open between 6:30pm- 6:30am doors were assumed to be open between 7am- 8pm and closed all other times. The basic scenarios were assessed against the following thermal insulation alternatives:

- External walls: no insulation, internal insulation, external insulation
- Iron roof with/without insulation
- White painted iron roof with/without insulation
- Concrete floor with/without insulation

Overall, 96 combination scenarios were simulated to evaluate various strategies. Adaptive thermal comfort standards defined in CEN standard BS EN 15251 [22] and CIBSE TM52 [20] has been considered to assess risk of overheating and thermal comfort in buildings. Three criteria are used to assess the risk of overheating (Table 4). A building/room that fails any two of the three criteria is assumed as overheated/ thermally uncomfortable.

Table 4. Adaptive thermal comfort assessment criteria.

| Assessment Criteria | | Acceptable deviation |
|---|---|---|
| Criterion 1 | Frequency of occupied hours when operative temperature is greater than maximum comfortable temperature | Up to 3% of occupied hours |
| Criterion 2 | Severity of thermal discomfort by calculation of number of day degree hours of warm period >6°hrs a day | 0 day |
| Criterion 3 | Severity of thermal discomfort by reporting<br>Number of hours in which ΔT > 4°K (ΔT = Toperative- Tmax, rounded to the nearest whole degree) | 0 hour |

## 3. Results

Tables 5, 6, 7 and 8 summarise the results of all 96 combination scenarios. Each scenario has a unique ID which identifies its simulation condition. The IDs indicate the geometry, construction and insulation categories. The effects of including/excluding insulation have been evaluated for each condition listed below:

A. Geometry categories:
   1. Base case with 1 window on south
   2. Base case with 2 windows on north and south
B. Construction categories:
   1. Brick
   2. Hollow concrete
C. Insulation categories:
   1. Walls
      a. Solid: no insulation
      b. Internal wall insulation
      c. External wall Insulation
   2. Roof
      a. Iron roof without insulation

   b. Iron roof with internal insulation
   c. White painted iron roof without insulation
   d. White painted iron roof with insulation
3. Floor
   a. Solid concrete floor: no insulation
   b. Concrete floor with insulation

According to the results, none of the scenarios passed thermal comfort criteria when the roof was covered with bare iron sheet. Indeed, although there were some improvements, none of the wall and/or floor insulation strategies were effective enough and the first 24 combination scenarios (ID 1-24 in Table 5) failed all three assessment criteria. Yet, in comparison, external wall insulation marginally improved the conditions while internal wall insulation considerably deteriorated indoor thermal comfort conditions for both Brick and Hollow Concrete walls. Overall, the best-case scenario was achieved for brick walls with external insulation (ID 3 and ID 9).

Insulated concrete floor also deteriorated indoor thermal conditions (ID 13-24) compared to the base case scenarios (ID 1-12). Similar to the first 12 scenarios with bare concrete floors, external wall insulation improved indoor thermal comfort conditions. The only exception is for ID 15 and ID 21 for brick walls where external insulation slightly deteriorated the conditions compared to bare brick walls. Further research is required to evaluate and explain the reasons for such deteriorations. The results also indicate that thermal comfort improved for the scenarios with 2 windows.

Table 5. Results of combination scenarios for iron sheet roof (IDs 1-24).

| ID | Criterion | | | Roof | Floor | Wall | Insulation | Windows | Result | Failed in |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | Construction | | | | | | |
| 1 | 12.69% | 127 | 14 | Ir | Con | Br | None | 1 | Fail | 3 |
| 2 | 21.10% | 283 | 457 | Ir | Con | Br | In | 1 | Fail | 3 |
| 3 | 12.32% | 105 | 9 | Ir | Con | Br | Ex | 1 | Fail | 3 |
| 4 | 18.74% | 232 | 163 | Ir | Con | Ho-Con | None | 1 | Fail | 3 |
| 5 | 21.51% | 288 | 508 | Ir | Con | Ho-Con | In | 1 | Fail | 3 |
| 6 | 14.39% | 153 | 20 | Ir | Con | Ho-Con | Ex | 1 | Fail | 3 |
| 7 | 12.07% | 119 | 14 | Ir | Con | Br | None | 2 | Fail | 3 |
| 8 | 20.05% | 264 | 319 | Ir | Con | Br | In | 2 | Fail | 3 |
| 9 | 11.74% | 94 | 10 | Ir | Con | Br | Ex | 2 | Fail | 3 |
| 10 | 17.66% | 211 | 121 | Ir | Con | Ho-Con | None | 2 | Fail | 3 |
| 11 | 20.26% | 265 | 353 | Ir | Con | Ho-Con | In | 2 | Fail | 3 |
| 12 | 13.58% | 147 | 17 | Ir | Con | Ho-Con | Ex | 2 | Fail | 3 |
| 13 | 15.02% | 156 | 34 | Ir | Ins-Con | Br | None | 1 | Fail | 3 |
| 14 | 23.50% | 300 | 658 | Ir | Ins-Con | Br | In | 1 | Fail | 3 |
| 15 | 16.63% | 179 | 41 | Ir | Ins-Con | Br | Ex | 1 | Fail | 3 |
| 16 | 20.49% | 243 | 262 | Ir | Ins-Con | Ho-Con | None | 1 | Fail | 3 |
| 17 | 23.85% | 303 | 697 | Ir | Ins-Con | Ho-Con | In | 1 | Fail | 3 |
| 18 | 18.36% | 207 | 100 | Ir | Ins-Con | Ho-Con | Ex | 1 | Fail | 3 |
| 19 | 14.32% | 150 | 31 | Ir | Ins-Con | Br | None | 2 | Fail | 3 |
| 20 | 22.09% | 278 | 468 | Ir | Ins-Con | Br | In | 2 | Fail | 3 |
| 21 | 15.53% | 160 | 31 | Ir | Ins-Con | Br | Ex | 2 | Fail | 3 |
| 22 | 19.39% | 230 | 187 | Ir | Ins-Con | Ho-Con | None | 2 | Fail | 3 |
| 23 | 22.34% | 285 | 501 | Ir | Ins-Con | Ho-Con | In | 2 | Fail | 3 |
| 24 | 17.20% | 195 | 63 | Ir | Ins-Con | Ho-Con | Ex | 2 | Fail | 3 |

Abbreviations: Ir.: Iron sheet; Con.: Concrete; Br.: Brick; Ho.: Hollow; Ins.: Insulated; W.: White; In.: Internal; Ex.: External

Insulated iron sheet roof significantly improved the conditions (Table 6). All brick walls passed thermal comfort requirements, apart from scenarios 38 and 44 where the application of internal insulation deteriorated the conditions.

Roof insulation along with external wall insulation and bare concrete floor (IDs 26, 29 and 32) achieved ideal conditions as they passed all three thermal comfort assessment criteria. For hollow concrete blocks, compared to bricks, the situation was slightly worse. Unlike the previous 24 scenarios, thermal comfort conditions slightly deteriorated for buildings with 2 windows.

Table 6. Results of combination scenarios for insulated iron sheet roof (IDs 25-48).

| ID | Criterion | | | Roof | Floor | Wall | Insulation | Windows | Result | Failed in |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | Construction | | | | | | |
| 25 | 0.86% | 4 | 0 | Ins-Ir | Con | Br | None | 1 | Pass | 1 |
| 26 | 1.58% | 6 | 0 | Ins-Ir | Con | Br | In | 1 | Pass | 1 |
| 27 | 0.08% | 0 | 0 | Ins-Ir | Con | Br | Ex | 1 | Pass | 0 |
| 28 | 4.65% | 25 | 0 | Ins-Ir | Con | Ho-Con | None | 1 | Fail | 2 |
| 29 | 2.39% | 10 | 0 | Ins-Ir | Con | Ho-Con | In | 1 | Pass | 1 |
| 30 | 0.19% | 0 | 0 | Ins-Ir | Con | Ho-Con | Ex | 1 | Pass | 0 |
| 31 | 1.13% | 8 | 0 | Ins-Ir | Con | Br | None | 2 | Pass | 1 |
| 32 | 2.58% | 9 | 0 | Ins-Ir | Con | Br | In | 2 | Pass | 1 |
| 33 | 0.25% | 0 | 0 | Ins-Ir | Con | Br | Ex | 2 | Pass | 0 |
| 34 | 4.60% | 25 | 0 | Ins-Ir | Con | Ho-Con | None | 2 | Fail | 2 |
| 35 | 3.26% | 12 | 0 | Ins-Ir | Con | Ho-Con | In | 2 | Fail | 2 |
| 36 | 0.43% | 1 | 0 | Ins-Ir | Con | Ho-Con | Ex | 2 | Pass | 1 |
| 37 | 2.32% | 10 | 0 | Ins-Ir | Ins-Con | Br | None | 1 | Pass | 1 |
| 38 | 4.75% | 31 | 1 | Ins-Ir | Ins-Con | Br | In | 1 | Fail | 3 |
| 39 | 0.76% | 3 | 0 | Ins-Ir | Ins-Con | Br | Ex | 1 | Pass | 1 |
| 40 | 6.87% | 46 | 2 | Ins-Ir | Ins-Con | Ho-Con | None | 1 | Fail | 3 |
| 41 | 5.75% | 41 | 1 | Ins-Ir | Ins-Con | Ho-Con | In | 1 | Fail | 3 |
| 42 | 1.32% | 6 | 0 | Ins-Ir | Ins-Con | Ho-Con | Ex | 1 | Pass | 1 |
| 43 | 2.36% | 12 | 0 | Ins-Ir | Ins-Con | Br | None | 2 | Pass | 1 |
| 44 | 5.74% | 34 | 2 | Ins-Ir | Ins-Con | Br | In | 2 | Fail | 3 |
| 45 | 1.14% | 4 | 0 | Ins-Ir | Ins-Con | Br | Ex | 2 | Pass | 1 |
| 46 | 6.88% | 42 | 2 | Ins-Ir | Ins-Con | Ho-Con | None | 2 | Fail | 3 |
| 47 | 6.64% | 42 | 3 | Ins-Ir | Ins-Con | Ho-Con | In | 2 | Fail | 3 |
| 48 | 1.62% | 8 | 0 | Ins-Ir | Ins-Con | Ho-Con | Ex | 2 | Pass | 1 |

Abbreviations: Ir.: Iron sheet; Con.: Concrete; Br.: Brick; Ho.: Hollow; Ins.: Insulated; W.: White; In.: Internal; Ex.: External

As stated in Table 3, for the white iron sheet roof, it was assumed that painting the bare roof with white paint/cover would reduce solar absorptance from 0.7 to 0.2 (Table 7, IDs 49-72). Similar to roof insulation, white painted roof proved to be very effective and significantly improved indoor thermal comfort conditions.

Table 7. Results of combination scenarios for white sheet roof (IDs 49-72).

| ID | Criterion | | | Roof | Floor | Wall | Insulation | Windows | Result | Failed in |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | Construction | | | | | | |
| 49 | 0.78% | 5 | 0 | W-Ir | Con | Br | None | 1 | Pass | 1 |
| 50 | 2.80% | 11 | 0 | W-Ir | Con | Br | In | 1 | Pass | 1 |
| 51 | 0.14% | 0 | 0 | W-Ir | Con | Br | Ex | 1 | Pass | 0 |
| 52 | 4.39% | 22 | 1 | W-Ir | Con | Ho-Con | None | 1 | Fail | 3 |
| 53 | 3.48% | 13 | 1 | W-Ir | Con | Ho-Con | In | 1 | Fail | 3 |
| 54 | 0.25% | 0 | 0 | W-Ir | Con | Ho-Con | Ex | 1 | Pass | 0 |
| 55 | 1.14% | 6 | 0 | W-Ir | Con | Br | None | 2 | Pass | 1 |
| 56 | 3.32% | 13 | 1 | W-Ir | Con | Br | In | 2 | Fail | 3 |
| 57 | 0.31% | 0 | 0 | W-Ir | Con | Br | Ex | 2 | Pass | 0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 58 | 4.27% | 23 | 1 | W-Ir | Con | Ho-Con | None | 2 | Fail | 3 |
| 59 | 3.90% | 16 | 1 | W-Ir | Con | Ho-Con | In | 2 | Fail | 3 |
| 60 | 0.46% | 2 | 0 | W-Ir | Con | Ho-Con | Ex | 2 | Pass | 1 |
| 61 | 1.39% | 7 | 0 | W-Ir | Ins-Con | Br | None | 1 | Pass | 1 |
| 62 | 3.93% | 20 | 1 | W-Ir | Ins-Con | Br | In | 1 | Fail | 3 |
| 63 | 0.40% | 1 | 0 | W-Ir | Ins-Con | Br | Ex | 1 | Pass | 1 |
| 64 | 5.23% | 35 | 1 | W-Ir | Ins-Con | Ho-Con | None | 1 | Fail | 3 |
| 65 | 4.57% | 25 | 2 | W-Ir | Ins-Con | Ho-Con | In | 1 | Fail | 3 |
| 66 | 0.64% | 3 | 0 | W-Ir | Ins-Con | Ho-Con | Ex | 1 | Pass | 1 |
| 67 | 1.70% | 9 | 0 | W-Ir | Ins-Con | Br | None | 2 | Pass | 1 |
| 68 | 4.53% | 22 | 2 | W-Ir | Ins-Con | Br | In | 2 | Fail | 3 |
| 69 | 0.71% | 4 | 0 | W-Ir | Ins-Con | Br | Ex | 2 | Pass | 1 |
| 70 | 5.25% | 31 | 3 | W-Ir | Ins-Con | Ho-Con | None | 2 | Fail | 3 |
| 71 | 5.08% | 24 | 2 | W-Ir | Ins-Con | Ho-Con | In | 2 | Fail | 3 |
| 72 | 1.04% | 4 | 0 | W-Ir | Ins-Con | Ho-Con | Ex | 2 | Pass | 1 |

Abbreviations: Ir.: Iron sheet; Con.: Concrete; Br.: Brick; Ho.: Hollow; Ins.: Insulated; W.: White; In.: Internal; Ex.: External

The combination of white paint with roof insulation, as expected, further improved the conditions (Table 8). This was particularly evident for hollow concrete blocks however painted insulated roof also improved the conditions for brick walls. Yet, some of the scenarios marginally failed the thermal comfort requirements: ID 88, 94 and 95.

Table 8. Results of combination scenarios for white insulated sheet roof (IDs 73-96).

| ID | Criterion | | | Roof | Floor | Wall | Insulation | Windows | Result | Failed in |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | | Construction | | | | | |
| 73 | 0.50% | 1 | 0 | W-Ins-Ir | Con | Br | None | 1 | Pass | 1 |
| 74 | 0.49% | 2 | 0 | W-Ins-Ir | Con | Br | In | 1 | Pass | 1 |
| 75 | 0.02% | 0 | 0 | W-Ins-Ir | Con | Br | Ex | 1 | Pass | 0 |
| 76 | 2.83% | 13 | 0 | W-Ins-Ir | Con | Ho-Con | None | 1 | Pass | 1 |
| 77 | 0.75% | 3 | 0 | W-Ins-Ir | Con | Ho-Con | In | 1 | Pass | 1 |
| 78 | 0.05% | 0 | 0 | W-Ins-Ir | Con | Ho-Con | Ex | 1 | Pass | 0 |
| 79 | 0.66% | 3 | 0 | W-Ins-Ir | Con | Br | None | 2 | Pass | 1 |
| 80 | 0.98% | 4 | 0 | W-Ins-Ir | Con | Br | In | 2 | Pass | 1 |
| 81 | 0.10% | 0 | 0 | W-Ins-Ir | Con | Br | Ex | 2 | Pass | 0 |
| 82 | 2.89% | 14 | 0 | W-Ins-Ir | Con | Ho-Con | None | 2 | Pass | 1 |
| 83 | 1.34% | 8 | 0 | W-Ins-Ir | Con | Ho-Con | In | 2 | Pass | 1 |
| 84 | 0.19% | 0 | 0 | W-Ins-Ir | Con | Ho-Con | Ex | 2 | Pass | 0 |
| 85 | 1.30% | 7 | 0 | W-Ins-Ir | Ins-Con | Br | None | 1 | Pass | 1 |
| 86 | 1.85% | 10 | 0 | W-Ins-Ir | Ins-Con | Br | In | 1 | Pass | 1 |
| 87 | 0.27% | 0 | 0 | W-Ins-Ir | Ins-Con | Br | Ex | 1 | Pass | 0 |
| 88 | 4.47% | 27 | 0 | W-Ins-Ir | Ins-Con | Ho-Con | None | 1 | Fail | 2 |
| 89 | 2.59% | 12 | 0 | W-Ins-Ir | Ins-Con | Ho-Con | In | 1 | Pass | 1 |
| 90 | 0.49% | 1 | 0 | W-Ins-Ir | Ins-Con | Ho-Con | Ex | 1 | Pass | 1 |
| 91 | 1.48% | 8 | 0 | W-Ins-Ir | Ins-Con | Br | None | 2 | Pass | 1 |
| 92 | 2.52% | 11 | 0 | W-Ins-Ir | Ins-Con | Br | In | 2 | Pass | 1 |
| 93 | 0.49% | 1 | 0 | W-Ins-Ir | Ins-Con | Br | Ex | 2 | Pass | 1 |
| 94 | 4.51% | 27 | 0 | W-Ins-Ir | Ins-Con | Ho-Con | None | 2 | Fail | 2 |
| 95 | 3.20% | 13 | 0 | W-Ins-Ir | Ins-Con | Ho-Con | In | 2 | Fail | 2 |
| 96 | 0.76% | 4 | 0 | W-Ins-Ir | Ins-Con | Ho-Con | Ex | 2 | Pass | 1 |

Abbreviations: Ir.: Iron sheet; Con.: Concrete; Br.: Brick; Ho.: Hollow; Ins.: Insulated; W.: White; In.: Internal; Ex.: External

## 4. Discussions

According to the results, the best conditions were achieved for the following combination scenarios where all three assessment criteria were met:

- ID 27: Insulated roof, Concrete floor, Brick wall, External Insulation
- ID 30: Insulated roof, Concrete floor, Hollow concrete blocks wall, External Insulation
- ID 33: Insulated roof, Concrete floor, Brick wall, External Insulation
- ID 51: White painted roof, Concrete floor, Brick wall, External Insulation
- ID 54: White painted roof, Concrete floor, Hollow concrete blocks wall, External Insulation
- ID 57: White painted roof, Concrete floor, Brick wall, External Insulation
- ID 75: White insulated roof, Concrete floor, Brick wall, External Insulation
- ID 78: White insulated roof, Concrete floor, Hollow concrete blocks wall, External Insulation
- ID 81: White insulated roof, Concrete floor, Brick wall, External Insulation
- ID 84: White insulated roof, Concrete floor, Hollow concrete blocks wall, External Insulation
- ID 87: White insulated roof, Concrete floor, Brick wall, External Insulation

The best conditions were achieve only for the external wall insulation. The worst combination which almost always failed all three criteria, regardless of roof or wall insulation (excluding Table 8: IDs 72-96), were a) bare hollow concrete walls; followed by b) internally insulated hollow concrete walls.

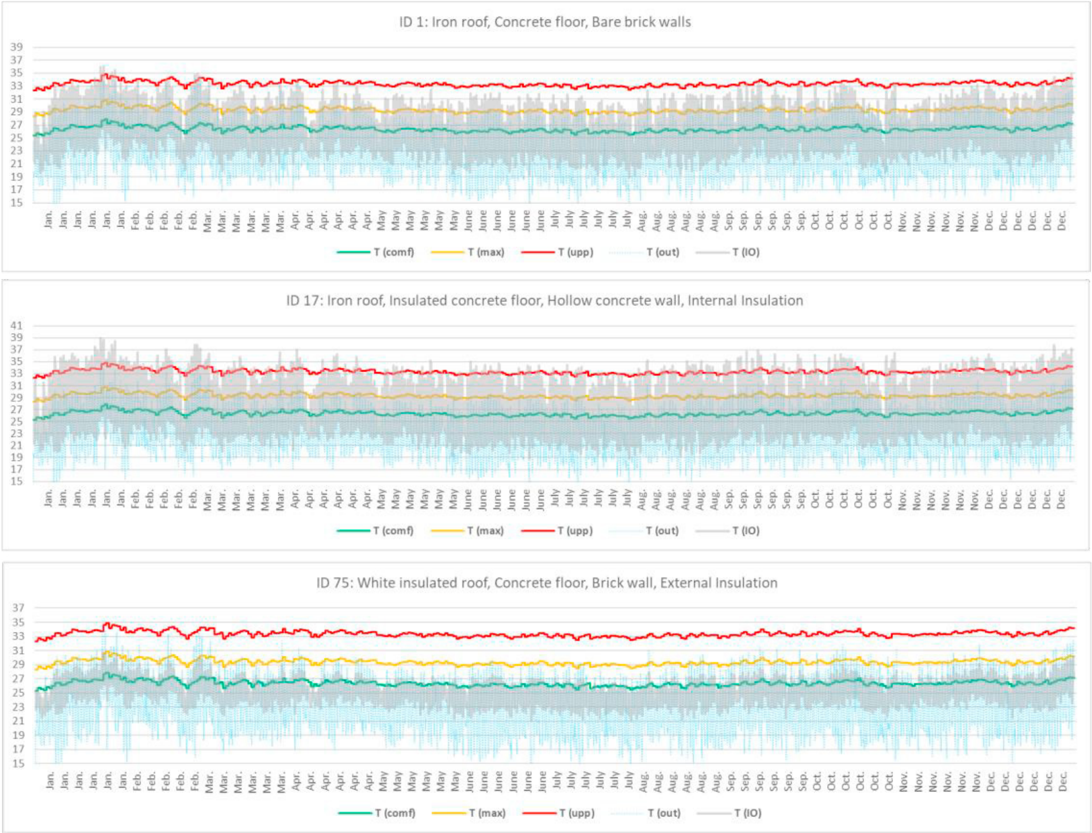

Fig. 2. Thermal comfort conditions for the base case (top); worst case (middle) and best case scenarios (bottom).

Figure 2 compares the operative temperature for the base case (ID 1: Iron roof, Concrete floor, Bare brick walls) the best, and the worst case scenarios: (ID 75: White insulated roof, Concrete floor, Brick wall, External Insulation) and (ID 17: Iron roof, Insulated concrete floor, Hollow concrete wall, Internal Insulation), respectively. As shown, the operative temperature ($T_{IO}$) for ID 75 is considerably more stable and is always below the maximum comfortable temperature ($T_{max}$) compared to the base case and the worst case scenarios. Unlike ID 75, the operative temperature for ID 1 and ID 17 frequently reaches the upper limit temperature ($T_{upp}$) which is an indicator of the severity of thermal discomfort.

According to the results, roof construction is the most critical building element affecting the thermal comfort conditions in low-income housing in Uganda. This confirms the findings of previous studies [17,18]. Insulating the roof would significantly improve the conditions and should therefore be considered as a major refurbishment strategy to mitigate negative effects of climate change. The findings also indicate that the conditions were always worse for hollow concede blocks compared with brick walls. Thus, hollow concrete blocks (and other low thermal mass construction methods/materials) should be avoided as much as possible. Yet, for the bare hollow concrete walls, thermal comfort considerably improved when walls were insulated externally (ID 6). This was clearly evident especially for Criterion 3 which reduced from 163 to 20 days a reduction of around 88% in the risk of overheating. External insulation was also very effective for brick walling and considerably reduced the risk of overheating.

Criterion 3 is an indication of extreme heat conditions showing the severity of thermal discomfort when operative temperature is 4 ºC above the maximum comfortable temperature ($T_{max}$ in Table 3 above). Criterion 3 is also an indicator of global warming and the “future climate scenarios” [22]. External wall insulation could therefore help to reduce the negative effects of climate change and global warming on low-income populations.

It should be noted that roof insulation has been significantly effective and some of scenarios only marginally failed the requirements when the roof was insulated. Therefore, external wall insulation may not be necessary or it could be considered as the second priority after roof insulation. This was more evident for the brick walls. For hollow concrete walls, the application of external insulation was considerably more effective and is therefore beneficial in combination with roof insulation. This appears to be due the lower thermal mass of hollow concrete blocks compared to brick walls and despite their lower thermal conductivity.

A key observation was that unlike brick walls, where internal insulation deteriorated the conditions, for hollow concrete blocks internal insulation slightly improved the conditions (except for cases 1-24 with bare iron sheet roof); however, internal insulation was never as effective as external insulation. Internal insulation should therefore be avoided specially for materials with higher thermal mass such as bricks or solid high density concrete blocks.

Similar to internal insulation, floor insulation also deteriorated the conditions and should be avoided. A possible explanation for this is the high thermal mass of the concrete floor and low average ground temperature of 23.5 ºC which was considered in the simulations. More investigation is required to evaluate the effects of floor insulation and thermals mass.

For the white painted roof, although the thermal comfort conditions were almost identical to insulated roof; it should be noted that built-up dirt, rust etc. could significantly increase the solar absorptance of painted roofs and neutralize/reduce the effectiveness of the roof. Therefore, roof insulation may be a preferred option particularly when it comes down to long-term maintenance.

The results also indicate that thermal comfort improved with 2 windows in the first 24 scenarios whereas it slightly deteriorated when the roof was painted or insulated. This could be due to the extremely bad conditions in the first 24 scenarios where the roof was covered with bare iron sheet and cross ventilation improved the conditions. Further research is required to evaluate the effects of openable windows and natural ventilation on thermal comfort in low-income tropical housing.

## 5. Conclusions

This paper evaluated the effects of thermal insulation on thermal comfort in low-income tropical housing. 96 combinations scenarios were simulated for free-running, low-rise buildings with brick and hollow concrete walls and iron sheet roofs as the major construction methods/materials in Uganda. The results of this study indicate that roof insulation is the most effective strategy to improve thermal comfort and reduce the risk of overheating. External wall insulation was also found to be effective although not as effective as roof insulations. Internal wall insulation should be avoided for brick walls (and walls with high thermal mass) as it could deteriorate indoor thermal comfort conditions. Internal insulation, in contrast, may be considered for hollow concrete blocks (and other materials with low thermal mass) as it can improve indoor thermal comfort. However, the priority should always be given to roof insulation flowed by the external wall insulation.

Floor insulation also deteriorates the conditions and should therefore be avoided. Due to the effectiveness of roof insulation and marginal improvements when combined with wall insulation, external wall insulation may be disregarded due to cost implications considering the context of low-income housing.

Painting the roof to reduce its solar absorptance also proved to be as effective as roof insulation. Therefore, depending on availability of materials, workmanship and costs, white paint could be a good alternative to roof insulation; however, it should be noted that, compared with insulated roof, painted roof may require more maintenance as built-up dirt, dust and rusted iron could significantly increase the solar absorptance properties of the roof offsetting the benefits of white paint.

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