Thermal comfort in low-income housing in informal settlements in Lima, Peru
Towards a localised adaptive comfort standard

Argyris Oraiopoulos1, Martin Wieser2, Marion Verdiere2, Pamela Fennell1, Paul Ruyssevelt1
1Energy Institute, University College London, London, UK
2Department of Architecture, PUCP University, Lima, Peru

Abstract
The rapid urbanisation of the Global South is of growing concern to policy makers especially since the formation of informal settlements is the prevalent pattern of growth. Housing conditions in these settlements are largely precarious and health hazards, for the low-income urban dwellers, are part of their daily living experiences. This work explores thermal comfort of the houses in some largest informal settlements using hourly measured internal temperatures from 30 homes in Lima, Peru. The results reveal the magnitude of exposure to adverse indoor environmental conditions in these homes. This first step in understanding some of the key issues these communities are facing, is critical in improving the planning decisions towards dignified housing in low-income communities in the Global South.

Highlights
- Internal temperatures in homes in informal settlements were found to be outside a comfort zone, based on adaptive criteria
- Internal temperatures below the lower limit of the adaptive criteria were recorded for all construction types
- Occupants expressed satisfaction despite measured data indicating otherwise

Introduction
The Global South is expected to be receiving over 90% of the growth in urban population from 4 billion to almost 7 billion by 2050. It is therefore imperative housing conditions are studied extensively, to increase the awareness around the health hazards often experienced in these settlements, mainly due to the inappropriate design and construction of houses. In addition, since the majority of these houses are lacking the existence of any heating or cooling related appliances, it is important to explore the risks associated with a potential uptake, especially in air-conditioning systems, which nonetheless is already taking place in households of higher income. This first step in understanding some of the key issues these communities are facing, is critical in improving the planning decisions towards dignified housing and secure infrastructure.

In Lima the population has doubled since 1980, to around 10 million inhabitants by 2022, with 50% living in self-constructed, low-income houses in informal settlements, mainly in the hillside areas of the Peruvian Andes. The inhospitable terrain together with the economic struggle of the local communities, have resulted in poor housing conditions that have adverse health impacts on large parts of the population (Gutiérrez et al. 2021).

This work is part of a larger project aiming to investigate the access to dignified housing and energy justice in informal settlements in the Global South. This paper presents one of the first studies of thermal comfort, making use of quantitative as well as qualitative data from indoor environmental conditions in informal settlements in Lima. There have been no previous studies on the thermal comfort of dwellings in marginal neighbourhoods in the urban areas of Peru.

Background
Thermal comfort has been a subject of research for many decades (Haldane (1905); Winslow et al. (1937); Gagge et al. (1969)), with two main approaches, the steady state model and the adaptive model, which is mainly based on the theory that the human body adapts to the outdoor conditions (Nicol (1993)). The most widely accepted definition “a condition of mind which expresses satisfaction with the thermal environment” (ISO (1990)), reveals its rather complicated and multidisciplinary nature. According to Rupp et al. (2015) there may be a number of factors that influence the sensation of thermal comfort, like cultural and behavioral aspects, age, gender, space layout, the possibility of control over the environment, thermal history and individual preferences. Taleghani et al. (2013) noted that the prediction of thermal comfort is rather difficult and apart from cultural influences it depends on environmental and personal factors.

The majority of thermal comfort theories, however, have been developed based on studies in the Global North. The adoption of these from international bodies, such as the ASHRAE, and their widespread implementation to cities across the Global South has, in many cases, resulted to the design of indoor environments, which are failing to meet the needs of the local population. Alnuaimi and Natarajan (2020) reported the consistent mechanical over-cooling of indoor spaces across four cities in India, Philippines, and Thailand. Although the observed temperatures were considered appropriated, based on design recommendations from standards such as the ASHRAE-55, thermal com-
comfort data from real buildings suggest excessive discomfort due to cooler temperatures than desired by occupants. With the globally rising demand for cooling threatening the future of climate change mitigation policies, it is important to be able to provide factual estimations of cooling needs. The parsimonious installation of air conditioning units will play a significant role in achieving the UN Sustainable Development Goal for electricity access (SDG7) in the Global South (Mastrucci et al. (2019)).

Such findings are also supported by research in North-East India, where researchers attempted the development of thermal comfort models taking into consideration variables like local indoor and outdoor temperature, relative humidity and clothing patterns (Singh et al. (2015)). The authors concluded that it is not possible to obtain a generalized thermal comfort model for all climatic zones. Further research making use of questionnaire-based field surveys indicated that preferred temperatures were 2.8°C lower than the comfort temperatures (Singh et al. (2017)). Similarly, Manu et al. (2016) found that occupants in naturally ventilated Indian offices were more adaptive than the prevailing ASHRAE and EN models would suggest, leading to the development of the India Model for Adaptive Comfort (IMAC).

In South America, Natarajan et al. (2015) compared thermal comfort data gathered in office buildings in Bogota, Colombia, and found the ASHRAE adaptive model underestimating discomfort in the natural ventilated offices due to lack of perceived or actual control. Molina and Yaguana (2018) focused on defining indoor environments comfort standards of urban dwellings in the city of Cuenca, Ecuador, taking into consideration factors such as temperature, air quality, and natural lightning. The authors reported that the levels of thermal comfort accepted by local users differ from those in international standards including ASHRAE-55. Rijal (2021) conducted thermal measurements and a thermal comfort survey during the winter in traditional vernacular houses, in the extreme cold climate of the Himalayan region of Nepal. Residents of houses with thick brick walls and mud roofs were highly satisfied with mean comfort temperature at 10.7°C, much lower than the thermal comfort standards recommendations.

Since thermal comfort is intrinsically subjective it is important to explore the thermal adaptation of people in different regions to allow for the development of localized adaptation policies for low energy building design (Yao et al. (2022)). The adaptive thermal comfort is a function of regional and local parameters, since the adaptation process, as well as the expectations and perceptions of people, are region specific and governed by local socio-cultural requirement. Therefore, more climate- and culture-localized standards should be given priority in the Global South.

In the case of Peru, there are few studies on local thermal comfort, most focusing on higher altitude regions in the Andean Highlands and in the Northern region. Such findings are also supported by research in North-East India, where researchers attempted the development of thermal comfort models taking into consideration variables like local indoor and outdoor temperature, relative humidity and clothing patterns (Singh et al. (2015)). The authors concluded that it is not possible to obtain a generalized thermal comfort model for all climatic zones. Further research making use of questionnaire-based field surveys indicated that preferred temperatures were 2.8°C lower than the comfort temperatures (Singh et al. (2017)). Similarly, Manu et al. (2016) found that occupants in naturally ventilated Indian offices were more adaptive than the prevailing ASHRAE and EN models would suggest, leading to the development of the India Model for Adaptive Comfort (IMAC).

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of fire and collapse. In these conditions of vulnerability, people constantly have to face risks, resist evictions and resist the loss of heritage in the neighbourhood.

The presented work concentrates on these two areas, José Carlos Mariátegui and Barrios Altos, which are essential in the development of Lima and make up for a significant part of its population.

**Temperature data**

Hourly measured internal air temperatures were measured from the main living space of 15 houses, in each of the settlements of José Carlos Mariátegui and Barrios Altos, from December 2021 until January 2023, using data loggers. During this time external temperatures were also measured in both sites. In Lima the hottest months of the year are usually February and March, while the coldest are July and August. The external weather data instrumentation as well as the data logger inside the homes is shown in Figure 1.

![Figure 1: External weather data instrumentation (left), data logger inside the homes (right)](image)

**Survey data**

The surveys were administered by Pontificia Universidad Católica del Perú in Lima, and were conducted with the aid of the local NGOs. All surveys were conducted within the period of temperature measurements. In José Carlos Mariátegui the survey was managed over an extended period between December 2021 and January 2023, while in Barrios Altos it was completed between March 2022 and December 2022. The main focus of the surveys was thermal comfort, allowing insights regarding perception of comfort both at the time of the survey but also throughout the summer and winter periods. Amongst many questions that were asked in terms of thermal comfort, the main question which this paper focused on are the following:

- **In general terms, how satisfied are you with the internal temperature of the house throughout the year?**

**Buildings**

In parallel to recording data on thermal comfort, during the surveys building envelope related data were also collected, categorising buildings in terms of thermal mass into light (wood construction or drywall without insula-

1The design of the survey was based on the official ASHRAE Standard 55 document: https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

2there where no means of mechanical ventilation installed in any of the houses and also none of the houses had large unglazed openings

\[ T_{upper} = 0.31x(T_m + 21, 3) \] (1)

**Thermal comfort criteria**

For the assessment of thermal comfort inside the homes the theory of adaptive comfort was used and more specifically the ASHRAE Standard 55-2017 (2017) ASHRAE (2020), since there are no national standards or norms in Peru, which determine a certain comfort zone. The adaptive comfort approach, developed by de Dear and Brager (1998) and Humphreys et al. (2016) analysed data from naturally ventilated buildings and concluded that indoor temperatures, which considered to be most comfortable increased significantly in warmer climates and decreased in colder contexts, indicating that humans have an inherent ability to adapt to environmental fluctuations and especially to seasonal variations of external weather conditions (Dear and Brager (2002); Kim et al. (2018); Martins et al. (2022); Fennell, Ruysevelt, Rawal, and Poola (Fennell et al.)).

The equipment that was used to measure the internal temperatures in the homes is capable of recording the internal mean radiant temperature and relative humidity. Yet, the ASHRAE Standard 55 requires the operative temperature to be applied. The CBE Thermal Comfort Tool Tartarini et al. (2020) was used to calculate the upper and lower limits of the adaptive comfort standard can also infer the operative temperature as an average of the air and radiant temperatures as long as:

- the occupants perform a quasi-sedentary physical activity
- they are not exposed to direct sunlight
- they are not exposed to air speeds greater than 0,10 m/s

The tool can be applied only for naturally conditioned spaces controlled by the occupants and if the following criteria are met:

- there is no mechanical cooling or heating system in operation
- metabolic rates ranging from 1.0 to 1.3 met
- Occupants are free to adapt their clothing to indoor and/or outdoor thermal conditions within a range of at least 0.5-1.0 clo.

Under these considerations, the formulas used to define the upper \( T_{upper} \) and lower \( T_{lower} \) limits are:
Results

External weather conditions

Before analysing the results for thermal comfort in homes, is it essential to inspect the external weather conditions in the two informal settlements. Figure 3 shows the external air temperature and relative humidity in of José Carlos Mariátegui and Barrios Altos.

These observations could mean that the light thermal mass buildings in José Carlos Mariátegui could present higher risks in terms of adverse health impacts, compared to Barrios Altos, especially during the warmer periods of the year.

Measured internal temperatures and adaptive comfort limits

Internal temperatures in homes without mechanical cooling or heating, were measured throughout the year in the two informal settlements. Theses where analysed based on the construction of the house as Figures 4 and 5 show. It can be observed that in the case of Jose Carlos Mariátegui, the light construction house presents a very wide range of temperatures both in winter and summer, while the heavy construction results in a much more tight range in both settlements. During summer (February) the internal temperatures in the light construction house exceed 30°C on a daily basis, often going above 35°C, even reaching 39.5°C in the case of Jose Carlos Mariátegui. In the case of Barrios Altos the medium construction house presents smaller daily variation, especially in the winter month of August, possibly due to reduced solar heat gains, since Barrios Altos has higher building density and is located in much closer to the coast, compared to Jose Carlos Mariátegui. One thing to note is the adaptive comfort envelope (based on the ASHRAE-55 standard), which for winter (August) is between 19°C and 26°C, while for summer (February) is between 21°C and 28°C, despite a difference of around 7°C in mean external temperature. The similarities in the ranges of these envelopes, between winter and summer, operate in favour of summer in terms of adaptive comfort, as it can be seen in Figures 4 and 5, meaning it is more likely to report comfort during summer than during winter.

Thermal comfort evaluation - Survey responses and adaptive criteria

This work combines hourly measured internal temperatures, for the duration of a year, together with survey responses from the occupants of the homes. After careful inspection of the data, the authors decided to omit data from three homes in Jose Carlos Mariátegui and two in Barrios Altos, as some anomalies were detected for which further investigation is required before they can be made.
The responses of the occupants however vary greatly, with pronounced issue with heat, especially in the light constructions. The measured external temperature are also presented.

The ASHRAE-55 adaptive comfort criteria were applied to the measured temperatures and the percentage of time during which the temperatures were above or below the adaptive comfort limits was calculated are presented in Figures 6 and 7, for 12 homes in Jose Carlos Mariátegui and 13 homes in Barrios Altos respectively.

Overall, it can be observed that the dominant problem, in most homes across both settlements, has to do with temperatures below the lower adaptive limit (blue bars) for most of the time during the colder months June-October. In Jose Carlos Mariátegui there seems to be a more pronounced issue with heat, especially in the light construction homes.

The responses of the occupants however vary greatly, with many households stating rather satisfied with the internal comfort.
temperatures throughout the year, a result which contradicts the outcome from the application of the ASHRAE-55 adaptive comfort criteria. One of the possible reasons for this discrepancy between the survey responses and the measured temperature data, could be the fact that many of the occupants in informal settlements migrate from regions higher up in the Andean slopes, where the climate is considerably colder throughout the year and have therefore been accustomed to lower temperatures for many years prior to migrating.

**Thermal comfort evaluation - Severity**

When considering adverse health impacts in terms of thermal discomfort, the severity of the discomfort is often of interest to researchers and policy makers. Figure 8 captures the severity of discomfort by presenting the degree hours above or below the upper or lower limit of the ASHRAE-55 for an average day, for every month in the year. This has been calculated by aggregating all the degree °C hours in a month and diving by the days in that month. This way an overall outcome on the severity of discomfort can be examined across the year. It can be observed that in Jose Carlos Mariátegui the health risks are much higher, especially during the colder months and for light construction houses. In Barrios Altos there is a single house of medium construction presenting excess discomfort where further investigation is required.

**Conclusion**

This work is one of the few studies that combine hourly measured internal temperatures, for the duration of a year, together with survey responses from the occupants of homes, and the only one in informal settlements in Lima, Peru. Although the sample size is relatively small for the extend of the communities in Jose Carlos Mariátegui and Barrios Altos, it allows for some robust conclusions to be made.

Firstly, it was observed that, despite the external weather conditions in both settlements were rather mild (minimum winter daily temperatures around 12°C and maximum daily summer temperatures slightly above 30°C), internal temperatures in homes were outside what could be considered a comfort zone, based on adaptive criteria. In some houses with medium construction (heavy walls + light roof) the minimum hourly internal temperatures were kept well above 30°C throughout the day and night during the hottest month of February. In light construction houses, the temperatures during summer could reach almost 40°C but they would drop below 24°C over night, allowing the dissipation of heat to some extent. It is evident that the light roofs contribute greatly to thermal discomfort, and future improvements of building envelopes should focus on retrofitting higher thermal mass materials on roofs.

Secondly, although severely high internal temperatures during summer are extremely worrying, especially for more vulnerable occupants, it was the low temperatures observed for many months of the year (May-November) which were highlighted in this study, in both informal settlements. Internal temperatures below the lower limit of the adaptive criteria (ASHRAE-55) were recorded for all construction types (light, medium, heavy, traditional), raising the need for better housing conditions as well as access to heating equipment and therefore to energy related infrastructure.

Thirdly, regardless of the outcome based on measured data, the survey responses allowed for further insights to thermal comfort in the informal settlements. These revealed the subjective nature of thermal comfort. Many of the occupants expressed they were rather satisfied with the thermal conditions in the houses, despite the measured data indicating otherwise. This could be attributed to the fact that many of the dwellers migrated from regions higher up in the Andean slopes, and therefore are accus-

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8 The Annex F Method B, ‘Degree-hours criteria’ in BS EN 15251 British Standards Institution (BSI) (2007), proposes a degree-hours method for taking into account both severity and occurrence of indoor overheating, which can have adverse health impacts.
Figure 8: Degree °C hours above or below the upper or lower limit of the ASHRAE-55 for an average day, for every month in the year, for Jose Carlos Mariátegui (left) and Barrios Altos (right)

tomed to colder climates than the one they experience in either Jose Carlos Mariátegui or Barrios Altos.

It has to be noted that this study took place during the years of the COVID-19 pandemic and accessing occupant’s home to place monitoring equipment and carry-out face to face surveys was a great challenge. The sample size does not allow making inferences across the population, still important insights have been collected. Future research should extend the questionnaire survey to capture socio-economical related variables as well as increasing the sample size.

Overall, this work contributed critical evidence to the continuous investigation of thermal comfort in the Global South. The outputs of the research will be used as inputs to calibrate Urban Building Energy Models, which will enable the simulation of large parts of the informal settlements. These models will then be used for the analysis of future scenarios in terms of climate change, impacts of heating and cooling equipment uptakes and health risk mapping, contributing to inclusive decision making towards dignified housing and habitat for all.

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