# Reducing extreme discomfort in the global South – A comparison of a calibrated model and locally measured data from informal housing in Peru

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## Abstract

With most growth in urban population happening primarily through informal urbanisation, it is vital to identify cost effective measures for improving the often-poor housing conditions, which can have adverse health impacts on large parts of the population. The aim of this research is to investigate the indoor environmental conditions of self-constructed houses in low-income informal settlements in Lima, Peru, before and after implementing fabric retrofit strategies. Data loggers were placed in a family house in the informal settlement of José Carlos Mariátegui in Lima, measuring internal temperature and humidity at hourly intervals for two years. At the start of the second year the house underwent fabric improvement measures and particular roof insulation, following the recommendations of a calibrated dynamic thermal model. The results presented in the paper compare internal temperatures before and after retrofit as well as the modelling predictions. Overall, the measured data reveal the extreme indoor temperatures occupants are experiencing daily and the impact roof insulation has on these, with the modelling output predicting the reduction in daily peak internal temperature up to 3-5°C, and the measured data indicating an average of about 5°C on site, during warm months. The application of roof insulation on these self-constructed homes can be carried out by community members and was shown to be a cost effective measure, accounting between 5-10% of the total cost if it was to be implemented at the start of the construction process.

**Keywords -** extreme discomfort, internal temperature, retrofit, low-income, fabric insulation.

## 1. Introduction

For many decades urbanisation has been the main pattern of population growth globally, with the global South being at the centre of this growth, hosting 27 of the 33 biggest megacities around the world (Randolph & Storper, 2023), accommodating over 75% of the world's urban population (United Nations, 2022b). By 2050 the Global South may account for over 90% of the growth in urban population, reaching 7 billion inhabitants (United Nations, 2022a).

The primary mechanisms for housing urban dwellers and accommodating this rapid population growth in the global South, emerge primarily through the efforts of inhabitants themselves, building self-constructed homes and incrementally consolidating entire communities, in informal settlements. While the proportion of the global population residing in informal settlements is decreasing, their total population is increasing, with the number of people living in informal settlements exceeding 1 billion, according to the UN, (United Nations, 2022a).

Apart from the lack of basic services, and the difficulties in ensuring sustainable access to energy, the process of self-constructing homes comes with numerous other challenges. Acquiring land in hazard prone areas, sourcing materials, transporting these through often inhospitable terrain, weather-proofing various types of structures, are only some of the adversities settlers face in the pursuit of dignified living.

In most early formations, such self-construction practices result in the use of inadequate building materials, lack of sufficient living area, leaky building fabric, insufficient window areas for ventilation and daylight. Additionally, the often-dubious tenure status prevents early settlers from investing their already limited financial resources in improving the quality of their home, since the risk of eviction is always imminent. The result is poor housing conditions, which allow for extensive thermal discomfort and low indoor environmental quality, with adverse health impacts for the occupants. It is therefore vital to develop low-cost solutions for improving thermal comfort in low-income houses, which can be easily integrated in existing houses by community members.

This paper presents the output of such work, where roof insulation has been installed in a low-income self constructed home in the informal settlement of JCM in Lima, Peru, and the monitored as well as modelling results confirm the success in reducing thermal discomfort.

The following sections will present relevant important works, the methodology applied and the obtained results. A discussion of the implications of the work and the main messages for policy makers conclude the paper.

## 2. Background

Energy efficiency retrofits have been implemented and studied extensively in the global North across regions (Economidou et al., 2020; Fernandes et al., 2021), for residential (Saffari & Beagon, 2022), commercial (Lou et al., 2021; Ruparathna et al., 2016) as well as historical buildings (Webb, 2017). In the global South however, the subject of energy efficiency has seen less attention, especially in low-income areas where self-constructed homes are prevalent. In one of the earlier works, Mathews et. al. (1995) modelled the impact of cardboard on wintertime thermal discomfort, when applied as thermally insulating material on the envelope of self-constructed homes in South Africa (Mathews et al., 1995). The selection of cardboard, among other materials, was to accommodate the local communities' needs for accessibility, reusability, mobility and durability.

In more recent studies, more focus has been given to thermal discomfort due to high temperatures. In sub-Saharan Africa, surveys have indicated that over 65% of respondents described thermal conditions as uncomfortably warm. This has increased the need to explore ways of reducing internal temperatures by non-mechanical means, to avoid increasing energy demand for air conditioning (Adaji et al., 2019). In that perspective, studies making use of controlled experimental facilities in South Africa, showed that the use of reflective coatings on the roof and external walls of informal houses can reduce daily maximum temperatures as well as daily minimum temperatures by 4.3°C and 2.2°C respectively, in a warm and temperate climate near the city of Johannesburg.

Studies using empirical data to enrich the dynamic thermal modelling of informal dwellings in South Africa, calculated that the use of reflective paint on lightweight corrugated sheet roofing (cool roofs), can reduce excessive indoor heat stress by 42-63% (Hugo, 2023). Cool roofs were also the subject of a cross-city modelling study covering South Africa, India, Brazil, Kenya and Indonesia, assessing the impact of building design-related drivers on heat stress exposure. Their results showed that cool roofs, a rather universal solution, can reduce annual heat stress exposure by up to 91%, while by improving the building envelope to local building codes overall, the number of annual heat stress incidents in a city can drop by up to 98% (Nutkiewicz et al., 2022).

Contrary to these findings however, results of an experimental study making use of low-cost retrofit measures, showed that increasing the reflectance of the roof in a full-scale purposely built model of an unoccupied informal dwelling, was the least impactful measure, as it did not decrease the indoor temperature significantly. It was the application of thermal insulation which resulted in the reduction of internal temperature between 0.2-4.4°C (Bonaccorso et al., 2019). In further analysis, by using a validated dynamic thermal model, the researchers showed that an insulation board, made from recycled Tetra Packs, can effectively reduce indoor temperatures currently (2020s) and in the future (2050) by around 3°C, when combined with scheduled ventilation. This solution came at a cost of less than 1€/m2, making it relatively low-cost as well as easy to implement by local communities in South America and the Caribbean (Bonaccorso & Da Graça, 2022). Similar findings were drawn in an experimental study in Peru, using three full-scale purposely built unoccupied housing modules of different external wall construction (adobe, cement, wood), to investigate indoor thermal conditions under various roofing materials. The results showed that roof insulation can reduce indoor thermal discomfort, especially for the adobe and cement constructions (Wieser, 2016).

The presented work builds on these findings and by including empirical data from occupied homes as well as validated dynamic thermal building models, it reinforces the impact of insulating the roof of low-income self constructed homes in informal settlements can have, in reducing extreme discomfort.

## 3. Methods

### 3.1. Cases study house

This work is part of a larger project where internal temperatures were monitored in 45 houses in informal settlements in the city of Lima between 2021 and 2023. This study focuses on a rather representative house of lightweight construction in the José Carlos Mariátegui neighbourhood on the Andean hills, comprising a drywall construction for the external walls and a corrugated fibre cement sheet roof. This type of homes presents the worst thermal performance compared to other typical constructions (adobe, brick, cement), resulting in extreme thermal discomfort as found in previous work (Oraiopoulos et al., 2023). This was the main reason this house was selected to undergo roof insulation retrofit work, as well as the feasibility of performing works on the home and the obtained consent of the owner. The case study house, presented in Figure 1 below, has its four main sides fully exposed with one closely aligned next to the hill, leaving a small gap mainly due to earthquake risk structural considerations. One part of the house is made of drywall (living room, dining room and kitchen) and the other more precarious made with wooden boards (bedrooms).

Figure 1: Case study house. Onsite photo (left), 3D reality image from drone survey (right).

### 3.2 Data collection

Both outdoor and indoor environmental data were collected for a period 18 months between December 2021 and June 2023. The outdoor conditions were monitored hourly using a micro station data logger mounted on top of a concrete roof of one of the parish buildings, central to the informal settlement of José Carlos Mariátegui (see Figure 2 (left)). This was measuring: external air temperature (°C) relative humidity (%), solar radiation (W/m2), wind speed (m/s) and wind direction (°). The indoor conditions were also measured hourly, using a data logger placed in the main living space of the house (see Figure 2 (right)). This was measuring: internal air temperature (°C), relative humidity (%) and mean radiant temperature (°C). The pre-retrofit period was during the first 15 months of the monitoring (December 2021 – March 2022) and the post-retrofit period included the last three months of the presented data in this work (April 2023 – June2023).

Figure 2: Outdoor micro station data logger (left)

As the focus of this study is thermal comfort, the analysis will mainly concentrate on the temperature data and the differences between the pre-retrofit and post-retrofit periods.

### *3.3 Model calibration*

A dynamic thermal simulation model of the case study house was developed to help the decision-making process with regards to the exact specifications of the roof insulation, which was to be applied, to avoid any unintended consequences as well as over-costing of the works. The model was constructed using DesignBuilder, a performance analysis tool and easy-to-use interface for the widely used EnergyPlus software (see Figure 3)

*Figure 1: Case study house. Onsite photo (left), 3D reality image from drone survey (right).*

The main inputs to the model, summarised in Table 1, concerned the geometry, the thermal (construction) and the behavioural (activity) aspects of the house and the occupants. These were captured by measurements, questionnaires and local building materials and standards.

*Table 1: Main inputs to the dynamic thermal simulation model in DesignBuilder*

| Geometry | Construction | Activity |
|---|---|---|
| Drywall zone (D)<br>Floor area: 30m$^2$<br>Average height: 2.7m<br>Wood zone (W)<br>Floor area: 30m$^2$<br>Average height: 2.4m<br>Orientation (D): 37° | Ground:<br>reinforced concrete slab on the ground, without insulation; e=100mm<br>Walls:<br>drywall construction system with exterior fibre cement sheet (e=6mm), air chamber (e=100mm) and interior plasterboard sheet (e=120mm).<br>U-value = 1.997 W/m$^2$-K<br>Roof:<br>fibre cement corrugated sheet; 0.4cm.<br>U-value = 4.839 W/m$^2$-K<br>Windows:<br>single clear glass (e=4mm), metal frame.<br>U-value = 6.257 W/m$^2$-K<br>Door:<br>opaque wooden door (e=35mm).<br>U-value = 2.823 W/m$^2$-K | Occupancy density:<br>4 occupants/60 m$^2$ = 0.07 ppl/m$^2$<br>Internal gains = 2.93 W/m$^2$<br>Hourly schedule, activity template, derived from household surveys:<br>Until 07:00: 1<br>Until 08:00: 0.5<br>Until 14:00: 0.25<br>Until 20:00: 0.75<br>Until 24:00: 1 |

The external weather input data were given additional considerations since José Carlos Mariátegui is located at 18 kms from the international airport and at a 385m higher altitude on the Andean hills. Therefore, using the nearest official source for the .epw file was not regarded as representative of the local climate as it could add a significant source of potential error to the results. For this reason, the .epw file was edited using the onsite measured temperature, humidity, radiation, and wind data, to allow for increased confidence in the results.

The calibration of the model was centred around two main parameters, which are challenging to estimate and difficult to measure, the ventilation and infiltration rates. The infiltration rate calibrated value was based on a winter design week between 26th August and 1st September, for the ventilation to be kept at the minimum possible variation. Simulations were run at intervals between 2-8 ACH, with the best results given when infiltration was set to 8 ACH. The evaluation was based on statistical indicators as well as the visual inspection of the measured against the model data as seen in Figure 4 (left). Since a building calibration technique based on internal temperatures is not frequent in literature (Calama-González et al., 2021), the statistical indicators used were those often applied in energy-based calibration studies and given in the ASHRAE Guideline 14 (ASHRAE, 2002), namely CVRMSE and NMBE as also applied by (Petrou, 2023). This study also included the coefficient of determination (R2) to provide an indication of the overall fit of the data profiles. The ventilation rate calibrated value was based on a summer design week (12-18 March 2023) and was calculated to 40 ACH (for a window opening setpoint at 24°C) based again on the values of statistical indicators (R2, CVRMSE, NMBE). The results of the calibration can be seen in Table 2 below.

*Table 2: Case study house model calibration statistics between measured and modelled internal temperature.*

| | $R^2$ | CVRMSE (%) | NMBE (%) |
|---|---|---|---|
| Infiltration = 8ACH (calibrated during winter) | 0.93 | 6.25 | 0.41 |
| Ventilation = 40 ACH (calibrated during summer) | 0.94 | 3.93 | -0.83 |

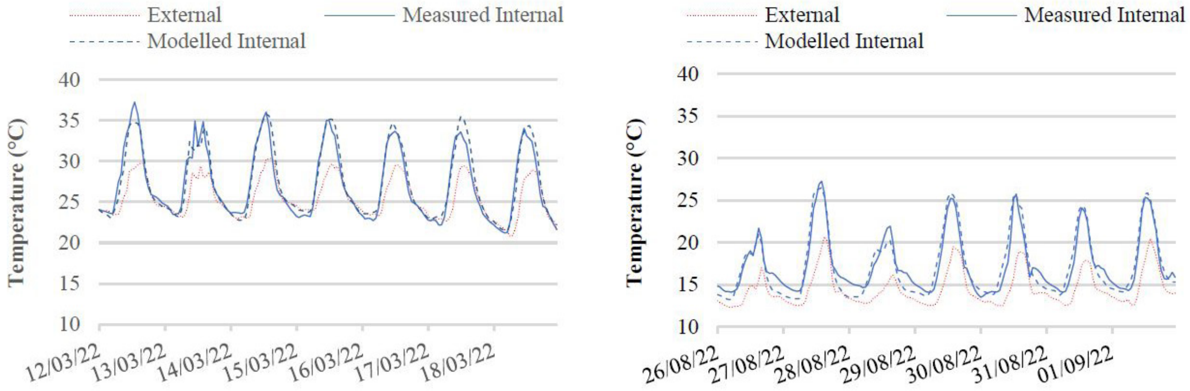

*Figure 4: Measured against modelled internal temperature data for an infiltration rate at 8ACH (calibrated during wintertime, left) and ventilation rate of 40 ACH (calibrated during summertime, right)*

The validated model was then used to assess the effectiveness of the different materials and thickness levels for the insulation of the roof. The results are presented in section 4.

## 4. Results and Discussion

This section presents the results from the roof insulation simulations as well as the measured data pre and post the retrofit works.

### *4.1 Roof simulation*

The roof insulation material, which was selected for being economical, lightweight, easy to acquire and easy to install, is an insulating panel composed of two layers of fibre cement and 5cm of expanded polystyrene (EPS) with a U-value=0.656 W/m2-K. This was added to the roof layer in the model and the simulation results for both summer and wintertime are presented in Figure 5 below.

The results from the simulations indicate that there is a reduction of thermal discomfort during both summer and wintertime. During summer the modelled daily peak internal temperature decreases by up to 3-5°C, while the daily minimum internal temperature (during nighttime) only increases by less than 1°C. During winter, the modelled daily peak internal temperature reduces by no more than 1°C, while the hourly internal temperature during nighttime increases by 1-2°C.

Since informal houses in Lima do not incorporate any mechanical heating or cooling, the insulation had to be arranged such as to control both solar incidence during hot weather and prevent heat loss during cold weather. The simulations suggested the installation of the specified roof insulation can offer these conditions as it was shown to improve thermal comfort substantially during both summer and wintertime, without the addition of any significant unintended consequences.

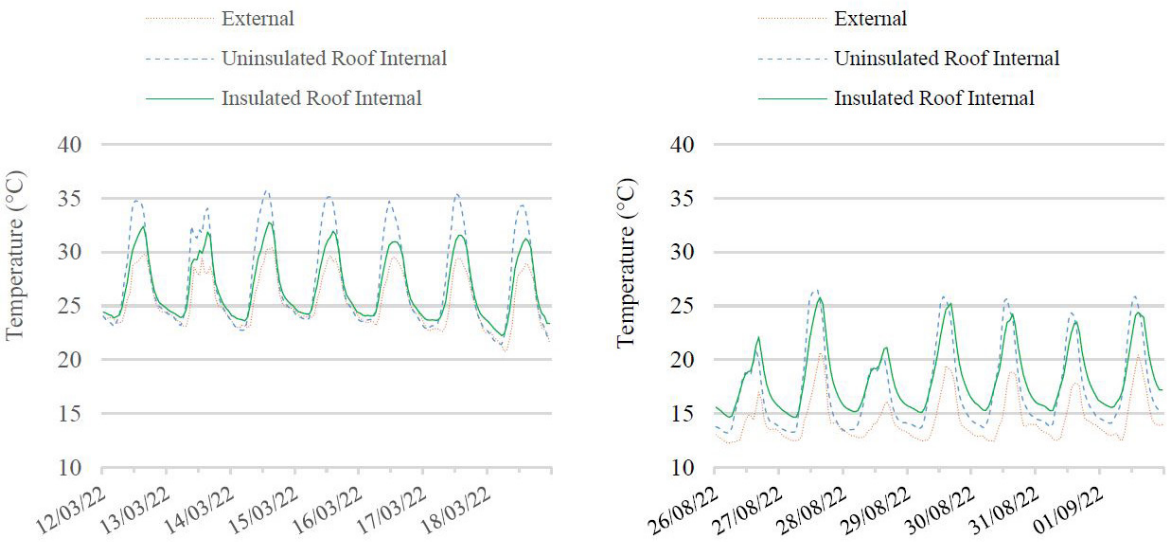

*Figure 5: Simulation results of the calibrated model for the impact of insulation on internal temperatures during both summer (left) and wintertime (right).*

### 4.2. Roof Insulation

Based on the modelling results, the installation of the roof insulation was carried out with the aid of a local NGO (CENCA). The installation of the insulated panels required structural reinforcement, hence the works lasted three days. The corrugated fibre cement sheets were placed again as an external layer to provide protection from the weather, as seen in Figure 6.

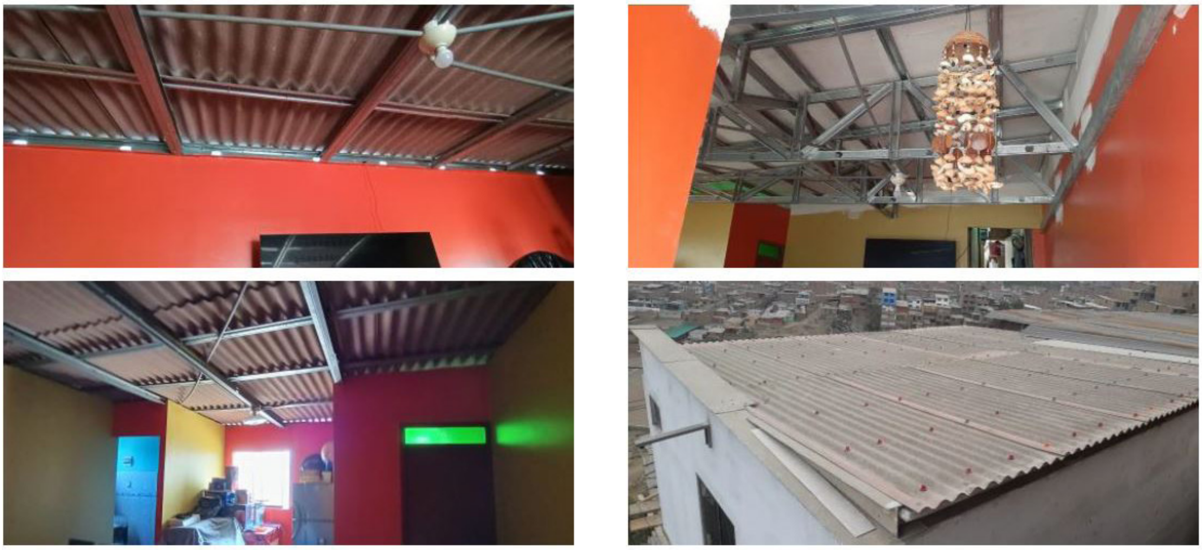

*Figure 6: Roof details before retrofit (left) and after the installation of the insulation (right).*

The total cost of the roof insulation for the 30m2 area was approximately US$1,200. This included material and labour, but also the removal and reinstallation of the existing roof, as well as the steel reinforcement structure, (approximately US$600 for labour and US$600 for materials). The local NGO CENCA is currently financing the construction of lightweight housing modules with uninsulated roofs, of similar floor area and materials, at an approximate cost of US$4,200 (approximately US$1000 for labour and US$3200 for materials), of which some US$600 are for the uninsulated corrugated sheet roof. Assuming the cost of labour will not change substantially, when constructing a new house with insulated roof, the increase in the overall cost should not exceed 5-10% compared to constructing a house with an uninsulated roof. It can also be noted that if the steel reinforcement structure is fully optimised for the appropriate load, the roof insulation cost could be further reduced to a value not exceeding 5% of the overall cost of the house, especially in the case of constructing more than one home.

### *4.3. Roof monitoring*

Following the installation of the roof insulation, the hourly monitoring of the internal temperature continued for the following 3 months. This work presents the measured impact of the roof insulation on internal temperatures during warm external weather in April, in Lima. Due to the extremely warm weather during winter months of 2023 (June-August) in South America and specifically the region of Peru, it has not been possible to assess the impact of the roof insulation during colder external temperatures. However, the monitored data suggest the reduction in thermal discomfort is substantial. Figure 7 and Figure 8 present the external and internal temperature throughout the monitoring period in lower and higher temporal resolution, which includes pre- and post-retrofit periods.

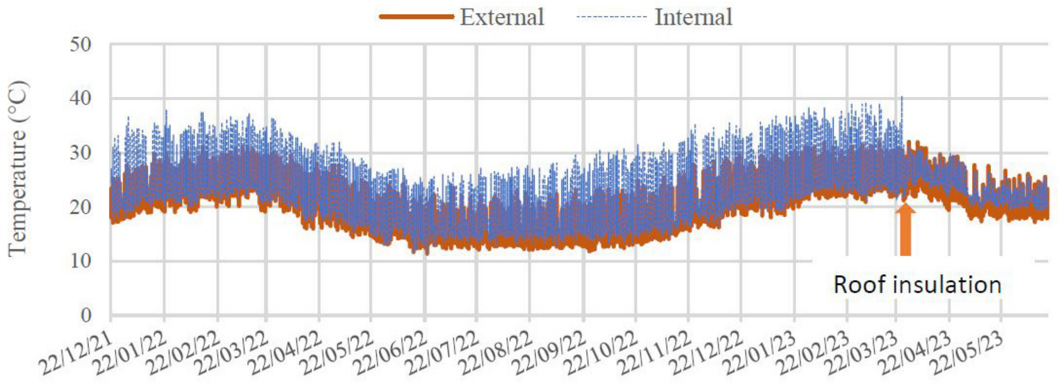

*Figure 7: Monitoring period: External and internal temperatures pre and post roof insulation retrofit date (25-28/03/23).*

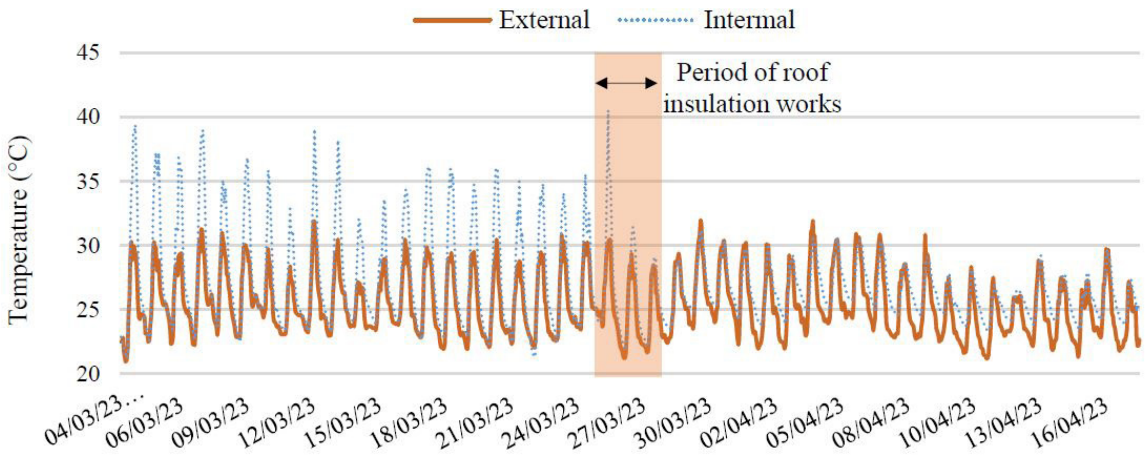

*Figure 8: External and internal temperatures pre and post roof insulation retrofit date (25-28/03/23).*

As it can be seen from Figure 7, the daily maximum internal temperature exceeds 30°C regularly from December up to April annually, often exceeding 35°C and reaching temperatures of almost 40°C, posing a significant health risk to occupants. In Figure 8 however, it is clearly indicated that the daily peak internal temperature post-retrofit was decreased by an average of about 5°C and in some cases up to 10°C, compared to pre-retrofit values. This is a significant reduction of the extreme discomfort the occupants experience on a daily basis during the warm months. The nighttime temperatures have also been affected, with the daily minimum shifted by 1-2°C. These findings are in line with the results from the calibrated model and confirm the impact of roof insulation in reducing extreme discomfort in low income, self-constructed homes in informal settlements.

## 5. Conclusions

This paper presented a study on the impact of roof insulation in low-income, self-constructed homes in informal settlements in Lima, Peru. Monitored data were used to calibrate a dynamic thermal model which was utilized in simulating the proposed retrofit design and test the impact ahead of the works. Overall, the results uncovered the large infiltration and ventilation rates possible in these houses, and the monitored data once more revealed the extreme thermal discomfort the occupants experience throughout the year. The findings show that roof insulation can reduce extreme thermal discomfort during warmer months, by lowering daily peak internal temperatures. Although during the period of monitoring, the region experienced an extreme lack of colder temperatures, the results from the calibrated model provide confidence of similar performance during colder weather. This was the first study of its kind in this informal settlement, suggesting the cost of future works can be reduced further, to maximum 5% of the total cost of a house, making this an affordable way to reduce extreme thermal discomfort.

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