A thermal comfort model for high-altitude regions in the Ecuadorian Andes

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I, Isabel Mino-Rodriguez, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

In the

beloved memory of

Martin Mino Calle

Abstract

Of Ecuador's 3.75 million households, 33% live in poor-quality and substandard dwellings. Construction standards provide metrics and criteria for energy and comfort performance evaluation; that plays a significant role in designing adequate and affordable dwellings. Due to a lack of supporting evidence, the thermal comfort criteria have been adopted from international standards, such as ASHRAE 90.2:2018. In the absence of accurate contextualised comfort models, building standards can trigger a combination of wasting energy and exacerbating discomfort. Furthermore, householders' environmental perception may be affected by particular weather and geographical conditions. Therefore, this research aims to define thermal comfort criteria, aligned with residents' perception in subtropical highlands, to be used for the thermal performance assessment in dwellings in the Ecuadorian Andes.

The research combined cross-sectional thermal comfort surveys and thermal performance simulation. Data was collected in three locations between 2400 and 3000 meters above sea level. This thesis's main outcomes add knowledge on why and how people adapt to high-altitude locations. Thermal comfort temperatures are significantly different across the study locations due to altitude. Moreover, the comfort temperature differences also rely upon the broader limits of comfort acceptability for lower altitudes and acclimatised subjects. On the contrary, the range is narrower at higher altitudes and non-acclimatised residents. The derived high-altitude thermal comfort algorithm for the Ecuadorian Highlands resulted from the regression of the comfort temperature and the 24-hour mean outdoor air temperature. Over 80% of comfort hours were estimated for the study archetypes based on the high-altitude comfort model. International comfort models consistently overestimate the percentage of hours of discomfort for all the study archetypes. Moreover, the discomfort could increase up to 30% for dwellings in compliance with the thermal insulation requirement of the Ecuadorian construction standard (NEC11). The research outcomes are expected to contribute with grounded evidence to the development of local construction policy.

Impact Statement

The thesis advances understanding of thermal comfort and the adaptation and behavioural strategies of residents in high-altitude locations in the Ecuadorian Highlands. The knowledge, expertise, and results in this thesis aimed to benefit both thermal comfort research audience and public policy design in Ecuador. The key theoretical, methodological, and practical contributions of this thesis are:

- The primary outcome in this research is the definition of contextualised thermal comfort algorithms and acceptability comfort limits for high-altitude regions in the Ecuadorian Andes. Although the model was developed with data from three locations nearby Quito, the algorithms could be used as a reference for other high-altitude regions in Ecuador and South America due to similarities in contextual and cultural background. Furthermore, the research extends knowledge regarding the applicability of existing thermal comfort models and highlights the limitations to use the models in areas located 3000m above sea level. Furthermore, the thermal comfort algorithm is a crucial addition of knowledge towards policymaking in Ecuador. The high-altitude algorithms could guide the determination of the minimum thermal insulation requirements for free-running dwellings in local building codes. The method used allows for the contextualisation and tailoring of indices and parameters to the Ecuadorian Highlands' climatic and socio-cultural conditions.

- Two of the main methodological contributions of this research relates to a) the design and validation of data collection instruments and b) the definition of a simplified calibration process for the simulation of free-running buildings. On the one hand, the data collection instruments were designed and reshaped to overcome the inherent requirements, limitations, and constraints for conduction thermal comfort research in developing countries. The thermal comfort surveys used in the current research are helpful for the broader research community, particularly in Latin American countries. The structure and wording of environmental assessment questions were tested and piloted to be used in this research and the international project 'Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings'. In addition to the basic set of questions for thermal comfort studies, further questions were designed and evaluated in this research as an initial step to define a proxy to measure adaptation in high-altitude environments.

On the other hand, another significant contribution of this thesis is the comprehensive methodology for the calibration of free-running dwellings based on a detailed uncertainty and sensitivity analysis of input parameters where the indoor temperature is the key output for validation of models accuracy. Although the proposed calibration method was tested on a small number of cases with simple geometry, the methodological approach could be transferred and scaled up to other more complex free-running buildings.

Acknowledgements

The journey throughout this research has come with some redirections but undoubtedly plenty of achievements, growth and satisfaction. After three countries, four cities and different research groups, there are many people I am grateful to who supported me during the PhD. First, I owe gratitude to my supervisors Dr Hector Altamirano and Dr Ivan Korolija, for their guidance, support, and encouragement not only in my academic progress but in my personal development. I am deeply grateful to Professor Gary Raw for his invaluable support, constant guidance and constructive feedback. I am deeply grateful to Dr Jerko Labus (†) how guide my first steps and and encouraged me to start this journey.

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Contents

List of Figures

List of Tables

Nomenclature

Abbreviations

$adjPMV$	Predicted mean vote adjusted for the reduced atmospheric pressure
AMV	Actual mean vote
BSA	Body surface area
Clo	Clothing insulation
I_{clu}	Effective thermal clothing insulation
Met	Metabolic rate
$mTSV$	Mean thermal sensation vote
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASHRAE55:2017	Standards 55:2017 - Thermal environmental conditions for human occupancy
ASHRAE90.2:2018	Standard 90.2:2018 - Energy Efficient Design of New Low-Rise Residential Buildings
BES	Building energy simulation
BPS	Building performance simulation
EN	European Standard

HVAC	Heating, ventilation, and air conditioning
INAMHI	National Institute for Meteorology and Hydrology - Instituto Nacional de Meteorología e Hidrología
INEC	National Statistics and Census Institute - Instituto Nacional de Estadística y Censos
ISO15251:2007	DIN EN 15251:2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics
KG	Köeppen-Geiger climate classification
MIDUVI	Ministry of Urban Development and Housing - Ministerio de Desarrollo Urbano y Vivienda
NEC11	Ecuadorian Construction Standard - Norma Ecuatoriana de la Construcción
NREL	National Renewable Laboratory
REMMAQ	Metropolitan network for environmental monitoring network Quito - Red Metropolitana de Monitoreo Atmosférico
WWR	Window to wall ratio

Other symbols

a	Y intercept
AIC	Akaike Information Criterion
b	Slope of the regression line
BIC	Bayesian Information Criterion
$k-s$	Kolmogorov-Smirnov test
$k-w$	Kruskal-Wallis test
MAE	Mean absolute error

n	Number of observations
p	P value (p.value)
r	Pearson correlation coefficient
R^2	Coefficient of determination in multiple linear regression analysis
r^2	Coefficient of determination in linear regression analysis (r.square)
sd	Standard deviation
tH	Tukey HSD
VIF	Variance inflation factor
w	One-sample Wilcoxon rank test
$w-t$	Pairwise Wilcox test
df	Degrees of freedom
sig	Significance
t	t.test

Variables in this research

$\theta_{rm\alpha}$	Exponentially weighted running mean outdoor air temperature and the α value that corresponds to the degree of temperature response to the previous days
θ_{rm}	Exponentially weighted running mean outdoor air temperature
CO_2	Carbon dioxide
DB	Dry-bulb temperature
GHR	Global horizontal solar radiation
H	Absolute humidity
h_c	Convective heat transfer coefficient

h_{cc} convective heat transfer coefficient corrected when P_a significantly differ from the standard value ($101.33kPa$)

O_2 Oxygen

P_a Atmospheric pressure

P_{O_2} Partial pressure of Oxygen

PRE Precipitation

RH Relative humidity

t_g Globe temperature

t_n Neutral indoor operative temperature

t_o Indoor operative temperature

t_r Radiant temperature

t_a Indoor air temperature monitored continuously

t_{comf} Comfort temperature

t_{in} Indoor air temperature at survey time-t

t_{o-mean} Mean indoor operative temperature when voting between -1 to 1

$t_{out-ashrae}$ Daily mean dry bulb outdoor temperature calculated as the simple average between the daily maximum and minimum

$t_{out-iso}$ Daily mean dry bulb outdoor temperature calculated as the 24-hour average

t_{out-ma} Moving average of the dry bulb outdoor temperature from the last three hours

t_{out} Dry bulb outdoor temperature at survey time-t

$t_{pm\alpha}$ Prevailing mean outdoor temperature and the α value that corresponds to the degree of temperature response to the previous days

t_{pm}	Prevailing mean outdoor temperature
v_a	airspeed
WD	Wind direction
WS	Wind speed
APV	Air movement preference vote
ASV	Air movement sensation vote
HPV	Humidity perception vote
HSV	Humidity sensation vote
OSV	Overall satisfaction vote
TCV	Thermal comfort vote
TPV	Thermal preference vote
TSV	Thermal sensation vote

Chapter 1

Introduction

1.1 Overview

Thermal comfort international standards are a key component to tackle the ongoing challenge of providing adequate and affordable housing in Ecuador and Latin America. So far, construction guidelines and codes have focused on providing minimum criteria for functional, structural and safety requirements in buildings. Energy efficiency and thermal comfort models are only now being implemented in local codes, adopting criteria and recommendations from international standards. However, the real impact of energy efficiency and comfort criteria relies on tailoring performance criteria to the local context. In the absence of accurate models, building standards can trigger a combination of exacerbating discomfort and increasing resource use.

1.2 Housing deficit in Ecuador

A global action call to end poverty, protect the planet and ensure people's well-being has been integrated into the Sustainable Development Goals. Goal 11 – Sustainable cities and communities centred on providing adequate, safe and affordable housing for millions of people worldwide who live in overcrowded slums, health-threatening circumstances, and poor conditions (Funaro, 2011). Housing and neighbourhood conditions have a significant role in population welfare, quality of life, and development (Bouillon, 2012; Duryea and Robles, 2016). In most Latin American countries, the provision of adequate and affordable dwellings for the low-income population is one of the most significant challenges (Rojas, 2001). Adequate housing has been defined by UN-Habitat as a shelter that includes characteristics such as security of tenure, affordability, habitability, accessibility, cultural adequacy, and the availability of suitable services, materials, facilities and infrastructure (OHCHR, 2009). In 2012, one in three families in the region lived in unsuitable dwellings for habitation or units built with poor quality materials. Finding solutions to mitigate the shortage of affordable and adequate housing in a context of accelerated urban growth is a common concern.

In Ecuador, 52% out of 3.8 million households confront either a quantitative or qualitative deficit (INEC, 2010). Quantitative deficit refers to the shortage of units in relation to the number of households. However, Ecuador's qualitative deficit refers to dwellings under the minimum criteria for habitability[1], basic residential services[2], and envelope materials[3] (INEC, 2006). It is estimated that 19% of Ecuadorian families live in precarious housing units that require replacement. Moreover, 33% of the housing stock is classified as substandard, characterised by poor quality of buildings materials and lack of basic services. The situation is especially alarming in rural areas where more than two-thirds of the population face either a qualitative or quantitative housing deficit (INEC, 2010). In rural areas, 95% of the housing stock is built with poor quality materials (INEC, 2006). These precarious housing conditions tend to provide a poor indoor environment and unhealthy conditions (Habib et al., 2009).

Along with other countries in the region, the housing shortage is aggravated by the lack of affordable housing units, socio-economic inequalities, low-social investment and land scarcity (Alova and Burgess, 2017). Increasing population growth rates and rapid urban expansion exacerbate the problem (Acosta Paredes, 2003). The approach to tackle the housing problem centred on a national goal of securing access to adequate, safe and decent housing has been defined in the National Plan of Good Living 'Plan Nacional de Buen Vivir' (Senplades, 2014) The most important initiatives from the Ecuadorian government consist of increasing the number of direct housing subsidies and developing policies and technical standards. Housing subsidies are provided to construct new units and improve existing ones (Libertun de Duren et al., 2012).

Regarding policies and technical standards, until 2018, building codes only provided minimum criteria for functional, structural and safety requirements (Municipio del Distrito Metropolitano de Quito (DMQ), 2003). Energy efficiency criteria has only now been included in the last update of the Ecuadorian construction standard (Norma Ecuatoriana de la Construccion - NEC11) in the 2018 (Norma Ecuatoriana de la Construcción, 2018). Health and comfort are partly ac-

[1]The Habitability Index is defined as the square metres of usable floor space per person (Municipio del Distrito Metropolitano de Quito (DMQ), 2003).

[2]Minimum basic residential services refer to water supply connection, sewage network connection and electric power supply (Torres et al., 2002).

[3]Poor envelope materials or poor condition of the floor (i.e. cement screed, untreated wood/bamboo, earthen floor, raw stone), walls (adobe, bahareque, bamboo, plastic, and zinc) and roof (i.e. palm, straw, wood, sailcloth and plastic) (INEC, 2006).

counted for in this new section in the construction code, including recommendations for the minimum envelope thermal insulation requirements and indoor environmental quality criteria. The effort should be welcomed as it is the first attempt to incorporate energy, comfort, and health criteria in the national codes, but these require further review. Due to a lack of supporting evidence, the minimum requirements for the envelope thermal insulation and thermal comfort assessment have been adopted from the ASHRAE90.2:2018 standard for low-rise residential buildings (ANSI/ASHRAE/IES, 2018). When adopting existing policy from international standards, it is crucial to adapt the package of measures and requirements to the needs of a specific context (Thomas et al., 2013). The significant impact of energy efficiency does not rely only on the implementation of policy and regulations but on tailoring performance criteria and indices, particularly thermal comfort indices, to the local context's climatic, economic and socio-cultural conditions.

1.3 The role of thermal comfort models in energy efficiency standards

Energy efficiency plays a crucial role in mitigating the climate impact of buildings while ensuring high performance and reducing emissions. Several building standards, policies, and incentives have been created to tackle the concerns of energy performance. Most of these provide a conventional approach for assessing the environmental impact of building performance based on primary energy consumption or CO_2 emissions equivalent units (Grove-Smith et al., 2018). The great challenge comes with maintaining comfortable and healthy inhabited environments while reducing resources demand (D'Oca et al., 2016). In recent decades, the urgent need to reduce energy consumption's economic and environmental effects turned research attention towards the study of thermal comfort. Research in the field has concentrated primarily on addressing topics such as developing models and indices and establishing thermal comfort international standards and evaluation methods (Djongyang et al., 2010).

Thermal comfort models adopted at international standards, such as ASHRAE standards and the European Standard (EN), are based on studies conducted mainly in the global north to respond to a particular context and cultural background. It is estimated that half of the energy consumption in buildings is used for heating and cooling purposes in those countries. Consequently, energy targets are closely linked to the provision of thermal comfort for mechanically conditioned buildings. Herein lies the importance of current thermal comfort models to accurately predict subjective responses to the thermal environment in real buildings. Based on the methodological and fundamental approach, existing thermal comfort models are classified as heat balance (Fanger's heat balance model and Pierce two-node model) and adaptive comfort models (ASHRAE55:2017 and ISO15251:2007). The heat balance models are built on the principles of heat balance and human thermoregulation physiology to determine a range of comfort temperatures at which most occupants will feel comfortable. The adaptive comfort model was derived from field studies analysing the acceptability of a real-world thermal environment, which strongly depends on the context and occupant behaviour and expectations.

Current thermal comfort models, both the heat balance and adaptive comfort models, fail to fully explain the wide range of observed thermal responses in field studies. The adaptive comfort model predicts comfort temperature from the correlation between comfort votes and environmental parameters. The model summarises useful information observed on the scattered data on thermal comfort graphics representing the population's diversity of responses (Schweiker et al., 2018). In contrast, the Fanger's heat balance model is based on individuals exposed to climate chambers or uniform conditions, ignoring real-world natural variable conditions. Besides, Fanger's heat balance model applies only to environments up to 3000m above sea level; hence, it cannot be used for some high-altitude locations in the Andes. In comparison, the adaptive comfort standards are recommended when the running mean or prevailing mean temperature is above 15 °C (ISO15251:2007) or 10 °C (ASHRAE55:2017). Therefore, considering those constraints, neither comfort standard should be applied to predict comfort in high-altitude locations. A variety of thermal comfort models have resulted for different regions as a response to the existing discrepancies between recommended thermal comfort models and subjective votes of participants in fieldwork studies.

Furthermore, thermal sensation differs between individuals, even under the same environmental conditions, due to the complex interaction between the indoor environment and occupants. Six main factors are considered to affect thermal sensation, four physical variables (air temperature, air velocity, relative humidity, mean radiant temperature) and two personal variables (clothing insulation and activity level, i.e. metabolic rate). Moreover, several physiological, psychological and behavioural adaptation factors affect thermal perception (de Dear et al., 1997). Despite broad evidence concerning human thermal comfort from physiological, adaptive, and social convention paradigms, little is known about the complex interaction between these adaptation factors. Global and local challenges exacerbate the urgent need to understand these individual differences and incorporate the effect of diversity to enhance thermal comfort predictions. In the absence of accurate models for a particular climatic and cultural context, building standards can trigger a combination of wasting energy, exacerbating discomfort and losing the benefit of existing ways in which people adapt to their local climate.

1.4 Problem statement

To create adequate and affordable dwellings while reducing and optimising resource demands requires a tailored definition of metrics and evaluation criteria according to the particular context, climate and socio-cultural conditions requirements for the dwellings' performance assessment. Thus, there is the need to research the applicability of ASHRAE90.2 recommendations to the Ecuadorian Andes. Figure 1.1 summarised the region's housing problem and the possible consequences of adopting non-contextualised thermal comfort models.

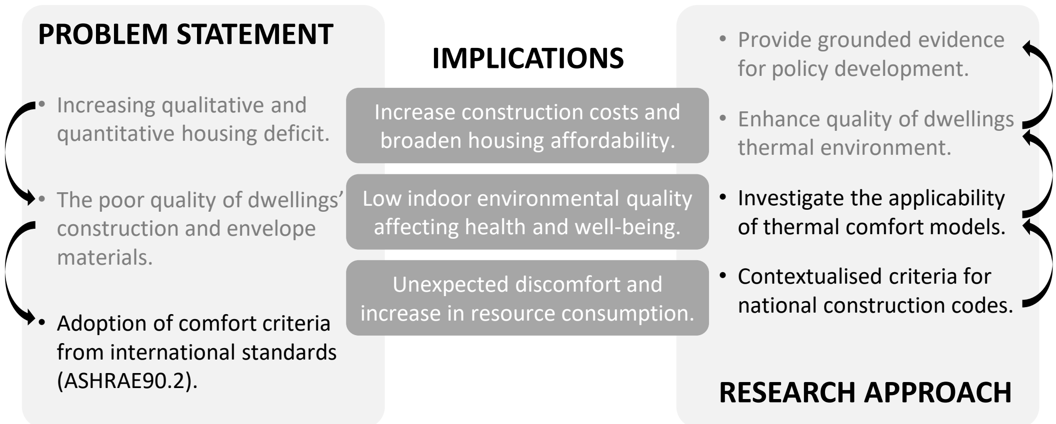


Figure 1.1: Problem statement and proposed research approach

The existing housing stock corresponds to uninsulated units that operate under free-running conditions throughout the year. Adopting minimum requirements for building envelope thermal insulation and thermal comfort models might increase construction costs exacerbating housing affordability. In addition, enhancing the envelope thermal insulation requirements and minimising airtightness might generate unexpected discomfort, leading to a previously non-existent heating or cooling energy demand. Lastly, considering that there is no energy consumption associated with dwellings conditioning and that users rely on adaptation to restore comfort, thermal comfort models become the main criteria for thermal performance evaluation.

The Andes regions' subtropical climate is characterised by narrow annual temperature oscillation, diurnal temperature variation, low atmospheric pressure and high solar radiation levels. Current thermal comfort models result from experiments and fieldwork conducted across various climate zones, including temperate, hot-humid and cold weather. Nevertheless, little research has been conducted to evaluate the subject's assessment of the thermal comfort of dwellings located in subtropical highland climates, particularly in the Andes. Evidence from studies conducted in other high-altitude regions, like the Himalayas, has highlighted the adaptation of long-term residents in dwellings where lower comfort temperatures and broader temperature ranges are acceptable for inhabitants.

Lastly, local inhabitants' adaptation to the cold and low-pressure environment may lead to differences in the indoor environment perception. Thus, it is important to study the singularities of residents and their thermal preferences. A deeper understanding of the main factors driving differences in thermal perception might allow the enhancement of thermal comfort acceptability, diversification of mechanisms to provide comfort and energy demand and consumption reduction.

Based on the abovementioned, the question that arises is whether current thermal comfort models are appropriate for predicting thermal comfort and evaluating the thermal performance of dwellings in the Ecuadorian Andes. Otherwise, is there scope for adjusting the existing thermal comfort models to maintain thermally satisfied occupants while optimising resource demand?

1.5 Aim and objectives

The importance of this research lies in the necessity to provide grounded evidence for the definition of thermal comfort criteria for the evaluation of dwellings' performance, and informing the construction codes for the Ecuadorian Andes. In response to the need for research and the lack of evidence of thermal comfort fieldwork studies, this research formulates one research aim and three specific research objectives.

Research aim:

- To define thermal comfort criteria, aligned with residents' perception in subtropical highlands, to be used for the thermal performance assessment in dwellings in the Ecuadorian Andes.

Research objectives:

- To investigate the drivers leading to diverse thermal responses of subjects exposed to high-altitude environments in a subtropical highland climate.

- To define a thermal comfort model that better predicts residents' subjective responses from free-running dwellings in Ecuador's subtropical highlands.

- To evaluate the applicability of thermal comfort models in the subtropical highlands in assessing the thermal performance of housing archetypes in the Ecuadorian Andes.

The research aims to study thermal comfort perception and the thermal performance assessment of dwellings in high-altitude environments. Thus, the study sites were restrained to locations between 2400 and 3000 meters above sea level. For this purpose, the research combined methods for collecting objective and subjective data. Fundamentally, the research used cross-sectional thermal comfort surveys and dwelling audits and building performance simulation (BPS). The cross-sectional thermal comfort survey for investigating drivers of diversity and informing the development of a thermal comfort model for the highlands. Meanwhile, dwellings audit (interviews and monitoring) and BPS for assessing the thermal performance of representative archetypes and evaluating the applicability of the thermal comfort models.

1.6 Research scope

This research's scope is the development of a thermal comfort equation aligned to the perception of residents in the Ecuadorian Andes. The adaptive comfort approach, used to derive the high-altitude comfort model in this research, clearly define the indoor temperature in relation to the outdoor temperature assuming subjects adapt to the prevailing conditions. However, little is know about the adaptation process in low pressure environments. Thus, the proposed research approach seeks to understand the thermal preferences and behavioural strategies of acclimatised and non-acclimatised residents in high-altitude regions in the Ecuadorian Andes. For this purpose, the proposed research combines a cross-section thermal comfort survey in different high-altitude locations in Ecuador and thermal performance simulation to evaluate the high-altitude thermal comfort model's applicability.

The thermal comfort survey aims to collect the subjective assessment from acclimatised and non-acclimatised residents in the studied locations. Besides, other key demographics to consider for thermal comfort studies are age and gender. This research's sample was limited to participants aged between 18 and 65 years old due to ethics and social constraints, keeping as close as possible a proportional male-to-female ratio. Furthermore, testing the high-altitude thermal comfort model's applicability in local dwellings was restrained to archetypes representing the study region's main archetypes. The selected dwellings belong to the defined high-altitude locations. The selected archetypes correspond to uninsulated and free-running dwellings based on the studied region's dominant housing stock patterns. Only single-family detached homes were selected to simplify data collection, calibration and modelling for thermal performance assessment.

1.7 Overview of the thesis

The thesis contains seven further chapters, as seen in Figure 1.2. **Chapter 2** provides an overview of the study context and climate in the highlands. The systematic literature review focuses on thermal comfort models and drivers of diversity in thermal perception in high-altitude regions. The methodological approach in **Chapter 3** is described in five main sections. The first section describes the theoretical approach and research design implemented in this research. The second section describes the site selection process of the three study locations. The methods used for the design and implementation of the thermal comfort survey are detailed in the second section. The third section describes the methodological approach used for the thermal performance assessment of the selected archetype. Lastly, the chapter concludes with a summary of the approach followed to address ethics, risk assessment and data protection implications.

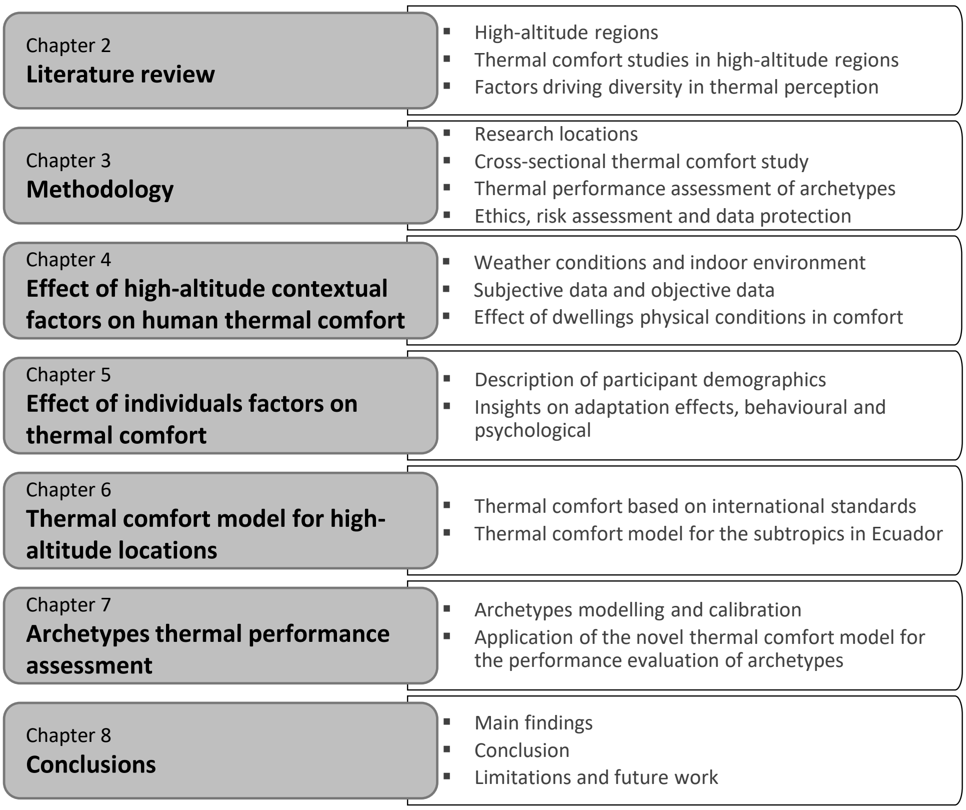


Figure 1.2: Overview of the thesis structure

The results from this research are presented in four chapters. **Chapter 4** and **Chapter 5** explore the different drivers of diversity from the context and individuals, respectively. Both chapters discuss the effect of diversity factors in thermal sensation due to physiological, psychological, behavioural, social, cultural and contextual conditions. **Chapter 6** focuses on analysing the subjective responses collected for the studies and compares the results with the current thermal comfort models from international standards. Furthermore, the chapter describes the implications and development of the high-altitude thermal comfort model derived from the collected data. **Chapter 7** evaluates the applicability of the novel thermal comfort model for high-altitude regions on the annual thermal performance of dwellings in the Andes. The analysis employs calibrated energy models from the studied archetypes. Finally, **Chapter 8** discusses the main research findings and annotates the conclusions drawn from this research. The chapter finalises by describing the limitations of this work, implications for policy guidance, and future research recommendations. Supplementary material is organised into five appendices includes additional literature review material (Appendix A), data collection instruments (Appendix B), evaluation of participant's simultaneous response (Appendix C), ethics, risk assessment and data protection (Appendix D), and monitoring and calibration data (Appendix F).

1.8 Publications from this thesis

One peer-reviewed journal paper and one peer-reviewed conference paper have been published. Furthermore, four additional peer-reviewed journal papers are in progress to publish the most relevant findings from this research.

Peer-reviewed journal paper

- Mino-Rodriguez, I. Naranjo-Mendoza, C. Korolija, I. (2016) 'Thermal assessment of low-cost rural housing — A case study in the Ecuadorian Andes'. *Buildings*, 6, 36.

  The relevant PhD chapters: Chapter 2 (Literature review) and Chapter 3 (Methodology).

Peer-reviewed conference paper

- Mino-Rodriguez, I.; Korolija, I.; Altamirano, H, (2018) 'Thermal comfort in dwellings in the subtropical highlands - Case study in the Ecuadorian Andes'. *Conference Proceeding: 10th Windsor Conference - Rethinking Comfort*, Windsor, UK.

  The relevant PhD Chapters: Chapter 2 (Literature review), Chapter 5 (Effect of individuals factors on thermal comfort) and Chapter 6 (Thermal comfort model for high-altitude locations).

Peer-reviewed journal paper - In progress

- Mino-Rodriguez, I. Korolija, I. Altamirano, H. Raw, Gary. (In progress) 'Explaining the diversity of subjective thermal performance assessment of residents in the Subtropical highlands'.

  The relevant PhD chapters: Chapter 2 (Literature review), Chapter 4 (Effect of high-altitude contextual factors on human thermal comfort) and Chapter 5 (Effect of individuals factors on thermal comfort).

- Mino-Rodriguez, I. Korolija, I. Altamirano, H. Raw, Gary. (In progress) 'An adaptive comfort model for residential buildings in subtropical high-altitude regions – Study in the Ecuadorian Andes'.

  The relevant PhD chapters: Chapter 2 (Literature review), Chapter 3 (Methodology), and Chapter 6 (Thermal comfort model for high-altitude locations).

- Mino-Rodriguez, I. Korolija, I. Altamirano. (In progress) 'Evaluating the applicability of the adaptive comfort model for dwellings in the Subtropical highlands'.

  The relevant PhD chapters: Chapter 2 (Literature review), Chapter 3 (Methodology), Chapter 6 (Thermal comfort model for high-altitude locations) and Chapter 7 (Archetypes thermal performance assessment).

- Mino-Rodriguez, I. Korolija, I. Altamirano. (In progress) 'Calibration method for simple free-running buildings based on indoor air temperature'.

  The relevant PhD chapters: Chapter 2 (Literature review), Chapter 3 (Methodology), and Chapter 7 (Archetypes thermal performance assessment).

Chapter 2

Literature review

2.1 Overview

It is estimated that 81.6 million people live permanently in environments located at altitudes above 2500m (Tremblay and Ainslie, 2021). People live under the constant stress of low atmospheric pressure in high-altitude regions, increasing solar radiation and diurnal temperature oscillation. When the atmospheric pressure is significantly lower than the standard value at sea level (101.33kPa), the evaporative heat transfer increases, and the convective heat transfer decreases. Therefore, besides the effect of temperature and solar radiation on thermal balance, the total heat exchange between the human body and the environment increases as atmospheric pressure decreases (ASHRAE, 2009; Wang et al., 2010). The impact of these physiological strain and human adaptation in thermal perception needs to be understood to improve high-altitude comfort prediction. Despite some background adjustments to the models recommended by some guidelines, evidence from existing research highlights the importance of contextualising thermal comfort criteria to socio-cultural and climatic conditions.

The literature review in this chapter aims to gain insight into thermal comfort studies and the diverse means of adaptation in high-altitude regions. The chapter has been structured into three sections. The first section introduces high-altitude regions in the world and the weather in these regions. The second and central part of the review focused on thermal comfort studies in high-altitude regions. The section provides an overview of thermal comfort models incorporated in current international standards and a thorough description of thermal comfort studies' main findings in low-pressure environments. Lastly, the third section provides an overview of the contextual (climate and buildings physical conditions) and individuals (behavioural, physiological, and psychological adaptive processes) drivers of diversity affecting occupants' thermal perception.

2.2 High-altitude regions

High-altitude regions are not only one of the most threatening environments for human health, survival and reproduction but are also the least economically developed regions (Bigham, 2016; West et al., 2012). High-altitude population resilience and adaptability results in a lower feeling of discomfort or irritation even in extreme conditions. Resilience and tolerance to thermal extremes are even higher among inhabitants with low socio-economic backgrounds (Shastry et al., 2016).

The term 'high-altitude' refers to the vertical distance above sea level and stand for environments located at a high elevation. Nevertheless, the definition of a high-altitude threshold differs between high and low latitudes (Inouye and Wielgolaski, 2003). Although no threshold has been defined as altitude boundaries, physiologically high altitude refers to the limit where humans experience symptoms related to low-pressure environments. Hence, based on the physiological effect of high altitude, three altitude ranges have been defined as follows: high-altitude (1500 to 3500m), very high altitude (3500 to 5500m) and extreme altitude (above 5500m) (Paralikar and Paralikar, 2010). Three regions hosting high-altitude populations are the Tibetan plateau and Himalayan valleys (Southwest Asia), the Ethiopian Highlands (Africa) and the Andes (South America), shown in Figure 2.1.

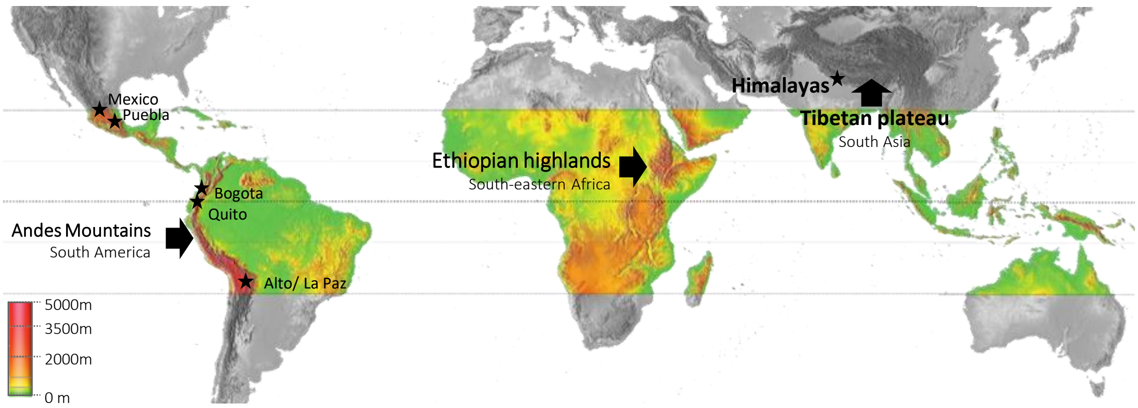


Figure 2.1: High-altitude regions

The Andes Region extend continuously near the west coast of South America from Colombia in the north to the southern part of Chile in the south. The mean maximum altitude at the tropics and subtropics is over 4000m above sea level, altitude decrease as the Andes runs south (Garreaud, 2009). Ecuador, the area of interest in this research, is located in the western part of South America and is divided into three continental regions: Coastal, Andean and Amazon regions, as seen in Figure 2.2.

Figure 2.2: Ecuador's location and geographical regions

The Andean region is home to over 45% of the population of the country. The major cities in the highlands, such as Quito (Capital city), Cuenca, Ambato and Riobamba, are located above 2600m above sea level (See Appendix A.1).

2.2.1 Climate in high-altitude regions

The effect of mountains own mass on the air circulation patterns, precipitation, and radiation create a great variation of climate. However, some general patterns differentiate high altitude from low altitude climate (Inouye and Wielgolaski, 2003). The effect of the altitude above sea level and soil relief produce multiple microclimates over short horizontal distances. As altitude above sea level increases, temperature, atmospheric pressure, absolute humidity, and dust content decrease. The thinner atmosphere enhances the incidence of solar radiation, especially of ultraviolet wavelength. Precipitation increases above 4000m, and intensity differs between windward and leeward mountain slopes. Similarly, wind speed increases considerably in the valleys, where mountains act as barriers and funnel the air movement. According to the latitude, high mountains collect permanent snow and ice on their peaks and ridges (Inouye and Wielgolaski, 2003; West et al., 2012). The major physical changes in atmospheric pressure, air temperature, humidity and solar radiation are described below:

- **Atmospheric pressure** decreases with increasing elevation from sea level; the higher the altitude, the less air overhead. Barometric pressures variation depends on altitude, latitude and seasonality. The fall of barometric pressure does not affect the oxygen (O_2) concentration that remains unchanged. However, the human body adjusts to overcome the reduction of the partial pressure of oxygen (P_{O_2}) of the inspired air.

- The decrease in **air temperature** (*DB*) is roughly linear with altitude ascent in the troposphere. Although the figure of 1.0 °C per 150m is usually given as lapse rate, there is no uniform rate for the decline. At any given latitude, the monthly temperature variation is less at high altitude than at sea level and virtually disappear at the equator. Because of the effect of high solar radiation, a considerable diurnal variation in the range of 30.0 °C is observed under clear sky condition. The daily temperature oscillation is lower under overcast sky conditions (West et al., 2012).

- **Absolute humidity** (*H*) - the mass of water vapour per unit volume of gas at the prevailing temperature - is low at high altitude where the water vapour pressure is depressed at the reduced temperature (West et al., 2012) However, **relative humidity** (RH) is the metric of humidity used in thermal comfort studies and the available one to describe the water vapour concentration present in the air. RH represents the relationship between the actual vapour concentration and the saturation concentration at the same temperature.

- The incidence of **solar radiation** increases noticeably with altitude as the thinner atmosphere reduces the sunray absorption. The reduced density of the air causes increases radiation up to 100% at an altitude of 4000m compared to sea level. Besides, water vapour in the atmosphere absorbs substantial amounts of solar radiation (West et al., 2012). A 4% per 300m increment of ultraviolet radiation is observed in altitude due to less water vapour and particulate matter in the atmosphere (Parsons, 2014).

2.3 Thermal comfort models in high-altitude regions

Few thermal comfort studies have been conducted to investigate the low-pressure effect on thermal comfort and thermal performance assessments. This section reports the current knowledge and findings from a systematic literature review and theoretical (see Appendix A.2) and methodological contribution to thermal performance in high-altitude regions.

2.3.1 Thermal comfort models in current international standards

Thermal comfort has been defined as *' that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation'* (ANSI/ASHRAE/IES, 2017). Thermal comfort occurs when the body's temperature is within narrow ranges, the skins' moisture is low, and thermoregulation effort is minimal. However, cognitive judgement is also influenced by physiological, psychological, and behavioural adaptations (ASHRAE, 2009). Different thermal comfort models have been developed for understating and predicting satisfaction with the thermal environment. Based on the methodological and fundamental theory, the models have been classified as a) classic heat balance models, b) adjusted heat balance models, c) adaptive comfort models, d) thermophysiological models (Schweiker et al., 2018). Despite the large number of existing thermal comfort models, the ones commonly used in thermal comfort research are the models incorporated in current international standards, Fanger's heat balance model and the adaptive comfort model (ANSI/ASHRAE/IES, 2017; EN ISO, 2005, 2007a).

Fanger's heat balance model, derived from research conducted in a controlled climate chamber, combines the heat balance theory and thermal regulation physiology. This model asserts that human satisfaction or dissatisfaction with the thermal environment results from four environmental parameters and two personal variables. The environmental parameters are air temperature (t_{in}), mean radiant temperature (t_r), airspeed and, relative humidity (RH). Additionally, the two personal variables correspond to the activity level (Met) and clothing insulation (Clo). Fanger's heat balance model, or simply referred to as the PMV model, uses two main indexes for estimating comfort conditions, the predicted mean vote (PMV) and the predicted percentage of dissatisfaction (PPD). PMV predicts the mean value of thermal votes of a group of subjects exposed to the same steady-state environment according to the ASHRAE seven-point thermal sensation scale (Table 2.1). The recommended limits for comfort zone are $-0.5 < PMV < +0.5$, and those voting outside these limits are counted as dissatisfied. PPD defines the percentage of people predicted to be dissatisfied due to uncomfortably warm or cold conditions (ASHRAE, 2009; EN ISO, 2005).

Table 2.1: ASHRAE seven-point thermal sensation scale

-3	**-2**	**-1**	**0**	**+1**	**+2**	**+3**
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

The adaptive comfort model asserts that *'if a change occurs, which produce discomfort, people react in ways which tend to restore their comfort'* (Humphreys and Nicol, 2002). Thus, occupants play an essential role in achieving their thermal preferences through their interaction with the context. When the adaptive opportunities are insufficient, deviation from thermal neutrality occurs, leading to thermal discomfort. Furthermore, occupants' expectations about the indoor environment are greatly influenced by prevailing outdoors conditions, behaviour modifications, and habituation (Brager and De Dear, 1998; Djongyang et al., 2010). The index used to express the effect of the surrounding thermal environment in the human body is the operative temperature

(t_o) (Nicol and Humphreys, 2010). Based on the results of several field studies in free-running buildings, the optimal t_o is predicted by a simple regression of indoor temperature with the prevailing outdoors conditions as in Equation 2.1 (Humphreys et al., 2007).

$$t_n = b \cdot t_{out} + a \tag{2.1}$$

Where t_n is the neutral indoor temperature, t_{out} is the outdoor reference temperature. The function slope (b) is proportional to the degree of adaptation to the different climatic conditions, and a is the y-intercept. Values for a and b might differ among studies due to cultural background, climate and other contextual factors (Carlucci et al., 2018). The linear regression coefficient and the outdoor reference temperature calculation constitute the main differences not only between fieldwork studies but between thermal comfort standards.

On the one hand, the adaptive comfort model used to determine the correlation between comfort votes and environmental parameters is based on one or more independent variables. The linear model disregard useful information observed on the scattered data in thermal performance graphics representing the diversity of responses within the population (Schweiker et al., 2018). The adaptive comfort standards applies to free-running buildings where occupants interaction with the environment and adaptation are dominant in restoring comfort. The human adaption to the surrounding environment is mainly related to three main drivers a) psychological, b) physiological, c) and behavioural (Brager and De Dear, 1998). Nevertheless, the model does not include in the calculation any adaptation factor or other environmental parameters. Little is known about the complex interaction between adaptation factors, making it difficult to attribute the thermal comfort status to a particular adaptation category (Liu et al., 2012).

On the other hand, the PMV model is based on individuals' responses to climate chamber or uniform conditions, ignoring the real world's natural variable conditions. The fundamental difference between the PMV model and adaptive comfort model relies on the thermal acceptability for users in air-conditioned buildings compared to users of the free-running buildings, respectively (Frontczak and Wargocki, 2011). The PMV model is primarily intended for thermal assessment in mechanically conditioned and steady-state environments with negligible adaptive opportunities (Carlucci et al., 2018; de Dear, 1998). Although the model partly accounts for behavioural adjustments (clothing) and environmental interventions (adjusting airspeed), predictions overestimate or underestimate occupants' discomfort in free-running buildings. One of the main arguments against the PMV model is that occupants are considered passive thermal stimuli recipients. Besides, the model ignores contextual and background differences affecting subjective responses (de Dear, 1998).

Current thermal comfort models, both the PMV and adaptive comfort models, fail to fully explain the wide-ranging of observed thermal responses in field studies. The effect of low atmospheric pressure is partially accounted for in the existing guidelines. In order to account for atmospheric pressure significantly different from the standard value ($101.33kPa$), the convective and evaporative heat transfer equations should be adjusted (ASHRAE, 2009). These corrections consequently affect the calculation of operative temperature and clothing insulation. Furthermore, although solar radiation levels are higher at high-altitude, heat transfer mechanisms are accounted for when considering the mean radiant temperature for thermal balance (Parsons, 2014).

2.3.2 Thermal comfort studies in high-altitude regions

A few thermal comfort models resulted from thermal comfort studies conducted in mid and high-altitude in the Tibetan plateau and Andes mountains. Despite the research focused on residential buildings, studies in educational and office buildings were included in the review due to the little existing evidence of thermal comfort studies in high-altitude regions. Research studies in the Tibetan plateau have been mainly conducted in residential buildings in China (Yan and Yang, 2014; Yang et al., 2013; Yu et al., 2017)and Nepal (Rijal and Yoshida, 2006; Rijal et al., 2010). Thapa et al. (2018c) performed several thermal comfort field studies in Nepal assessing the effect on elevation educational (Thapa et al., 2016), office (Thapa et al., 2018b), and residential buildings in India (Thapa et al., 2018a). In the subtropical highlands in the Andes, there is evidence from thermal comfort studies in office buildings in Colombia (García et al., 2019; Natarajan et al., 2015) and in educational (Guevara et al., 2021), office (Gallardo et al., 2016b), and residential buildings (Molina and Yaguana, 2018) in Ecuador.

In most of the studies, the respondents are residents that have lived in the studied location for at least one year (Thapa et al., 2018c) but more often for over five years (Gallardo et al., 2016b; García et al., 2019; Natarajan et al., 2015; Rijal and Yoshida, 2006; Rijal et al., 2010; Thapa et al., 2018a; Yan and Yang, 2014; Yang et al., 2013; Yu et al., 2017). Thus, the subjects are well adapted to the prevailing outdoor environmental conditions. Permanent residents in high-altitude regions experience a broad outdoor temperature oscillation regularly, which appease their expectation regarding the indoor environment's conditions. Despite the low indoor air temperature registered, most of the studies reported high acceptance of the indoor temperature and a mean thermal sensation vote (AMV) close to neutrality. For instance, in Nepal (150–2600m), Rijal et al.

(2010) reported over 93% (AMV=0.2) of comfort votes during winter and 97% (AMV=-0.4) during summertime when individuals were exposed to indoor temperatures of 17.8 and 32.0 °C, and 6.5 and 13.3 °C in summer and winter respectively.

Residents at higher elevation were more adapted to cold than residents at lower elevations and voted accordingly. Interestingly, the author reported experiencing more extreme thermal sensation as the altitude increases compared to the ones reported by the residents (Rijal et al., 2010). Similarly, a high percentage of neutral votes were registered by Thapa et al. (2018a) in two locations in Nepal. In Kurseong at 1420m, 93.7% (AMV=-0.3) of the votes belong to the central categories in the seven-point ASHRAE scale (+1 to -1). In Tiger Hills (2656m), 95.1% of occupants reported being comfortable (AMV=-0.1). Despite the prevailing cold conditions, there were no votes registered for cold (-3). The difference in TSV between locations was statistically significant (Thapa et al., 2018a). Besides, there is a significant difference in TSV by gender. Female subjects tend to vote towards the cold side of the scale compared with the males' counterpart (Thapa et al., 2018a,c; Yan and Yang, 2014).

Yu et al. (2017) reported 74% of neutral votes at residential buildings in the Tibetan plateau. Whereas in Lhasa-China (3650m), over 62% (AMV=-1.27) of neutral votes were registered despite the mean indoor temperature was only 10.9 °C (Yan and Yang, 2014). The high percentage of comfort votes even at low indoor temperature could be partly explained by heavy clothing, reduced ventilation, and hot drinks intake. On the other hand, high solar radiation might affect the thermal sensation of residents. Furthermore, due to cultural and economic facts, long-term residents have low expectations regarding their indoor environment (Yu et al., 2017).

2.3.3 Neutral temperature in high-altitude field studies

A range of neutral temperature (t_n) has been derived for high-altitude regions as a response to different expectations and adaptation of users (Table 2.2). t_n corresponds to the temperature at which the thermal sensation is neutral (zero in the ASHRAE scale). Comfort field studies derive t_n by regressing the mean thermal sensation votes against the indoor temperature ($AMV = b.t_{in} - a$). Nevertheless, due to the limited number of observations or the narrow range of operative temperature, the regression is of low precision (Gallardo et al., 2016b) When the TSV is far from the neutral point, the regression method produces odd values (Thapa et al., 2016). Thus, in order to get reliable results, most of the reported t_n employed Griffiths' method using a standard coefficient derived from pooled surveys (Humphreys et al., 2016).

The t_n reported for locations between 1350m and 1700m lies between 20.4 °C and 26.7 °C

Table 2.2: Comfort temperature derived form AMV and PMV

					$AMV = b.t_{in} - a$			$PMV = b.t_{in} - a$				
Loc	**Altitude**	**Per**	t_a	t_n	b	a	r^2	t_n	b	a	r^2	**Ref**
Np	1350	An	t_g	20.4**	-	-	-	-	-	-	-	(Rijal et al., 2010)
Ind	1420	An	t_g	22.4	0.130	2.91	0.23	-	-	-	-	(Thapa et al., 2018a)
Np	1500	An	t_g	26.7**	-	-	-	-	-	-	-	(Rijal et al., 2010)
Np	1700	An	t_g	20.7**	-	-	-	-	-	-	-	(Rijal et al., 2010)
Ec	2560	An	t_{in}	20.0	0.331	6.64	0.62	-	-	-	-	(Molina and Yaguana, 2018)
Ind	2565	An	t_g	17.8	0.138	2.45	0.13	-	-	-	-	(Thapa et al., 2018a)
Np	2600	Wi	t_g	17.3**	-	-	-	-	-	-	-	(Rijal et al., 2010)
Cn	3650	Su	t_{in}	23.2	0.183	4.25	0.75	-	-	-	-	(Yang et al., 2013)
Cn	3650	Wi	t_{in}	18.9	0.141	2.67	0.64	-	-	-	-	(Yang et al., 2013)
Cn	3650	Wi[1]	t_{in}	16.2	0.147	2.38	0.70	-	-	-	-	(Yan and Yang, 2014)
Cn	3650	Wi[2]	t_{in}	20.3	0.137	2.78	0.64	-	-	-	-	(Yan and Yang, 2014)
Cn	3650	An	t_{in}	19.3	0.129	2.50	0.70	-	-	-	-	(Yan and Yang, 2014)
Np	3705	Wi	t_g	22.9	0.085	1.94	0.26 *	-	-	-	-	(Rijal and Yoshida, 2006)
Ind	1420-2565	An	t_g	20.6	0.088	1.82	0.09	26.1	0.139	3.63	0.35	(Thapa et al., 2018a)
Cn	-	Su	t_o	21.8	0.192	4.19	0.87	23.8	0.279	6.64	0.99	(Yu et al., 2017)
Cn	-	Wi	t_o	14.5	0.122	1.76	0.92	17.7	0.161	2.84	0.99	(Yu et al., 2017)
Residential buildings				19.8	0.152			22.5	0.193			
Ind	1950	An	t_g	20.8	0.194	4.04	0.36	-	-	-	-	(Thapa et al., 2016)
Ec	2800	-	t_o	21.8	0.293	6.41	0.88 *	23.7	0.220	5.22	0.87 *	(Guevara et al., 2021)
Ind	135-1950	An	t_g	25.9	0.091	2.36	0.17	22.3	0.204	4.55	0.84	(Thapa et al., 2016)
Educational buildings				22.9	0.193			23.0	0.212			
Ind	1640	An	t_o	22.0	0.130	2.87	0.54 *	24.1	0.135	3.26	0.76	(Thapa et al., 2018b)
Co	2600	Wa	t_o	23.0	0.663	15.24	0.05	22.2	0.175	3.90	0.83	(Natarajan et al., 2015)
Ec	2850	Wa	t_o	23.1	0.074	1.71	0.16	24.1	0.231	5.56	0.85	(Gallardo et al., 2016b)
Office buildings				22.7	0.289			23.5	0.180			
Ind	135-2565	Wa	t_o	23.9	0.070	1.67	0.38 *	-	-	-	-	(Thapa et al., 2018c)
Ind	135-2565	Co	t_o	27.0	0.060	1.62	0.24 *	23.0	0.199	4.57	0.77	(Thapa et al., 2018c)
Combined buildings				25.4	0.065			23.0	0.199			
All buildings				21.3	0.170			23.0	0.194			

Location (Loc) = China (Cn), Colombia (Co), Ecuador (Ec), India (Ind), Nepal (Np)
Period (Per) = Warm (Wa), Cool (Co), Winter (Wi), Summer (Su), Annual (An)
[1]Heating, [2]No-heating
t_a = Indoor air temperature (t_{in}), Globe temperature (t_g), Operative temperature (t_o)
t_n = ** mean t_n derived from reported data
* = Correlation coefficient (r)

while at higher altitudes, from 2560m to 2600m, the derived t_n is 17.3 °C and 20.0 °C. Lastly, in Lhasa– China (3650m) and Mustang-Nepal (3750m), t_n is 16.2 °C in free-running dwellings and 22.9 °C in heated spaces. The t_n for high-altitude regions is consistently lower as the altitude above sea level increases. Thapa et al. (2018c) observed that this relation is not linear but closely follows a second-order polynomial regression.

At one of the dwellings analysed by Rijal and Yoshida (2006), the mean t_n is 10.7 °C, highlighting people's adaptation to traditional houses' thermal environment. The mean clothing in that location is 5.96 *Clo* for females and 2.87 *Clo* for males. However, that clothing level would be outside the thresholds for the applicability of PMV and the adaptive comfort model. Some studies reported that the difference in t_n between locations is significantly different (Rijal and Stevenson, 2010; Thapa et al., 2018c). The lower t_n at higher altitudes could be explained by the fact that residents are exposed to lower temperatures than those residing at lower locations. Hence a decrease in comfort temperature could be expected with an increase in elevation. Comfort temperatures also vary with seasonality and gender (Thapa, 2020). Furthermore, when comparing t_n from fieldwork in different buildings type, one can notice that the mean t_n for dwellings (19.8 °C) is lower than the one for educational (22.9 °C) or office buildings (22.7 °C), denoting the greater adaptive opportunity at home.

The neutral point on the ASHRAE scale is not necessarily the optimum condition (Yang et al., 2013). The preferred temperature (t_{pCool}=20.3 °C, t_{pWarm}=22.0 °C) estimated by regressing preference vote in t_{in} is higher than t_n (t_{pCool}=15.5 °C, t_{pWarm}=18.3 °C). Even though subjects are adapted to high-altitude regions, their preference is towards warmer conditions (Thapa, 2020). The difference between t_n and the preferred temperature from several field studies in different countries have been reported to be up to 3.0 °C (de Dear, 1998).

The regression coefficient (b) of the equation of the actual thermal sensation votes (AMV) on indoor temperature (t_{in}) allows estimating the subjects' sensitivity to any change in the indoor temperature (Humphreys et al., 2016). In residential buildings, the lower slope (b=0.152) observed in the linear regression correlating AMV with t_{in} denotes that occupants are better adapted to the indoor environment and therefore have a minor change in warmth sensitivity. On the other hand, the slightly higher regression coefficient (b=0.193) in the linear regression of the PMV with t_{in} reveals the fact that the PMV model is more sensitive to the change in indoor temperature. Thus, the overestimation of neutral temperature as reported by Yu et al. (2017), where the derived t_n for summer is 21.8 °C and 14.5 °C for winter while PMV estimate 23.8 °C and 17.7 °C for summer and winter correspondingly. The overestimation of t_n for high-altitude regions has been consistently reported regardless of the building type (Gallardo et al., 2016b; Guevara et al., 2021; Thapa et al., 2018a,b; Yu et al., 2017).

Furthermore, the high correlation obtained from AMV regression with t_{in} shows that the t_n

closely follows the indoor condition (Table 2.2). The change of warmth sensitivity in office and educational spaces is considerably higher than the one at dwellings, most likely due to lower means of adaptation in those environments. Besides, differences in warmth sensitivity are also noticeable when analysing the regression coefficient by gender. Yan and Yang (2014) found that females are more sensitive to cold environments when comparing to male participants. The heavier clothing reported by female participants denotes the adaptive response to the indoor temperature.

2.3.4 Relation of comfort temperature with the indoor and outdoor temperature

Neutral temperature is also derived through a linear regression over the indoor temperature ($t_n = b.t_{in} - a$). The high regression coefficient in residential buildings (b=0.776) observed in Table 2.3 represents the fact that the neutral temperature is closely related to the indoor environment. At educational and office buildings, the relation between t_n and t_{in} is even higher, denoting the indoor conditions' considerable effect on the comfort temperature, which may be attributed to the lesser adaptive opportunity in these buildings.

The adaptive comfort model estimates the comfort temperature from the prevailing outdoor temperature and the indoor temperature ($t_n = b.t_{out} - a$). The mean regression coefficient (b=0.532) from the studies in high-altitude regions is higher than the one established in ASHRAE55:2017 (b=0.31) and ISO15251:2007 (b=0.33). The equation's steeper slope suggests quicker adaptive behaviour with changes in the outdoor environment (Thapa et al., 2018c).

The high coefficient (b=0.776) in the residential buildings equation highlight that comfort temperature closely followed the indoor environmental condition, which could be associated with the adaptation level of subjects with the indoor environment (Thapa et al., 2018b). Besides, the high and significant correlations reported from the comfort temperature with the indoor and outdoor environmental conditions support the statement that in naturally ventilated buildings, the change in outdoor temperature triggers occupants' reaction to restore comfort. Consequently, subjects that are continuously reacting tend to be more permissive with indoor conditions.

2.3.5 Comfort range in high-altitude regions

Broader ranges of acceptability of the indoor thermal environment have resulted from field studies in the highlands. Comfort temperatures derived from the abovementioned studies depict that the comfort zone for the occupants of residential buildings in high-altitude is much different to the one prescribed by the international standards (i.e. ASHRAE55:2017, GB/T 50785-2012) (Thapa, 2020; Yu et al., 2017). Yan and Yang (2014) reported 13.0 °C as an acceptable lower boundary of the indoor temperature for 80% of the occupants, suggesting that residents are acclimatised

Table 2.3: Regression of comfort temperature on indoor and outdoor temperature

			$t_n = b.t_{in} - a$				$t_n = b.t_{out} - a$			
Loc	**Altitude**	t_a	b	a	r^2	t_{out}	b	a	r^2	**Reference**
Np	1350-2600	t_g	0.827	3.93	0.99	-	-	-	-	(Rijal et al., 2010)
Cn	3650	-	-	-	-	t_{out}	0.474	13.80	0.74	(Yang et al., 2013)
Ind	1420	t_o	0.739	5.81	0.71	t_{out}	0.587	9.78	0.66	(Thapa et al., 2018a)
Ind	2565	t_o	0.737	4.65	0.51	t_{out}	0.466	11.67	0.58	(Thapa et al., 2018a)
Ind	1420-2565	t_o	0.827	3.56	0.69	t_{out}	0.527	10.90	0.64	(Thapa et al., 2018a)
Ind	1420-2565	-	-	-	-	t_{rm}	0.532	11.01	0.70	(Thapa et al., 2018a)
Ind	2565	t_o	0.752	4.42	0.72	t_{rm}	0.605	10.41	0.74	(Thapa, 2020)
Residential buildings			0.776				0.532			
Ind	135-1950	t_g	0.817	4.71	0.80	t_{rm}	0.654	10.65	0.78	(Thapa et al., 2016)
Educational buildings			0.817				0.654			
Ec	2850	t_o	0.903	2.29	0.95	-	-	-	-	(Gallardo et al., 2016b)
Ind	1640	t_o	0.739	5.73	0.88 *	t_{out}	0.639	9.02	0.82 *	(Thapa et al., 2018b)
Ind	1640	-	-	-	-	t_{rm}	0.747	7.12	0.84 *	(Thapa et al., 2018b)
Co	2600	-	-	-	0.05	t_{out}	0.41	16.00	0.41	(García et al., 2019)
Office buildings			0.821				0.599			
Ind	135-2565	t_o	0.849	3.58	0.91 *	t_{rm}	0.694	8.91	0.87 *	(Thapa et al., 2018c)
Combined buildings			0.849				0.694			
All buildings			0.799				0.576			

Location (Loc) = China (Cn), Colombia (Co), Ecuador (Ec), India (Ind), Nepal (Np)
t_a = Indoor air temperature (t_{in}), Globe temperature (t_g), Operative temperature (t_o)
t_{out} = Mean outdoor temperature (t_{out}), Running mean temperature (t_{rm})
* = Correlation coefficient (r)

to Lhasa's cold weather conditions Plateau (3650m). On the other hand, when the temperature exceeds 28.0 °C, the Tibetan plateau residents feel hot (Yu et al., 2017).

The continuous exposure to a wide oscillation of outdoor and indoor temperatures affects subjects who adjust their comfort range (Thapa et al., 2018c). Thapa (2020) proposed extending the limits of the comfort zone predicted by the model of the ASHRAE55:2007. He suggests shifting the acceptable temperature towards the left (lower indoor temperature) and extending the relative humidity towards 80% for the upper and 20% for the lower boundary (Thapa, 2020). Similarly, Yu et al. (2017) suggested shifting the comfort range established in the GB/T 50785-2012 towards lower temperature based on the Tibetan plateau's findings. The comfort zone for dwellings in this region suggests an acceptable temperature range between 10.2 °C and 22.9 °C for a low relative humidity (30%) and between 9.8 °C and 21.7 °C for high relative humidity (70%) (Yu et al., 2017). In the Andes, Molina and Yaguana (2018) propose a comfort temperature range from 16.6 °C to 23.6 °C for dwellings in Cuenca-Ecuador (2560m) for 80% of acceptability.

2.3.6 Other thermal comfort models for the highlands

Besides the thermal comfort models adopted in the international standards, several models have been developed to enhance comfort temperature estimation. Several authors have proposed different thermal comfort models based on Fanger's heat balance and adaptive comfort theories. Based on data collected in Lhasa, Shigatse, Qamdo, Nagqu, Nyingchi, Lhoka and Ngari, Yu et al. (2017) derive a λ value (0.34) to be used with the adaptive PMV ($aPMV = \frac{PMV}{(1+\lambda \times PMV)}$).

Thapa et al. (2018c) proposed a second-order polynomial regression (Equation 2.2) based on a compilation of the results from the field studies conducted in 10 buildings located at a different elevation (135 to 2565m). t_{nG} is the neutral temperature predicted from elevation,$'x'$ is the elevation (in km) of the studied location.

$$t_{nG} = 0.959x^2 - 6.854x + 28.83 \ (R = -0.783,\ N = 2574,\ p < 0.001) \tag{2.2}$$

Lastly, Singh et al. (2015) proposed a thermal comfort model for north India locations based on multiple regression analysis for predicting t_n from indoor temperature, outdoor temperature, relative humidity and clothing. The model is developed using data from summer and winter and validated with pre-summer and pre-winter data, correspondingly. Limitations of the proposed models are related to the few locations included for developing the model and the diverse building typologies. Both models have been proposed for a particular context, China and India, where individuals adaptation and contextual conditions differ from those in the Andes region. Furthermore, data includes locations (135m) where human beings are not under low atmospheric pressure strain and combine residential and non-residential (office and educational) buildings.

2.4 Factors driving diversity in thermal perception

Heat balance and adaptive comfort models fail to explain the scattered comfort votes observed in high-altitude field studies. Overall, differences observed between occupant's thermal comfort votes could be attributed to numerous drivers of diversity. Until now, little is known about the complex interaction of individual and contextual adaptation factors, making it difficult to attribute a thermal comfort status to a particular adaptation category (Liu et al., 2012). The ongoing challenge relies on understanding these interactions to enhance thermal comfort models' accuracy (Schweiker et al., 2018). However, consensus exists on the practical and scientific implications of a better understanding of diversity factors and their influence on thermal perception. From the practical point of view, identifying diversity factors would allow personalised and dynamic models and the diversification of mechanism and opportunities to restore comfort. Furthermore, the scientific challenge relies on integrating diversity factors effect in the models to enhance thermal comfort prediction (de Dear, 1998; Schweiker et al., 2018; Shipworth et al., 2016).

The main factors that promote diversity in thermal perception have been broadly defined in the literature as behavioural adjustment, physiological adaptation, and psychological habituation (de Dear, 1998). A more recent conceptual model differentiated between human and contextual drivers, and short-term' states' (seconds to hours) and long-term' properties' (months to years) (Shipworth et al., 2016). Figure 2.3 summarised a conceptual model of drivers of diversity used in this review to explain the difference between contextual and individual responses in high-altitude regions. The contextual factors known to affect occupants' perception are buildings' physical conditions and the indoor and outdoor environment. Besides, individuals preference and responses to climate, culture and personal experiences may arise one or a combination of physiological, psychological, and behavioural responses. Some factors are intrinsic to each individual, and others reflect the availability and variability of controls.

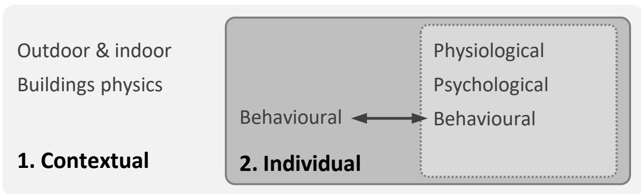


Figure 2.3: Diversity factors on human thermal comfort

2.4.1 Contextual factors - Outdoor conditions

Contextual factors on thermal comfort are related to environmental control mechanisms and the indoor and outdoor environment. These factors are known to have physiological and psychological effects on occupants. The physical environment is observable and measurable; thus, it is the most studied when assessing human thermal comfort. There is strong evidence that thermal perception depends on the climatic background, both short and long-term. In high-altitude regions, the constant stress of reduced atmospheric pressure, high solar radiation and daily temperature oscillations may elicit several physiological responses in humans, further detailed in Section 2.4.3. As mentioned previously, the main challenge relies on distinguishing between physiological (adaptation and acclimatisation) processes and non-physiological ones (Shipworth et al., 2016).

2.4.2 Contextual factors - Dwellings physical conditions

Environmental control mechanisms provided in buildings allow occupants to take action over their given indoor environment. However, control effectiveness relies not only on controls availability but the actual exercised control. In other words, to what extend occupants can adjust their occupied thermal environment (Liu et al., 2012). In most cases, the properties of buildings that provide opportunities to occupants to adjust the environment range from the regulation of ventilation (mechanical and natural) and adjusting heating and cooling systems. However, most cities and towns in high-altitude regions in the subtropics are developing countries where mechanical conditioning systems are not a common practice. Hence, buildings' thermal performance relies on passive methods to reach acceptable indoor temperatures (Chen et al., 2015; Liu et al., 2016; Yan and Yang, 2014). Several studies reported the impact of design strategies or interventions aiming to reduce heat loss and increase thermal storage to improve the indoor thermal environment. Due to the high intensity of solar radiation, active solar heating systems have drawn much attention as an effective design approach for these regions.

Studies conducted in Nepal's high-altitude regions (Fuller et al., 2009; Rijal and Yoshida, 2006) and China (Huang et al., 2016; Yang et al., 2013) have shown the implication of solar passive strategies for cold climates in the mountains above 2000m. Cost-effective and simple strategies such as reduction of external infiltration, increasing roof insulation (reduce heat loss), and the incorporation of sunspace considerably improved the indoor environment of low-cost housing in Humla–Nepal (2942m) (Rijal and Yoshida, 2006). The focal solar passive design strategies, the thick dry brick walls (450mm) and small windows of traditional dwellings in Lomangtang (3705m) provide acceptable indoor environmental conditions (Rijal and Yoshida, 2006). Similarly, in the Tibetan Plateau (3600m), the minimisation of heat loss and infiltration, increased solar heat gain and storage and optimised natural ventilation were effective solutions to improve the indoor environment in winter (Huang et al., 2016). By efficiently capturing solar heat, an increase between 2.0 °C to 5.0 °C in the indoor temperature could be achieved in existing dwelling in the Qinghai Tibetan plateau (2367m) (Liu et al., 2017). The thermal performance of traditional dwellings (mud) compared to modern construction (concrete) have also been studied in Saudi Arabia ($\sim$2200m). Mohamed et al. (2019) highlight the higher mean indoor temperature of traditional dwellings (22.7 °C) compared to the indoor environment of a concrete house (20.8 °C). Other solutions such as sunspaces and Trombe walls have been designed and optimised based on monitoring and simulation studies. An optimal sunspace design in the Qinghai-Tibetan plateau

(2367m) proposed a ratio of 1.5m depth and 45% window to wall ratio (WWR) to maximise the gains during the daytime and minimise the heat loss at night (Liu et al., 2019). Results from one-year monitoring of a Trombe wall used as a low-tech retrofitting passive solution implemented in a hot arid climate region showed reduced heating and cooling demand (Dabaieh et al., 2019). The same author has presented similar studies regarding vernacular strategies for high-altitude regions in Egypt, focusing on indoor environmental enhancement using passive strategies and local materials (Dabaieh and Elbably, 2015). Besides building design, other control mechanisms reported are firewood and electric heaters or similar to keep warm (Rijal et al., 2010; Yu et al., 2017).

The thermal performance of vernacular dwellings has been assessed in the Andes Region in Ecuador (Gallardo et al., 2016a; Mino-Rodriguez et al., 2014, 2016), Peru (Ninaquispe-Romero et al., 2012) and Chile (Palme et al., 2014). These studies reveal that the critical buildings' parameter affecting indoor thermal performance are the roof, floor, and airtightness. Earthen constructions have higher thermal stability when comparing to the modern uninsulated lightweight construction used in the region. However, an appropriate selection of envelope materials does not guarantee a comfortable thermal environment in existing dwellings. Nevertheless, the appropriate selection of passive strategies such as heat storage and passive solar heat gain will enhance the dwellings' thermal performance (Gallardo et al., 2016a; Mino-Rodriguez et al., 2014). Fuller et al. (2009) reach similar conclusions after monitoring and simulating vernacular dwellings in Simikot-Nepal ($\sim$2900), he concludes that indoor thermal conditions could be significantly enhanced more effectively by reducing infiltration than by increasing insulation levels (Fuller et al., 2009). Regarding modern uninsulated construction typology in the Andes, Rodríguez et al. (2019) achieve a 2.1 °C increase in the daily mean indoor temperature by reducing heat losses from external walls (add internal insulation) and windows (add a second layer) (Rodríguez et al., 2019). A similar research by Dietz et al. (2020) optimised the building envelope (increase insulation) and windows area to take advantage of the solar heat gains in a mining camp in Chile (4000m) (Dietz et al., 2020). It is worth noticing that the implementation of hermetically sealed buildings in mild climate as is Bogota-Colombia (2600m) might produce undesired overheating (Gonçalves and Fernández, 2015).

2.4.3 Individual factors - Physiological adaptation

People in the highlands have developed specific physiological responses to restore internal heat balance (Tompkins, 2011). Understanding the effect of climate stressors, diurnal temperature oscillation and low atmospheric pressure, and human adaptation to restore balance would provide insights into factors influencing thermal perception in high-altitude. Opposite to temperature, humidity and solar radiation, low atmospheric pressure is the only hazard that cannot be avoided by behavioural mechanism or appropriate shelter (West et al., 2012).

The human body's physiological responses to compensate for low pressure and temperature oscillation can be classified according to the duration (acute and chronic) and exposure intensity (rate of ascent). Figure 2.4 illustrate the time-span period required for the progressive reduction in physiological strain when exposed to repeated stress (Moore, 2017; Taylor, 2006).

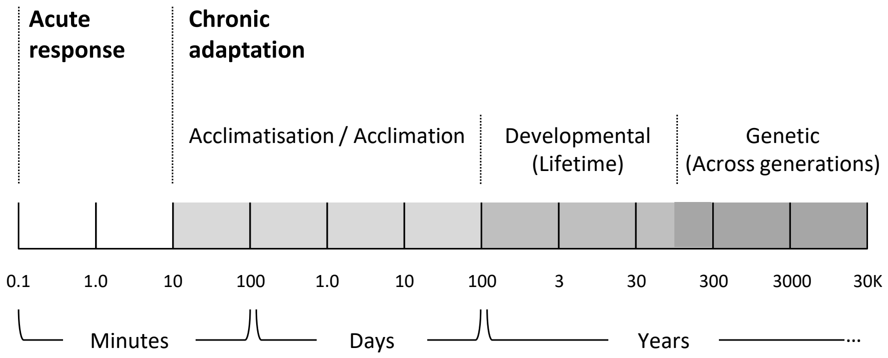


Figure 2.4: Time course of acute responses and chronic physiological adaptations

An acute physiological response is an immediate reaction of one or more systems in the human body to a stressor; conversely, chronic adaptations are the long-term adjustments in one or more body systems to sustain stressors. The physiological strains intensify with time and are known as acclimatisation or acclimation. The difference between acclimation and acclimatisation is related to the environment's conditions rather than the responses developed after repeated exposure. Acclimation refers to responses developed to a simulated environment, while acclimatisation corresponds to those elicited in natural environments (Gibson et al., 2017; Périard et al., 2015). Lastly, the adjustments taking place during a lifetime are referred to as developmental responses, and those occurring across generations are termed genetic adaptation (Castellani and Young, 2016; Moore, 2017). As this research focused on long-term residents adaption, the overview below centred on chronic adaptation among highlanders.

Physiological response to reduce atmospheric pressure

At high-altitude, humans risk is not related to reduced atmospheric pressure but the low oxygen pressure. The partial pressure of intake oxygen at the lungs decreases at low-pressure environments; consequently, less oxygen is transported to the cells. The physiological responses of native high-altitude populations, such as Andean (South America), Tibetan (Central Asia) and Ethiopian (Africa), are mainly observed in the pulmonary, cardiac, renal and hematologic systems (Johnson and Luks, 2016), summarised in Table 2.4.

Table 2.4: Physiological adaptation of high-altitude population to high-altitude

Physiological adaptation	Andean	Tibetan	Ethiopian
Resting ventilation	No increase	50% higher	NR
Hypoxic ventilatory response	Blunted (low)	Similar to sea-level	NR
Arterial oxygen saturation	Elevated	No increase	Elevated
Haemoglobin concentration	Elevated	Lowered	Minimal increase
Birth weight	Elevated	Elevated	NR

NR = No register

Findings highlight considerable differences between Andean (South America) and Tibetan (Central Asia) altitude residents. As for the third group, little evidence exists regarding Ethiopians' long-term adaptation (Africa) (Bigham et al., 2013; Moore, 2017). Furthermore, the physiological response of born and raise high-altitude residents varies from that of well-acclimatised lowlanders. The most important responses are related to breathing (ventilatory response) and haemoglobin concentration.

- Highlanders have lower total ventilation at rest and exercise, and blunted hypoxic ventilatory response, although in Tibetans this is less than in South Americans. Blunting mechanism is an important factor in the adaptability of species to high-altitude. Besides, highlanders have higher lung diffusing capacities when comparing to their counterparts in the lowlands.

- Increased haemoglobin concentration at altitude is one of the most acknowledge adaptations to hypoxia. Aymara (Indigenous from Bolivia) and Andean high-altitude natives have higher haemoglobin concentration than Tibetans and are significantly higher than lowlanders (West et al., 2012).

Furthermore, population adaptation differences have been found in metabolism, body temperature and composition, age, and gender. Findings reported improved metabolism at work; in other words, reduced energy expenditure at workloads compared to low-altitude residents. Regarding subjects' temperature, there is no significant fall of core temperature, but there is a lower temperature in high-surfaced extremities. The basal metabolic rate is slightly elevated in high-altitude residents; this mechanism may be explained as the combined effect of hypoxia and cold. Highlanders are lighter in weight than Europeans, but this difference is negligible compared with people of similar race and living standards. Lastly, despite notorious differences between highland and lowland population, there is not much evidence on distinct acclimatisation due to age or gender groups. Research on adaptation come together with unexplained differences at the individual's level, degree of acclimatisation and response rate to ascent. Two recurrent issues identified when studying acclimatisation and adaptation are the diversity of metrics for assessment and the difficulty to disentangle the effect of low atmospheric pressure from other climate variables. Low-pressure environments elicit diverse physiological changes, and thus different methods are required to evaluate each of the processes. Furthermore, investigating adaptation requires discerning the effect of high-altitude from racial, nutritional, social or economic factors (West et al., 2012).

Physiological response to temperature oscillation

Thermoregulation is the vital and dynamic process that allows the human body to restore or regulate the core temperature by balancing heat production and heat loss and minimising heat exchange with the environment(Tansey and Johnson, 2015). Hot and cold environment elicit different acute or chronic responses. Due to the highlands' inherent climate conditions, residents are exposed to diurnal thermal oscillation rather than extreme temperatures. The human response to heat stress depends on the type and severity of cold or hot environment exposure (Castellani and Young, 2016). Heat acclimatisation, or reduction of heat stress impact, occurs over the first two weeks of exposure. The primary acclimatisation responses are reduction in sweat salt concentration, sweating response triggering at a lower temperature, and increased plasma volume and cardiac output. The latest mechanism allows a significant increase in skin blood flow, increasing heat transfer to the skin and, consequently, increased heat loss (West et al., 2012). Cold exposure induces three progressive physiological adjustments: habituation, metabolic adjustments, and insulative adjustment, as described in Figure 2.5.

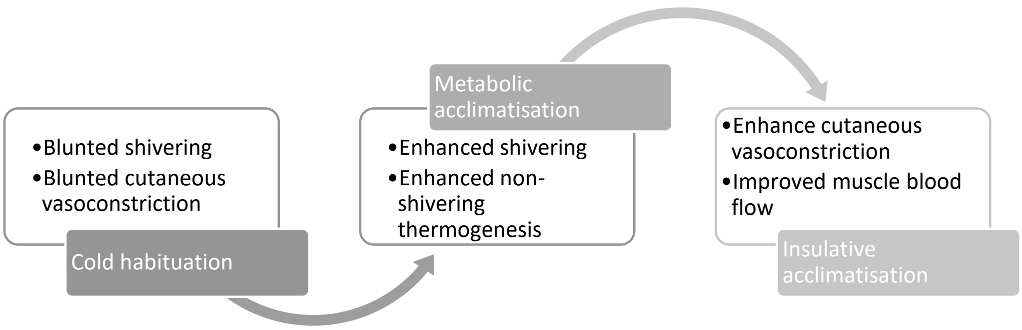


Figure 2.5: Progressive patterns of human acclimatisation to cold

Acclimatisation depends on the rate of temperature change (skin and core temperature) and the exposure duration. In comparison, the attenuation of cutaneous vasoconstriction to chronic or repeated cold exposure is habituation. Hence, shivering and vasoconstriction will be triggered at a lower temperature in habituated subjects than in the non-habituated. Thapa et al. (2018c) provided some insights into long-term adaptation to cold environments due to reducing shivering. Residents in Nepal were asked to report shivering; interestingly, participants in a lower location reported a higher rate of slightly shivering (15.7%) compared to the ones at a higher and colder location (13.%), highlighting the increased adaptation of permanent residents' to colder conditions in mountainous regions (Thapa et al., 2018c).

Metabolic acclimatisation is the response to repeated exposure to mild or moderate cold environments, resulting in exaggerated shivering or non-shivering thermogenesis. Higher resting metabolic rates enable acclimated residents to maintain warmer skin temperatures and less shivering during cold exposure. Nevertheless, an increased metabolic rate may also result from a specific diet or lifestyle rather than an adjustment to chronic cold exposure. There is little evidence to prove that the enhancement of shivering and non-shivering responses provide relevant benefits to cold thermoregulation. Lastly, insulative acclimatisation is the enhance mechanism to conserve heat as a response to severe cold exposure. This process is characterised by decreased skin temperature during cold exposure and is usually accompanied by a rapid and pronounced cutaneous vasoconstriction. Improved insulation at the body surface is only observed after long acclimatisation periods (cold water immersions) (Castellani and Young, 2016).

Subjects frequently exposed to cold environments enhance tolerance to that stressor, but significantly cold acclimatisation is not achieved. Humans residing or working in cold environments exhibit strong cold-induced vasodilatation. This fact suggests that thermal response to local cold exposure can be systematically improved by acclimatisation (Cheung and Daanen, 2012). This statement is supported by Taylor form studies on acclimated aborigines showing that the metabolic rate remained unchanged as the air temperature falls but the body and skin temperature decrease. A lower thermal conductance may be associated with enhanced peripheral shell insulation of the body (Taylor, 2006).

Physiological effect of low-pressure in thermal comfort studies

The effect of low-pressure environment in thermal comfort has been investigated at simulated environments with reduced oxygen concentration, rather than reduced air pressure (normobaric hypoxia) and with reduced air pressure at high-altitude regions or in variable pressure experimental chambers (hypobaric hypoxia). It is essential the differentiation, as some studies have reported significant differences in human response for hypobaric and normobaric hypoxia (West et al., 2012). The effect of physiological responses to low-pressure and temperature have been studied under controlled conditions in decompression chambers. Wang et al. (2010) observed that the increase of evaporative heat transfer resulted in lower skin temperature and higher clothing temperature than those found in subjects at sea level. While the reduction in heat transfers hampered heat dissipation from the clothing surface to the ambient environment, hence elevating the clothing temperature. However, no noticeable change in mean skin temperature was observed when comparing subjects exposed to normobaric hypoxia and hypobaric hypoxia (Wang et al., 2010). Besides, Ohno et al. (1991) observed higher skin temperature at the face and trunk than the extremities skin temperature, and higher heart rate apparently related to low pressure (Ohno et al., 1991).

Furthermore, these authors reported differences in subjects' thermal responses to the human body's physical response to compensate for the heat loss. Under moderate hypobaric conditions equivalent to 2300 meters above sea level, the mean thermal sensation rating drops, and people become more sensitive to draught, expecting lower air velocity (Wang et al., 2010). When the air velocity goes above 0.2 m/s, heat will be mainly transferred by convection, leading to increased overall heat loss and decreased thermal sensation rating. Besides the effect of thermal sensation, Wang et al. (2010) reported higher sensitivity to female subjects' cooler environments. Further studies by Golja et al. (2004) reported decreased cold sensitivity during hypoxia exposure. Such alteration may affect the individual's perception of thermal comfort and consequently attenuate thermoregulatory behaviour during cold exposure to altitude. Nevertheless, further studies suggested no significant effect of acute hypoxia on humans' thermal comfort zone (Golja et al., 2005).

Besides physiological differences due to acclimatisation and adaptation, individual factors such as age, gender, body composition, ethnicity, among others, affect significantly thermal comfort (Daanen and Van Marken Lichtenbelt, 2016). The combination within stressors and with other climate variables might intensify the experienced effect. For instance, the combined effect of cold and wind produce a cooling effect of a much lower temperature than still air on exposed skin. Wind also has the effect of reducing the insulation of clothing by causing an increased exchange of air within and underclothing layers (Parsons, 2014; West et al., 2012). Moreover, high humidity and cold might freeze clothing, reducing the insulation effect (Parsons, 2014). The combined effect of the low-pressure and cold environment has been investigated for sports and athlete's performance. However, there is little evidence on the combined physiological effect in long-term residents from the highlands. That is to say, the combined effect of adaptation to low-pressure environments (increase ventilatory response and haemoglobin concentration), enhanced blood flood and increased metabolic rate resulting from adaptation to cold environments. In terms of human thermoregulation, it is unclear if hypoxia significantly alters this mechanism (Gu and Jun, 2018).

2.4.4 Individual factors - Psychological responses

Psychological adaptation refers to altered perception and reaction to sensory information constructed from past thermal experiences and expectations. The constant exposure to a repeated thermal stimulus tends to diminish an evoked sensation (de Dear, 1998). The combined effect of past thermal experience and the socio-economic background is regarded as habituation (Liu et al., 2012).

People's long and short-term thermal history affects their thermal perception according to their personal (i.e. social conditions, economic consideration) and current contextual background (i.e. other people's responses and environmental conditions). Recent experiences may affect the thermal response to the experimented environment. For instance, subjects who experience a cool thermal environment the previous day reported warmer thermal sensations in summer and slightly cooler thermal sensations in winter (Liu et al., 2012). As Gauthier (2015) mentioned, the intensity of an initial stimulus will affect the subsequent ones, and the residual effect in a person's memory form the basis of expectations. Differences between individuals might arise even when experiencing the same thermal environment due to their particular cognitive or emotional state. Besides, an individual highly concentrated in a task will be less aware of the environmental conditions than one engaged in undemanding tasks. Psychological adaptation cannot be observed directly; rigorous research is required to identify if an influencing factor is mediated through a cognitive or emotional system (Shipworth et al., 2016).

Psychological factors affect subjects adaptation; hence, it is expected that the residents in the highlands who are frequently exposed to low-pressure environments and diurnal temperature oscillation are habituated and more resilient than lowlanders (Rijal and Stevenson, 2010; Thapa et al., 2018c; Yang et al., 2013). In the subtropical highlands, the diurnal temperature oscillation is broader than the seasonal variation. Thus, subjects developed different thermal expectation compared to subjects experiencing higher seasonal variation(Thapa et al., 2016). Furthermore, thermal expectations for warmer environments can increase or decrease based on contextual factors such as environmental parameters or control mechanisms. For instance, due to solar radiation level in Lhasa, the mean daily indoor air temperature was 18.0 °C and 7.4 °C respectively in a southern and northern heated space in the house when the mean outdoor temperature was -0.6 °C. People reported being satisfied with the southern space's higher temperature, increasing users' thermal expectations for other spaces in the house (Yan and Yang, 2014).

Furthermore, Yan and Yang (2014) reported the effect of perceived control in dwellings with and without heating systems. The mean t_n in dwellings with heating systems (16.2 °C) was lower to the one derived for occupants in dwellings without a heating system (20.2 °C). These differences in t_n could be attributed to psychological factors of perceived control. Although heating systems (electric heater or stove heater) were insufficient to warm-up space, the sense of having control alleviates the user's thermal expectations (Yan and Yang, 2014). Findings from previous studies reported that having control over aspects of the local thermal environment can increase satisfaction with a broader temperature range (Shipworth et al., 2016). Besides, occupants may be less bothered by an unwanted stressor when they perceived to have control over it (Liu et al., 2012).

2.4.5 Individual factors - Behavioural adaptation

Behavioural feedback involves all the conscious or unconscious acts that a person can take to induce or attempt to induce a change in the human body's heat balance. The conscious feeling of heat distress will trigger corrective actions - behavioural adjustments - as the most immediate feedback to the thermal environment (de Dear, 1998). Adaptive behaviour is a dynamic process where multiple factors influence the actions and their frequency. The availability, variability and control level - particularly of the environment and clothing - reflects the extent to which occupants can adjust their thermal conditions (Liu et al., 2012). Behavioural adjustments allow people to play an active role in preserving their comfort and can be observed in a real environment. Therefore, it is the most studied category of adaptation and is classified as follows (de Dear, 1998):

- Technological adjustments correspond to any change to the environment when control is available. This means of adaptation has been addressed in Section 2.4.1 and 2.4.2.

- Personal modifications are associated with any change in activity, body posture, food or liquid intake, and microclimate selection through clothing and shelters or locations. Adding or removing clothing layers is one of the most common behavioural adjustment used by a participant to restore heat balance. Humans have developed excellent cold-weather clothing, homes, and behavioural adjustments, which tend to be much more important than our physiological mechanisms for surviving in severe environments (Daanen and Van Marken Lichtenbelt, 2016).

- Cultural adjustments widely relate to activities such as schedule, dress code adaptation, among others.

Because the feeling of (dis)comfort is connected to skin temperature, behavioural and physiological responses are intertwined, and this feeling of (dis)comfort drives behavioural adjustments (Daanen and Van Marken Lichtenbelt, 2016). The adaptations of inhabitants in mechanically conditioned buildings are predominantly driven by behavioural adjustment of clothing and airspeed. Whereas in naturally ventilated buildings, physiological (acclimatisation) and psychological (shifting expectations) adaptive processes superimpose behavioural adjustments (de Dear, 1998).

The main behavioural adjustments observed in the Tibetan Plateau residents are wearing warming clothes, changing rooms, moving around for sunbathing, and dietary custom based on high-calorie and high-protein meals (Rijal et al., 2010; Yan and Yang, 2014; Yang et al., 2013). For instance, during the cool season, the consumption of hot beverages like tea, coffee, or hot soup increases. In high-altitude regions in Mustang-Nepal (3705m), subjects drank as much as 4–35 cups of buttersweet tea, a high-caloric hot drink to keep themselves warm (Rijal et al., 2010).

Clothing level is the primary means of adaptation reported in field studies, particularly in residential buildings where more flexibility is expected. Subjects tend to adapt their clothing to the environmental conditions to which they are exposed. Lower clothing insulation limits are usually constrained by culture, tradition or dress code (Thapa, 2020). Similarly, some regions' upper limits of clothing are determined by traditions, as in the Tibetan plateau. The heavy Tibetans robes offer flexibility to adapt to extreme weather conditions by draping sleeves to gain heat from direct solar radiation on a sunny day and unwrapping once the temperature drops (Yan and Yang, 2014).

At lower temperature, for instance, below 26.0 °C, subjects have a greater opportunity to adjust their clothing by adding or removing garments (Thapa et al., 2016). Clothing insulation levels decrease when indoor temperature increases. The clothing change rate varies across different temperature ranges; when t_{in} ranges between 16.0 and 25.0 °C, the clothing insulation fluctuates between 2.3 and 2.0 Clo. Moreover, when t_{in} is higher than 25.0 °C, clothing level ranges between 1.1 and 0.8 Clo (Yu et al., 2017). Clothing levels above 0.8 even when the temperature is 25.0 °C partly explain the subjects' adaptation to the prevailing outdoor conditions. The significant difference observed in clothing levels due to gender, season, and altitude level in high-altitude studies has been summarised in Table 2.5.

Table 2.5: Clothing insulation by gender and location from field studies

		Warm - Summer			Cool - Winter			Annual - Mean			
Loc	**Altitude**	**Male**	**Fem**	**All**	**Male**	**Fem**	**All**	**Male**	**Fem**	**All**	**Reference**
Np	1350	0.36	0.64	0.5*	0.88	1.28	1.08*	0.62	0.96	0.79*	(Rijal et al., 2010)
Ind	1420	-	-	-	-	-	-	-	-	0.70	(Thapa et al., 2018a)
Ind	1420	-	-	-	-	-	-	0.70	0.73	0.72*	(Thapa et al., 2018c)
Np	1500	0.49	0.79	0.64*	0.67	1.15	0.91*	0.58*	0.97*	0.78*	(Rijal et al., 2010)
Np	1700	0.39	1.1	0.75*	0.67	1.06	0.87*	0.53*	1.08*	0.81*	(Rijal et al., 2010)
Ind	2565	-	-	-	-	-	-	-	-	0.90	(Thapa et al., 2018a)
Ind	2565	-	-	-	-	-	-	0.78	0.97	0.88*	(Thapa et al., 2018c)
Ind	2565	-	-	-	-	-	-	0.97	0.78	0.88*	(Thapa, 2020)
Np	2600	0.84	1.12	0.98*	1.38	2.02	1.7*	1.11*	1.57*	1.34*	(Rijal et al., 2010)
Np	2600	-	-	-	-	-	-	-	-	-	(Rijal et al., 2010)
Cn	3650	-	-	-	-	-	-	1.47	1.63	1.55*	(Yan and Yang, 2014)
Cn	3650	-	-	0.46	-	-	-	-	-	-	(Yang et al., 2013)
Cn	3650	-	-	-	-	-	1.44	-	-	-	(Yang et al., 2013)
Cn	3650	-	-	-	-	-	1.48[1]	-	-	-	(Yan and Yang, 2014)
Cn	3650	-	-	-	-	-	1.59[2]	-	-	-	(Yan and Yang, 2014)
Np	3705	-	-	-	2.87	5.96	4.42*	-	-	-	(Rijal and Yoshida, 2006)
Ind	-	-	-	-	-	-	-	0.86	0.74	0.80*	(Thapa et al., 2018a)
Np	-	0.48	0.86	0.67*	0.88	1.28	1.08*	0.68*	1.07*	0.875*	(Rijal et al., 2010)
Residential buildings		0.51	0.90	0.67	1.23	2.13	1.64	0.87	0.98	0.90	
Ind	1950	-	-	-	-	-	-	1.01	1.09	1.05*	(Thapa et al., 2016)
Ec	2800	-	-	-	-	-	-	-	-	0.85	(Guevara et al., 2021)
Educational buildings								1.01	1.09	0.95	
Ind	1640	-	-	0.76	-	-	1.2	-	-	0.98*	(Thapa et al., 2018b)
Ind	1640	-	-	-	-	-	-	1.01	0.90	0.96*	(Thapa et al., 2018c)
Co	2600	-	-	-	-	-	0.85	-	-	-	(García et al., 2019)
Ec	2850	-	-	0.87	-	-	-	-	-	-	(Gallardo et al., 2016b)
Office buildings				0.82			1.025	1.01	0.90	0.97	
Ind	-	-	-	-	-	-	-	0.83	0.87	0.85*	(Thapa et al., 2018c)
Combined buildings								0.83	0.87	0.85	
All buildings		0.51	0.90	0.70	1.23	2.13	1.50	0.89	0.97	0.91	

Location (Loc) = China (Cn), Colombia (Co), Ecuador (Ec), India (Ind), Nepal (Np)
[1] Heating, [2] No-heating
* Mean clothing value calculated by the author from the data reported in the publications

Overall, in residential buildings, female participants' mean clothing is higher than their male counterparts (Table 2.5). Considering that females are more sensitive to cold conditions, a higher clothing level shows behavioural adaptation to the environmental conditions. In other words, females adjust their clothing as the indoor air temperature changes (Yan and Yang, 2014). Besides, heavier clothing could also be attributed to social and cultural differences. Only one study reported the opposite, where higher variation occurs in males clothing (Thapa, 2020). The authors reported that males have more opportunities to modify their clothing by folding or unfolding sleeves, wearing or removing socks.

In contrast, women clothing remains constrained to cultural and traditional factors (Thapa, 2020). Besides, females spend more time indoors, thus, are better adapted to indoor conditions (Thapa et al., 2018a). Furthermore, besides the findings already reported, differences have also been identified between dwellings with heating (*Clo*=1.48) and without heating systems (*Clo*=1.59) (Yan and Yang, 2014). As seen in Table 2.5, the clothing level increases as the altitude above sea level increases. The reported differences in clothing insulation across locations are statistically significant in several studies (Thapa et al., 2018a,c), same as the variation between seasons (Thapa et al., 2018a). At the higher location Mustang-Nepal (3705m), residents wear the traditional heavy costumes equivalent to a *Clo* of 2.87 for males and a *Clo* of 5.96 for female. At lower locations (warmer conditions), clothing may be restricted to social and cultural constraints. In comparison, broader clothing variation is possible at higher and cooler locations, mainly in the inner wears (Thapa et al., 2018c).

2.5 Summary

The literature review presented in this chapter collects and synthesises relevant findings in thermal comfort research in high-altitude regions and drivers that might explain the diversity in thermal perception. Weather is one of the most significant factors influencing thermal comfort and thermal performance assessment. People in the highlands live under the constant stress of reduced partial pressure of oxygen, high diurnal variation, increased wind speed, lower absolute humidity, and increased solar radiation levels. In order to overcome these constant strains, humans have undergone certain physiological responses to restore internal balance. Physiological responses to low-pressure environments may also elicit emotional changes and certain adaptive behaviours. However, how people adapt to low-pressure environments is not yet fully understood. The challenge of investigating adaptation in high-altitude environments requires the ability to disentangle the effect of low pressure from other climate variables. Furthermore, modern populations' mobility makes the study of long-term or genetic adaptation more difficult or even impractical to conduct (Liu et al., 2012). What is clear is that reduced pressure will influence the interaction between physical, physiological, psychological and behavioural adaptation, and hence the human thermal response (Parsons, 2014). Besides, local inhabitants' adaptation to cold and hypobaric environments may also lead to differences in the indoor environment's perception.

Research into long-term thermal performance in high-altitude dwellings reveals that besides the high diurnal temperature oscillation, solar radiation and wind significantly impact dwellings' thermal performance in these regions. High-altitude residents tend to prefer lower indoor temperature than those predicted by PMV or adaptive comfort models. The adaptive comfort model is based on empirical results, mainly from conditioned and non-conditioned low-altitude non-residential buildings. Hence, the applicability of the adaptive model in the highlands is questionable as people there have adapted to the particular conditions than those of subjects. Moreover, householders usually have more adaptive opportunities to restore comfort than people in non-residential buildings. The Fanger's heat balance model seeks to account for changes in atmospheric pressure by replacing the convective and evaporative heat transfer coefficients in the calculation of the PMV. Even so, results from field studies consistently report the overestimation of neutral temperature when using the PMV model. Furthermore, findings from the research in the highlands highlight that long-term residents have endured tolerance to cooler temperatures. Thus, the neutral temperature is significantly lower when compared to people at lower altitude in the same region.

In conclusion, the literature suggests that thermal comfort models used in the current international standards may not accurately predict residents' thermal comfort or preferences in the highlands. High-altitude residents have environments and adaptive opportunities that differ from those of the people on whom the international standards are based. Thus, the necessity of investigating the diverse range of contextual stressors and individuals adaptation factors that affect thermal perception. The integration of high-altitude drivers of diversity could enhance the prediction of the indoor environment's comfort and acceptability. From the practical point of view, enhanced models would allow the definition of adequate thermal comfort indices to reach the ultimate goal of improving dwellings thermal performance in high-altitude regions.

Chapter 3

Methodology

3.1 Overview

The chapter describes the methodological approach used in this thesis to get the necessary background for addressing the research aim and objectives. The research seeks to gain insights into thermal comfort and thermal performance assessment and investigating the weather and residents' adaption in high-altitude regions. For this purpose, the main methods used in this thesis were cross-sectional thermal comfort surveys and thermal performance simulation.

The chapter is structured into five sections. The first sections described the theoretical framework and the proposed research design. The definition of the research's scope and applicability is detailed in the second section; in other words, the study's location's delimitation. The third section described the design and implementation of the cross-sectional thermal comfort surveys intended for collecting subjective data and objective measurements for thermal comfort analyses. The fourth section described the archetypes' thermal performance assessment, which included thermal performance simulations and monitored data for calibration purposes. The input data for the archetypes models were collected through archetypes' audit and monitoring. Finally, the chapter concludes with an overview of the approach to address this research's main practical and ethical, risk assessment and data protection implications.

3.2 Theoretical framework and research design

Thermal comfort research involves a vast array of concepts ranging from values of subjective evaluation of the environment to the physical measurement of the indoor and outdoor environmental parameters. Besides, as in other thermal studies, the four environmental parameters and two personal variables for estimating the PMV model were collected. Additionally, this research seeks to describe and infer relationships between contextual and individual diversity drivers in thermal perception in high-altitude regions. In free-running buildings, occupants are active agents who respond to the changing indoor environments through different behavioural, physiological and psychological means. Thus, the thermal responses from high-altitude residents might differ from those of residents in low-altitude environments. Figure 3.1 expands the framework of diversity factors on human thermal comfort evaluated in this research.

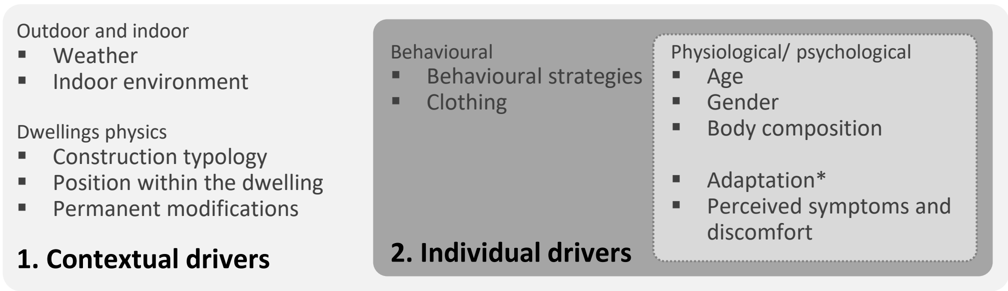


Figure 3.1: Diversity factors on human thermal comfort in high-altitude locations

Regarding contextual factors, outdoor and indoor environments were explored to gain insight into thermal perception differences. The analyses also extended to dwellings characteristics such as construction typology, position within the dwelling and any permanent modification. In terms of individuals' characteristics, differences in thermal perception were assessed based on demographics, adaptation level and perceived discomfort. Furthermore, to understand residents' interaction with the environmental conditions, behavioural adjustments to keep themselves warm or cool and clothing insulation were investigated.

Adaptation level of permanent resident and behavioural adjustments are two additional key concepts to be measured in this research. In terms of behavioural adjustments, several thermal studies have defined sets of questions as a proxy to identify adaptive actions as detailed in Section **??**. Little research focused on the adaptation of residents in high-altitude locations. Adaptation cannot be directly estimated, and it is difficult or even impractical to measure due to the mobility of the modern population. However, a set of questions was designed to differentiate between acclimatised participants from the non-acclimatised ones (Section 3.4.3.2). In this research, acclimatised residents are those living in high-altitude regions under similar weather conditions for more than three years, mid-acclimatised those between 1 to 3 years, and non-acclimatised (low acclimatised) the ones living in the studied areas less than a year.

The research design proposed three phases, as detailed in Figure 3.2. The inputs, main procedures and expected outcomes for each phase are described below:

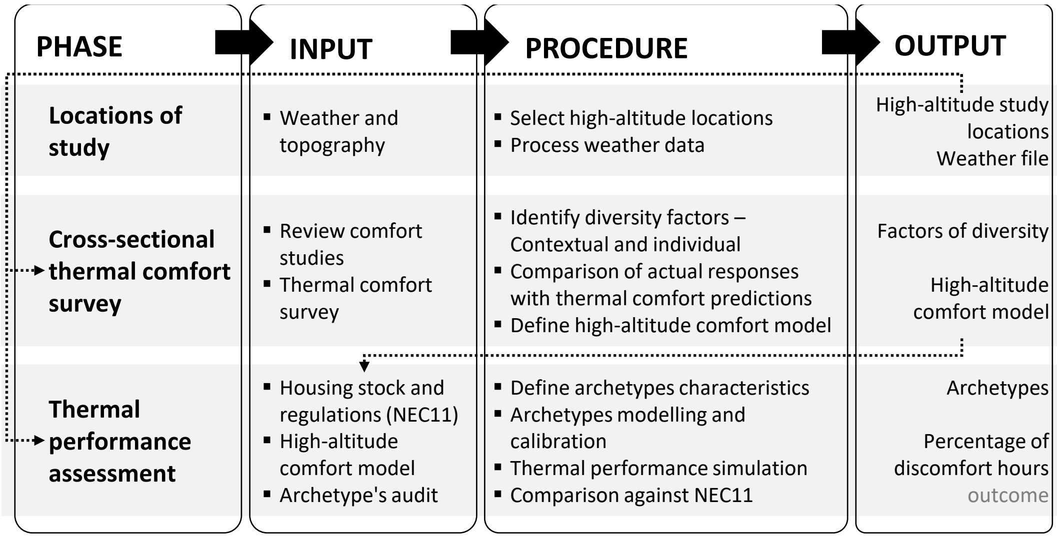


Figure 3.2: Proposed research design

1) The definition of the high-altitude locations aims to delineate the research's scope and applicability. The temporal and geographical applicability defines the overall scope of the research. In other words, it tells when and where the results are applicable.

2) The cross-sectional thermal comfort survey aims to gather subjective votes from a range of high-altitude residents at a point in time. In addition, other expected outcomes from the survey are a) to identify contextual and behavioural adjustments that could explain the diversity of thermal responses and b) to enhance thermal comfort prediction in the highlands. Last but not least, a contextualised high-altitude comfort model was derived from fieldwork data.

3) The applicability of the high-altitude thermal comfort model was evaluated through archetypes thermal performance simulation. The models' calibration applied a thorough uncertainty and sensitivity analysis of input parameters. Besides, monitored indoor temperature was used as the main output for the models' accuracy validation. The archetypes' thermal performance assessment was evaluated following the criteria of current thermal comfort models in the international standards (ASHRAE55:2017 and ISO15251:2007). Furthermore, to assess the impact of the minimum requirements for the envelope thermal insulation established in - Ecuadorian construction standard (NEC11), hypothetical simulations in compliance with the code were performed (Norma Ecuatoriana de la Construcción, 2018).

3.3 Locations of study

The selection of geographical scope described below focused on selecting locations at different altitude ranges while also assuring historical weather data availability. The data collection period corresponds to September 2017 to January 2018. However, the formulation of the study seeks into an annual temporal scope. Due to the condition of high-altitude locations near the equator, the annual variability is minimum. Thus, data collected within the defined period could be extended for the annual thermal performance evaluation.

3.3.1 Criteria for the selection of study locations

The context of the study corresponds to the high-altitude regions in the Ecuadorian Andes. The basis for defining the specific locations was the availability and suitability of weather data, the similarity of climate conditions, and altitude level above the sea level.

- Availability and suitability of historical weather data were the first criteria considered to define the research locations. Historic hourly data are available from INAMHI (Spanish acronym for National Institute for Meteorology and Hydrology), REMMAQ (Spanish acronym for Metropolitan network for environmental monitoring network Quito), and other private and public meteorological weather station. These monitoring stations collect data of the main environmental variables such as air temperature, humidity, atmospheric pressure, wind speed and direction. However, solar radiation, which changes considerably as altitude increase, is available only from the REMMAQ network. On the other hand, the suitability and applicability of the weather data to the territory were defined based on the criteria used to select suitable weather files for simulation. The National Renewable Laboratory (NREL) recommends that the location of analysis should be within a 30 - 50km radius and within few meters (100m) of elevation from the meteorological weather station (NREL, 2016). Hence, the selection of reference locations was limited to parishes situated within the stated distance and altitude range nearby REMMAQ meteorological weather station.

- The climate conditions were the second evaluated criteria seeking to reduce weather conditions variability due to mountain slope orientation. In mountainous regions, mountain slope orientation highly affects the weather parameters such as humidity, precipitation, and vegetation coverage (Emck, 2007; West, 1996). Hence, locations in the same mountain slope tend to have similar weather conditions. A mountain slope could be delimited by drainage basins that correspond to the land area that absorbs and drains precipitation into the same hydrological outlet. Therefore, to assure similar weather conditions, the study locations should be established on the same mountain slope.

- Altitude above sea level is the final parameter considered. The research aims to evaluate the effect of high altitude in thermal comfort assessment. Therefore, the study locations should be situated at different altitudes above sea level.

3.3.2 High-altitude study locations

Based on the criteria mentioned above, the selection of locations in this research limited to the parishes situated in the same mountain slope (or drainage basin) and within a distance between 30 and 50km and an altitude range of 100m elevation from an existing weather station.

The delimited area of study corresponds to the country's capital city (Quito) and surroundings. Quito was selected because of the availability of historical weather data and higher population density than other possible locations. Quito lies in the north of the country; the average altitude across the city is 2850m above sea level and has approximately 2.2 million inhabitants (INEC, 2010). The geographic coordinates and altitude above sea level of the weather stations and the study's potential locations are detailed in Table 3.1. As one could notice, the existing meteorological stations in Quito are located within a broad range of altitude levels ranging from 2330m to 3070m. That is within the range where humans are likely to feel the effect of hypobaric hypoxia (approx 2440m) and to the threshold where over three-quarters of the population present mild symptoms of acute mountain sickness (approx 3050m) (Cena et al., 2003).

Table 3.1: Location and altitude level of weather stations nearby Quito

Weather station reference	Latitude	Longitude	Altitude	Location
Tumbaco	-0.21	-78.40	2330	A
Los Chillos	-0.30	-78.46	2450	
Calderon (Carapungo)	-0.10	-78.45	2660	B
Cotocollao	-0.11	-78.50	2740	
Belisario	-0.18	-78.49	2835	
El Camal	-0.25	-78.51	2840	
Cutuglagua (Guamani)	-0.33	-78.55	3070	C

The research aims to study thermal comfort at high-altitude locations; thus, three parishes located at different altitude were selected for this research. The locations selected are Tumbaco (A), Calderon (B) and Cutuglahua (C), highlighted in Table 3.1. Locations A and C are parishes where the weather stations are located at the lower and highest points nearby Quito, respectively. At an intermediate altitude, Location B was selected according to the second criterion: a high percentage of the low-income population. The parishes are situated within or surrounding the Metropolitan District of Quito, as seen in Figure 3.3. Although the locations are situated within a 20km distance radius, the weather conditions vary due to altitude. The limits for each study location correspond to the administrative boundaries of the parish.

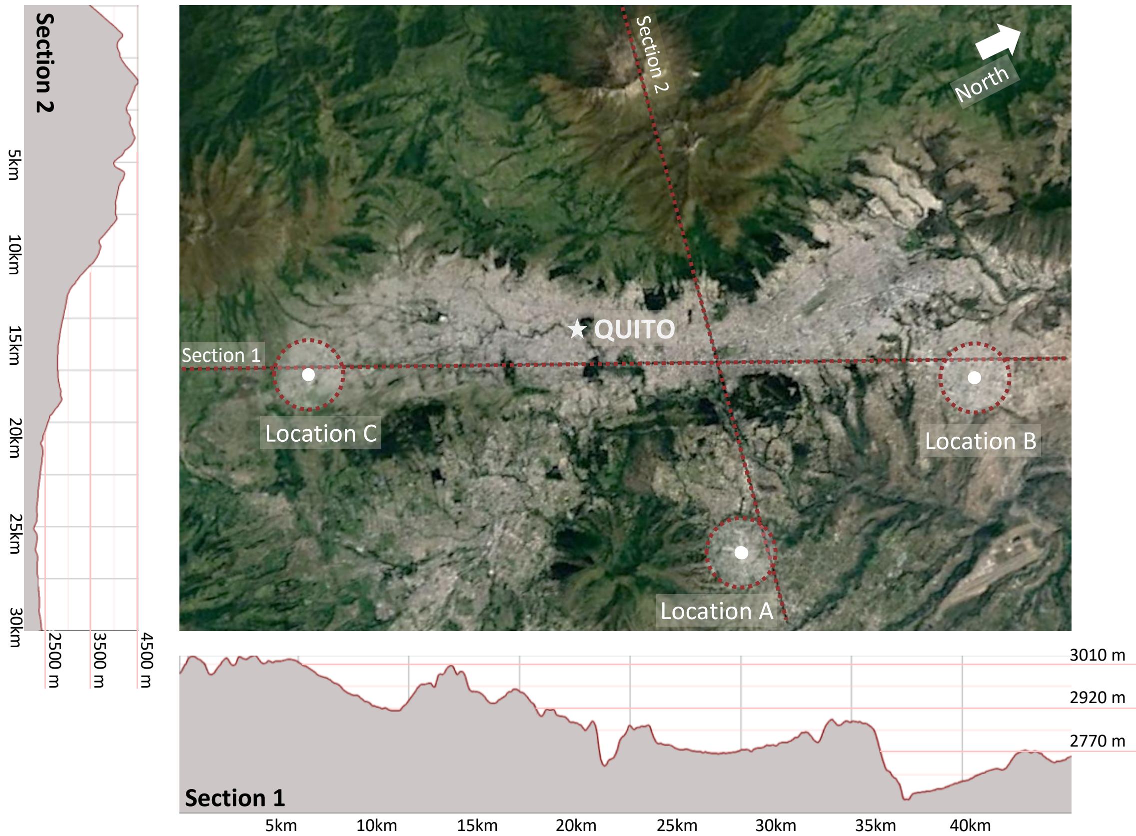


Figure 3.3: Geographical positioning of the research locations

Location A is 182 km^2 in the inter-Andean basin, at the east of Quito. The settlement was originally a rural area; however, due to urban expansion, the parish is now part of Quito's Metropolitan District. According to the latest population census in 2010, 49,944 inhabitants live in Tumbaco. Due to the existing infrastructure and land availability, this location is one of the development hubs in the city. The climate is a subtropical temperate or Cwb, according to Köeppen-Geiger (KG) climate classification (Beck et al., 2018). Location B is located northeast of Quito at 2610m above sea level. It is in the basin of Calderon, which has a dry subtropical climate (Csb). The population reached 152,242 inhabitants in an area of 79.17 km^2 (GAD - Calderón, 2015). Location C is a parish of Mejia Canton in the Cutuglagua basin. The population in 2010 was 16,746 inhabitants. The climate is this area is humid temperate (Cfb).

3.3.3 Weather data processing

Weather data served three main purposes, **a.** to provide an overview of the weather study locations, **b.** outdoor measurements for thermal comfort analysis, and **c.** weather file for building simulation. In order to fulfil these requirements, weather data were retrieved from REMMAQ network from February 2017 to January 2018. The weather data set include hourly values for dry-bulb temperature (DB), relative humidity (RH), global solar radiation (GHR), precipitation (PRE), wind direction (WD) and speed (WS). Humidity (W) and atmospheric pressure (P_a) were not available; hence, estimated from the other environmental variables.

An essential quality control procedure was applied to the raw data retrieved from the local meteorological stations, prior processing, and new variables. Common errors and inconsistencies in weather data were corrected through a two-step procedure for basic data quality control and assurance (Zahumenský, 2004). The first step was a plausible value check to control if the values of instantaneous data (generally one-minute data) were within acceptable range limits. The second step checked for time consistency to verify any unrealistic rate of change of instantaneous data (a step test) from the prior recording by more than a specific limit (Maximum step variability). Table 3.2 summarises the acceptable range limits for instantaneous values and the maximum variability to verify instantaneous data rate (time consistency) were defined based on the guidelines on quality control procedures for data from automatic weather stations from the World Meteorological Organisation (Zahumenský, 2004).

Table 3.2: Acceptable fixed-limit values and limits of maximum variability for instantaneous weather data

Variable	**Unit**	**Lower limit**	**Upper limit**	**Maximum step variability**
Air temperature	°C	-80	+60	3
Relative humidity	%	0	100	10
Atmospheric pressure	kPa	500	1100	0.5
Wind direction	Degrees	0	360	-
Wind speed	m/s	0	75	20
Solar radiation	W/m2	0	1600	1000

Besides, REMMAQs' technicians recommended removing checking for outliers, particularly dry-bulb temperature values below 6.0 °C and global horizontal solar radiation registered between 7:00 p.m. and 5:00 a.m. were corrected to zero. The whole data set was transformed into hourly values for each variable and organised as an EnergyPlus weather file for the thermal performance simulation.

The standard atmosphere has been widely used to predict the barometric pressure (P_a in *mmHg*), Equation 3.1, from altitude measure in *km* (h). This model was developed for aviation purposes; hence, the method underestimates the barometric pressure due to latitude variation, particularly in high mountains (West, 1996).

$$P_a = exp(6.63268\ -\ 0.1112\,h\ -\ 0.00149\,h^2) \tag{3.1}$$

Although the atmosphere equation model provides a reasonable estimation of barometric pressure, higher accuracy was obtained by a multiple regression model between temperature and altitude. The available pressure data from two locations were used for the regression model; the data set consisted of 18127 observations where 50% of the data were used to train the model and 50% for validation, achieving a correlation (r^2) of 0.99. The regression model is described in Equation 3.2 where t is the dry-bulb temperature (°C) and h is the elevation (m).

$$P_a = 98649.17 - 13.21t - 9.05h \tag{3.2}$$

The second calculated variable is the humidity ratio (W) that allows the comparison of moisture content in the air regardless of the air temperature. W is defined as the ratio of the mass of water vapour to the mass of dry air and was calculated as described in ASHRAE (2009).

After weather data was processed, annual weather data on an hourly basis was used for the purposes described at the beginning of the section. Typically, weather data files used for simulation correspond to historical weather data; however, actual weather data were preferred for the calibration and simulation of thermal performance models for this research. Hence, a weather data file in standard EnergyPlus format was created from the hourly data sets for each location following the procedure described in the auxiliary programs manual from EnergyPlus (U.S. Department of Energy, 2019). Description of the weather data, as well as the main descriptive statics are detailed in Section 4.3.

3.4 Cross-sectional thermal comfort study

Figure 3.4 described the different inputs used for the cross-sectional thermal comfort survey, the main procedures of analysis, and the expected outcomes. The design and implementation of the thermal comfort survey are thoroughly detailed in the following sections, while only an overview of the data analysis is presented in this chapter. The analyses performed to identify the drivers of diversity in thermal comfort, both in term of contextual and individual drivers, are detailed in

Chapter 4 - Effect of high-altitude contextual factors on human thermal comfort and Chapter 5 - Effect of individuals factors on thermal comfort. Furthermore, Chapter 6 - Thermal comfort model for high-altitude locations described the procedure followed to compare the actual thermal responses with standard thermal comfort models and the definition of a thermal comfort model to predict thermal comfort in high-altitude locations.

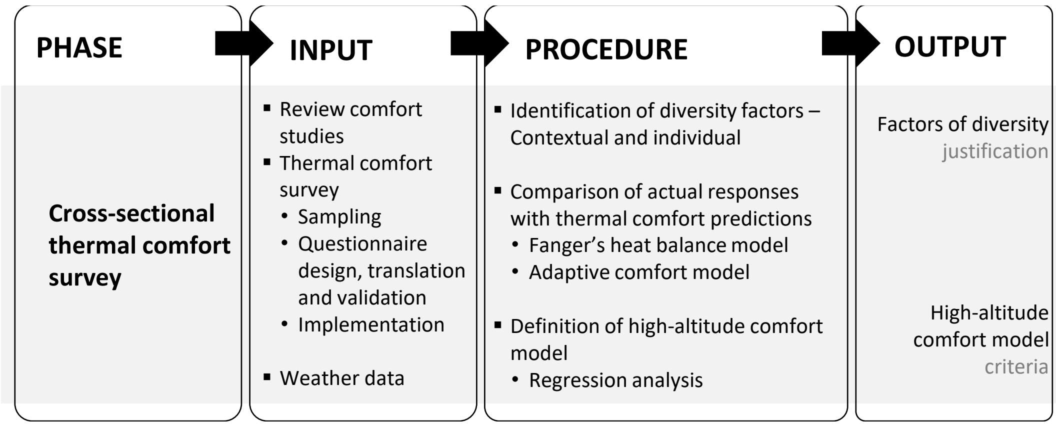


Figure 3.4: Cross-sectional thermal comfort survey input, procedure and expected outcomes

3.4.1 Surveyed occupants

As in most thermal comfort studies in housing, non-probabilistic sampling techniques were used due to unavailability and a widely spread population. Other factors constraining the sample were the limited availability of resources (i.e., time on site and budget). The research focused on the analysis of thermal comfort of residents living in three different high-altitude regions. In thermal comfort studies, 100 subjects for each location is a reasonable sample size in a transverse survey (Nicol et al., 2012).

The sample size considered a total of 128 complete surveys at each location and kept as close as possible to a proportional male-to-female ratio to produce results with enough power and validity. The target audience was limited to healthy adults between 18 and 65 years old. Older people and children were excluded from the sample since these two groups' physiology and health status might affect their thermal sensibility and perception. Besides, those two groups are considered to include vulnerable population groups[1], and the research sought to minimise potential ethical issues.

[1] Based on the Common Rule, Vulnerable groups could be: children, prisoners, pregnant women, fetuses, mentally disable persons and economically and educationally disadvantaged persons (Gordon, 2020). In this research, vulnerable groups include children, prisoners and mentally disable persons.

3.4.2 Thermal comfort survey

A thermal comfort survey was designed in a standardised form to gather subjective and factual data from occupants required as input for the evaluation of thermal comfort models. The designed survey seeks to identify individual and contextual factor that might explain the differences in subjective assessment and the definition of a suitable thermal comfort model for residents in the highlands, as previously explained in Section 3.2.

In terms of individual factors, the variables to be collected for further analysis are demographics (age, gender and body composition), clothing insulation and activity level. Besides, in order to gain gain insight into participants adaptation level to high-altitude locations questions were framed to inquire about respondents' birthplace, exposure to other climate and mechanically conditioned buildings (further detail in Section 3.4.3.2). Finally, additional information to understands occupants coping strategies (behavioural adjustments - Section 3.4.3.2 and main sources of discomfort at home (Section 3.4.3.2). The survey was intended to collect data at one point in time to determine relationships between variables at the study time. The materials were developed mainly in English and translated into Spanish (see data collection instruments in Appendix B.1). The translation account for Spanish variation in Ecuador; as in other languages, Spanish varies with the nationality of the native speakers. Herein lies the special attention placed on the translation, wording validation and questionnaire piloting.

3.4.2.1 Layout and content

The definition of the questionnaire's content involved an iterative process that started with an in-depth literature review of surveys design, thermal comfort questionnaires and scales. The different scales for the subjective assessment were defined based on previous studies and international guidelines (EN ISO, 2007a).

The designed questionnaires have five sections to collect data on participants demographics, adaptation factors, symptoms and discomfort at home, behavioural adjustments to restore heat balance, and subjective assessment of the indoor environment. The layout includes an introduction to the questionnaire followed by topic-related sections organised to allow for an intuitive and reasonable flow. Each section includes concise instructions about the questions' aim and content. The questions were numbered individually, visibly spaced and distinct from each other. In order to allow measurement devices enough time to stabilise, the questions related to the environment perception were left at the end of the questionnaire. A closing statement was included to thanks respondents and acknowledged their participation.

3.4.2.2 Questionnaires validation and piloting

A three-step process was employed to validate wording and questionnaire piloting: a) wording and questions translation with experts, b) wording and questions meaning tested with potential participants and, c) questionnaire pilot testing.

The subjective judgement scales' wording was discussed with seven bilingual (Native Spanish speakers and English) peers working in the building physics field. The experts provided feedback about the judgement scales wording and general comments about the survey structure and content. 'discomfort' was among the words discussed with experts. The literal translation to Spanish is 'incomodidad'[2] or 'molestia'[3] that would have a different interpretation than 'discomfort'.Instead, the word used for the comfort scale was in this study was 'agradable'. Worth mentioning that the structure and wording, particularly for the subjective assessment of the indoor environment, was not only tested and piloted to be used in this research but for the cross-national project 'Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings' (Schweiker et al., 2020). Besides the discussion with experts, the questionnaires was revised by a sociologist working with low-income and vulnerable groups in Ecuador. The feedback provided was related not only to the document's content and structure but also to building trust with the participants.

Furthermore, wording meaning and syntax equivalence were tested with potential participants to verify comprehension, flow and timing. The testing focused on checking the comprehension of specific questions and the whole questionnaire overall. The comments and feedback from this stage were incorporated in the final version of the questionnaire. Laslty, the questionnaire pilot test focused on checked the overall survey process, including sensors positioning and the survey's timing. Besides, the piloting procedure checked the questionnaires' layout, response variation, redundancy, and non-response options. After piloting, structural modifications included adding options for non-response, rearranging sections, and grammar check. The feedback gain included several recommendations to improve the fieldwork activities related to survey administration, document identifiers, and additional required information. Several documents were designed for the survey; hence, facilitating the identification of each of them is crucial. Finally, it was decided to provide additional information to the participants about notes taken during the survey to avoid insecurity and discomfort.

[2] Like in 'inconvenience' (something which causes) trouble or difficulty
[3] Like in 'bother' something that causes bother

3.4.2.3 Administration

This survey's data collection mode was verbal – interviews, face-to-face, using traditional paper and pencil interview (PAPI) questionnaires. Face-to-face surveys allowed the researcher to get more familiar with the participants and allowed respondents to ask for clarification if necessary. The interviewer read the questionnaire to ensure that respondents were asked the same questions under similar circumstances. Auxiliary showcards were used to help participants visualise the different response options, particularly for multiple choice answers and scales.

3.4.3 The thermal comfort questionnaire

The aim, questions and answer levels in the questionnaire are described in the following sections. The description included an explanation of the rationale behind each set of answers and scales. The final versions of the questionnaire in Spanish and English are available in Appendix B.1.2 and Appendix B.1.3. In addition, Appendix B.1.4 contains the observation sheets and Appendix B.1.6) the auxiliary showcards .

3.4.3.1 Introduction section

The questionnaire begins with the identifiers section and introduction text. The survey identifiers include survey and participant code and date. Personal or dwelling identifiers, such as participants name or dwelling address, were not included in the survey. The introduction text provides a brief overview of the project, the duration, the monitored environmental parameters and the plans to disseminate results. Besides, the introduction states participants right to withdrawal at any point, non-response to any question, voluntary participation and anonymity. The section finalised with an active confirmation of consent for voluntary participation.

3.4.3.2 Section A: Participant Information

Demographics data collection included age, gender, weight, height, garments and activity level. Age was collected in ranges in order to reduce participants' sensibility or uneasy situation. Besides, the section collects the parameters required to estimate the two personal variables, clothing insulation and metabolic rate. The type of data collected and the different response levels are summarised in Table 3.3.

Standard tables and screening are the most practical methods described in the international standards for collecting clothing insulation levels (Clo) and metabolic rate (MET) and provide a reasonable accuracy of 20% (CIBSE Guide A, 2015). Clo was estimated for each participant from individual garments; this method was used to allow the varied garments observed during

Table 3.3: Questionnaire data and answer levels - Section A: Participant information

Variable	**Description**	**Levels**
Age	Age group	1: <20; 2: 20 – 29 years; 3: 30 – 39 years; 4: 40 – 49 years; 5: 50 – 59 years; 6: 60 – 65 years; 7: >65 years; 8: Prefer not to disclose
Height	Height of the participant	-
Weight	Weight of the participant	-
Gender	The gender of the participant	1: Male 2: Female
Garment	Code of garments during the survey	List in Figure 3.5
Current activity	Observed current activity	List in Table 3.4;
Previous activity	Activity within the last 30 minutes	As previous (List in Table 3.4)

the surveys. The question included four different boxes for listing all garments used at the upper and lower body, as well as footwear and accessories. As a guideline for participant responses and answers coding, an auxiliary showcard provided a list of commonly used garments, as shown in Figure 3.5. In case a different garment not included in the list was reported, the researcher annotated it for further inclusion in the data processing step. Participants' posture and, when applicable, the chair or sofa's material was annotated during the survey in the researcher observation sheet as described in Section 3.4.3.2.

Participants are usually involved in a combination of activities of work and rest periods. Hence, the metabolic rate was estimated from the activity observed during the survey, usually seated quiet, and the activity performed within the last 30 minutes. Participants selected the activity from a showcard (Figure 3.6), the corresponding Met and metabolic rate were defined as shown in Table 3.4 (ASHRAE, 2009) .

Table 3.4: Metabolic rate and Met units for activities in the questionnaire

Code	**Activity Description**	Met **units**	**Metabolic rate** (W/m^2)
1	Reclining	0.8	45
2	Seated, quiet	0.9	55
3	Standing, relaxed	1.2	70
4	Light activity standing	1.6	95
5	Moderate activity standing	2.0	115
6	High activity	2.4	140

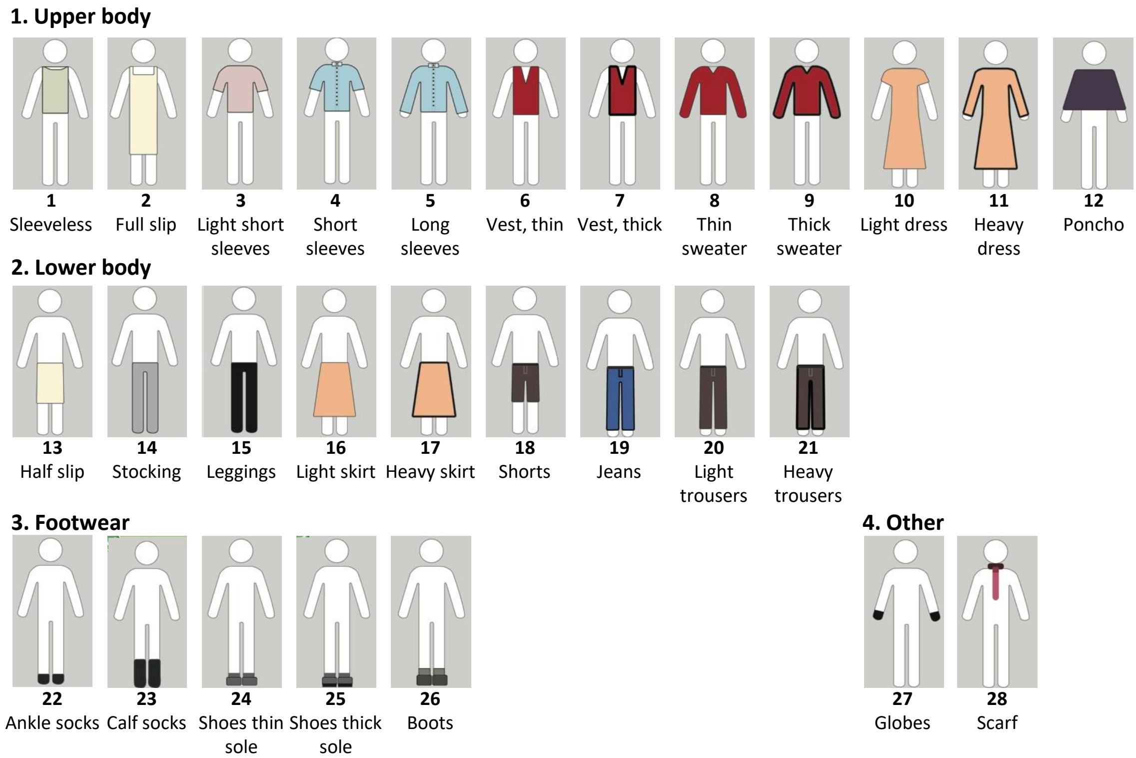


Figure 3.5: Individual garments and codes used in the auxiliary card for clothing data collection

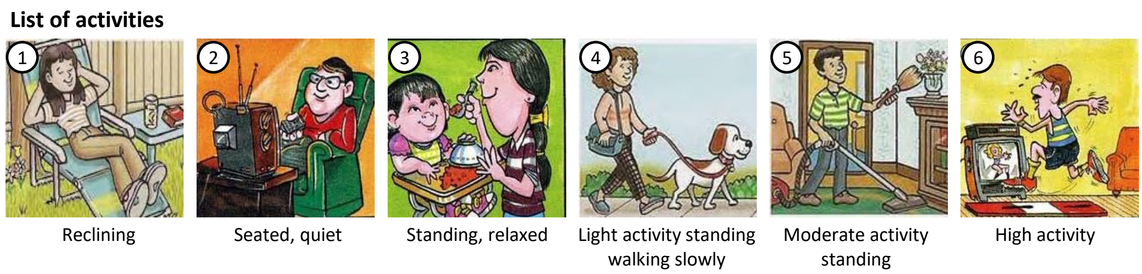


Figure 3.6: List of activities and codes used in the auxiliary card for data collection

Section B: Adaptation

This section collected relevant information to understand participants levels of exposure to high-altitude environments. Questions focused on participants' exposure to different environmental conditions due to their previous dwellings and daily commuting experiences. The collected variables and the answers' level are detailed in Table 3.5. This section inquired about participants' exposure to different altitudes, climates and mechanically conditioned buildings, as follows:

- Birthplace and living place refers to **a.** place where the participant was born, **b.** how long the respondent lived in the current home, and **c.** where they lived during the past three years?
- The hours at home and outdoors intended for capturing the level of exposure to indoors and

outdoors environments.

- Places visited and frequency refers to a) places to which participants commute within the city or outside the city and b) numbers of days commuting within a week.
- Frequency (number of days within a week) participants are exposed to mechanically conditioned spaces.

Table 3.5: Questionnaire data and answer levels - Section B: Adaptation

Variable	Description	Levels
Birth location	City/country of birth	-
ActDwelling	Time living in the current dwelling	1: <1 year 2: 1 - 3 years 3: >3 years
PreDwelling	In case previous is <3 years, time at the previous one	1: <1 year 2: 1 - 3 years 3: >3 years
PreDwelling location	Parish and city of the previous dwelling	-
PreDwelling roof	Predominant roof's material of the previous dwelling	-
PreDwelling walls	Predominant walls' material of the previous dwelling	-
PreDwelling systems	Any system for conditioning the dwelling	-
Hours at home	Average hours a day spend inside the house	-
Hours outdoors	Average hours a week spend outdoors	-
Days at other location	Days a week spend in a different parish or city	-
Other location	Parish or city visited weekly	-
Days HVAC	Days a week exposed to HVAC systems	-

The data collected were tabulated and transformed into adaptation indexes to explore thermal perception differences due to residents experiences at different altitude environments, thermal history from different regions, and different thermal expectations from exposure to mechanically conditioned buildings.

Section C: Symptoms and discomfort at home

This section collected responses of the frequency participants perceived symptoms and discomfort associated with poor indoor environmental quality in dwellings. A list of health and discomfort issues experienced in buildings was derived from guidelines and existing questionnaires (Andersson and Fagerland, 1988; Butcher and Craig, 2015). The included symptoms are fatigue, headache, nausea, irritated eyes, runny nose, dry throat, cough, itching ears, dry skin on the face and hands. Discomfort issues in this research refer to inconveniences or disturbances experiences because of the indoor environment such as draught, room temperature too high or too low, highly oscillating room temperature, stuffy 'bad' air, humidity, and dry air. In both cases, symptoms and discomfort, an empty box was left to include any other issues the residents would like to report.

Instead of a direct question inquiring about any perceived symptoms and discomfort, participants were asked how often they experience any stated disturbances. Often (once/twice a week), sometimes (once/twice every two weeks) and never were the three levels used to describe the occurrence frequency. Participants were also asked if they consider the experienced symptoms are associated with the dwellings' indoor environment. Furthermore, the closing questions aimed to investigate if the indoor temperature (hot or cold environments) impairs the ordinary course on residents' activities at home such as house chores or sleeping and the frequency of the problem's occurrence. The five variables to be extracted from this section are summarised in Table 3.6.

Table 3.6: Questionnaire data and answer levels - Section C: Symptoms and discomfort at home

Variable	Description	Levels
Symptoms	Perceived symptoms and frequency	1: Never; 2: Sometimes; 3: Often.
Symptoms at home	If symptoms are associated with the indoor environment at home	1: Yes 2: No.
Issues at home	Frequency of environmental issues experienced at home	1: Never; 2: Sometimes; 3: Often.
Problem to sleep	Problems to sleep due to uncomfortable temperature	1: None 2: Little 3: A lot
Problem in household	Problems to perform house chores due to uncomfortable temperature	1: None 2: Little 3: A lot

Section D: Control strategies

This section aims to gather information about the individual's behavioural and environmental adjustments. Behavioural adaptations correspond to the voluntary control strategies that householders currently use to keep themselves warm or cool as a response to discomfort. The environmental adjustment relates to the available controls provided at the dwellings for temporal adjustments or permanent modifications conducted to control the indoor environment.

Permanent changes are adaptations done to the room or house to improve thermal performance (i.e. redistribution of spaces, openings modifications). An open question was used to enquire about any permanent change done in the dwellings. Participants were asked to report any performed modification to improve the indoor temperature, so the spaces do not get too hot or too cold.

In contrast, temporary adjustments are the ones that can easily revert. Participants were asked about any actions taken to keep themselves warm or cool. Those questions formulated queries such as: on a typically cold day (hot day), what do you usually do to keep yourself warm (or cold)? For this case, a list of potential responses was established considering the most recurrent actions to keep warm and cool at home (operation of doors, windows and curtains, modifying clothing, intake of drinks or food, and switching on/off mechanical conditioning systems) (Gauthier, 2016). The researcher used the list to collect and codify the answers. The list was not available to participants to minimise influencing their responses. A blank space was left to annotate any response not listed. The variables and answer levels extracted from each question in this section are summarised in Table 3.7.

Table 3.7: Questionnaire data and answer levels - Section D: Control strategies

Variable	Description	Levels
Permanent modifications	Any permanent modification at home to enhance or control indoor temperature	-
Temporary responses	Temporary responses to keep themselves warm	-
Temporary responses	Temporary to keep themselves cool	-

Section E: Indoor environment

Environmental assessment questions collected sensation and preference votes for temperature, humidity, air movement and air quality. Thermal comfort surveys collect votes in terms of thermal sensation (from 'cold' to 'hot'), level of discomfort ('comfortable' to 'very uncomfortable'), thermal preference (from 'much colder' to 'much warmer'), and personal satisfaction ('Satisfied', 'Dissatisfied') (EN ISO, 2007a). Similar scales are used to assess humidity, air movement, and air quality (Guerra-Santin and Tweed, 2015a). The air movement sensation scale is a 5-degree one pole scale with a point of origin indicating the absence of air movement and four degrees of increasing intensity air movement. The questions and exact wording structure could be checked in Appendix B.1.2, while the different variables enquired and responses' level are summarised in Table 3.8.

Table 3.8: Questionnaire data and answer levels - Section E: Indoor environment

Begin of Table

Variable	Description	Levels
TSV	Thermal sensation vote	1: (+3) Hot 2: (+2) Warm 3: (+1) Slightly warm 4: (0) Neutral

Continuation of Table 3.8

Variable	**Description**	**Levels**
		5: (-1) Slightly cool 6: (-2) Cool 7: (-3) Cold
TCV	Thermal comfort vote	1: (0) Comfortable 2: (-1) Slightly uncomfortable 3: (-2) Uncomfortable 4: (-3) Very uncomfortable 5: (-4) Extremely uncomfortable
TPV	Thermal preference vote	1: (+3) Much warmer 2: (+2) Warmer 3: (+1) Slightly warmer 4: (0) No change 5: (-1) Slightly cooler 6: (-2) Cooler 7: (-3) Much cooler
HSV	Humidity sensation vote	1: (+3) Very humid 2: (+2) Humid 3: (+1) Slightly humid 4: (0) Neither humid nor dry 5: (-1) Slightly dry 6: (-2) Dry 7: (-3) Very dry
HPV	Humidity perception vote	1: (+3) Much more humid 2: (+2) Humid 3: (+1) A bit humid 4: (0) No change 5: (-1) A bit drier 6: (-2) Drier 7: (-3) Much drier
ASV	Air movement sensation vote	1: (0) No movement 2: (+1) Still 3: (+2) Just right 4: (+3) Breezy 5: (+4) Too breezy
APV	Air movement preference vote	1: (+3) Much more air movement 2: (+2) More air movement 3: (+1) A bit more air movement 4: (0) No change 5: (-1) A bit less air movement 6: (-2) Less air movement 7: (-3) Much less air movement
OSV	Overall satisfaction vote	1: (0) Satisfied 2: (-1) Dissatisfied

End of Table

Additional contextual observations

Additional annotations in the observations sheet collected data about the rooms' characteristics, predominant construction materials, and indoor environmental measurements. Participants were informed about the observations being collected and provide consent before performing any measurements and annotations. The dwellings observations sheet contained five sections as follows: a) identifiers, b) room context, c) indoor environment observations, d) weather data and e) interviewer comments. Surveys' identifiers relate to date, study location, survey identifier, starting time, vote time and finishing time. Annotations regarding room context included predominant roof and walls materials, participants' location and position, and any source of direct heat. Besides the participants' position, the chair or couch materials were also noted. Any hot or cold sources (e.g. portable heaters, fans) were observed, as well as any opening or ventilation mechanism. Observations of the indoor environmental variables were documented at the beginning, voting and end of the survey. The Spanish and English versions of the template are attached in Appendix B.1.4 and Appendix B.1.5, respectively.

3.4.4 Survey implementation

Fieldwork supporting team

Two students from a local university assisted during the data collection process on task related to participants' recruitment and filling observation sheets. The assistance of students was alternated, enabling a two-person team each day of surveys to avoid alone fieldwork and at the same time to minimise the intrusion in participants dwellings.

Recruitment

Different techniques were used to gain access to potential participants; invitations were distributed at community activities (meetings, religious meetings, others) and individual dwellings. The invitation letter (See Appendix B.1.1) circulated containing information about the project, the survey and the researcher contact details. Door-to-door invitations had a higher response rate than invitations at community activities; hence that was the primary recruitment method. On average, three to four people were approached in order to get one participant willing to complete the survey. In other words, around 1200 potential participants were invited to take part in the study. Once the participants agreed to participate, they all completed successfully the questionnaire (N = 398). Recruitment and surveys took place during weekends and weekdays to increase working and non-working respondents' response rate.

Data collection

The thermal comfort surveys took place between September 2017 and January 2018, as shown in the Figure 3.7. The sample corresponds to 287 dwellings across the three locations and 398 complete thermal comfort surveys from residents ageing between 18 years-old and 65 years-old (Table 3.9). The overall survey lasted around 15 when interviewing a single occupant and around 20 minutes when interviewing two participants. The participants were interviewed independently (n=180) or simultaneous in pairs at the same dwelling (n=218).

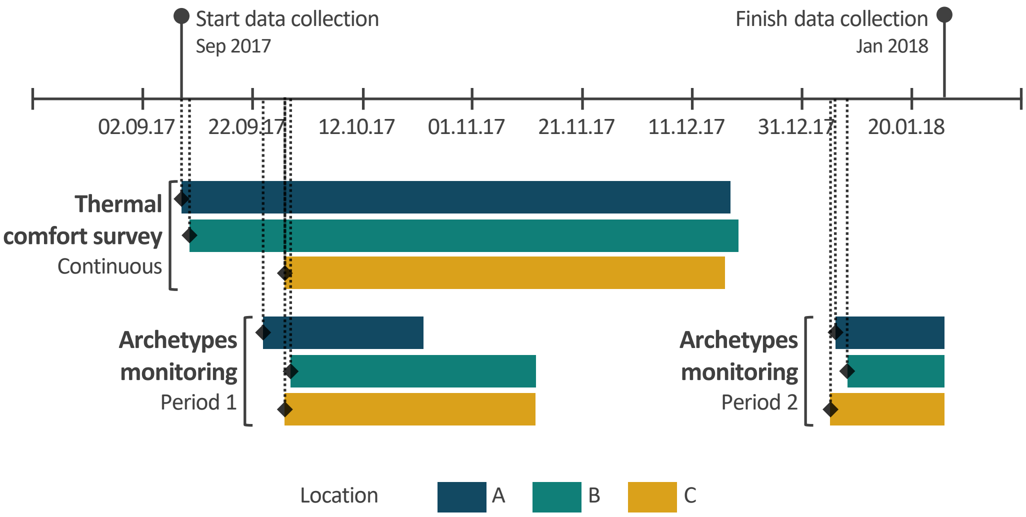


Figure 3.7: Research data collection timeline

Before conducting any analysis, data from simultaneous participants were checked for similarities between responses. The effect of non-independent responses was tested between groups (independent vs non-independent) and for the whole sample. The robust significance observed from the correlations between subjective and objective data confirmed that results would be similar regardless of the groups. Therefore, the research will use the whole sample (n=398) when individual subjects are the unit of analysis. In terms of dwelling sample, the unit for analysis corresponds to the surveyed dwellings (287 rooms in different dwellings). The analyses performed and results are described in Appendix C.

3.4.5 Objective spot measurements of the indoor environment

Indoor environmental measurements at each dwelling were collected three times during the survey. The collected physical variables were the main four environmental variables, dry-bulb air temperature (t_{in}), globe temperature (t_g), relative humidity (RH) and airspeed (v_a). Additional measured

Table 3.9: Summary of surveyed participants and dwellings by location

Location	Dwellings	Female	Male	Total
A	101	68	66	134
B	99	70	62	132
C	87	74	58	132
All	287	212	186	398

parameters include CO_2 concentration levels and atmospheric pressure (Pa).

Table 3.10 summarises the main characteristics of the sensors used in the fieldwork. The different instruments comply with the minimum characteristics of the equipment recommended in the international standards (ANSI/ASHRAE/IES, 2017; EN ISO, 2001). A heat stress monitor was used to measure t_{in}, t_g, RH and v_a. The monitor was fixed to a tripod and collocated nearby a seated subject at a vertical height of about 0.6m above the floor and not less than 1m inward from any wall. The exact position was decided in the light of room geometry and layout, avoiding direct sunlight, draught and heated or cooled surfaces.

Table 3.10: Technical specifications of the monitoring equipment - Spot measurements

Instrument	Variable	Unit	Instrument description	Range	Accuracy
QUESTemp 36	t_{in}	°C	The dry-bulb thermometer measures the ambient air temperature; shite plates surround the sensor to shield it from radiant heat.	0- 120	± 0.5
	t_g	°C	An approximation of the radiant heat exposure on an individual is measured by a 6inch (15.24 cm) blackened copper sphere mounted on the equipment case.	0 - 120	± 0.2
	RH	%	Relative humidity sensor is incorporated in the sensor case; slots allow air to circulate.	20 - 95	
	Va	m/s	Omni-directional anemometer measures air flow and is mounted behind the sensor case.	0 - 20	0.1
Testo 435 and multifunction probe	Pa	hPa	multi-functional measurement instruments	0 - 2000	0.1
	CO_2	ppm		0 - 10000	1.0

The indoor environmental measurements were annotated in the observation sheet. The first measurement was collected five minutes after arriving at the surveyed room, the second when collecting the indoor environment's subjective responses and the final one at the end of the survey.

3.4.6 Thermal comfort data processing

Objective and subjective data collected in the research were processed and analysed using RStudio, besides several statistical analysis packages RStudio Team (2020). Data processing included coding, changing and modifying categories, creation of new variables and construction of scales.

The proposed research is descriptive by nature, hence, sought into consistency patterns and correlations. For this purpose, the collected data were mainly analysed through graphical and statistical techniques. Due to the different collected type of data, categorical and continuous, different parametric and non-parametric statistical tests were used to test differences in means, medians, standard deviation (*sd*), distributions, correlations, and regressions. The derivation and analysis process for variables (i.e. operative temperature) used throughout the study are described in this section. The calculation or derivation of additional variables and scales required for particular analyses are described in each of the corresponding results chapters.

The thermal comfort data incorporates all the subjective responses collected in the survey and the indoor environment's spot measurements. All the data was entered into a data set manually, checked and further processed for calculating new variables or indexes. Data collected include qualitative and quantitative data; thus, different processes were to check and validate the datasets. According to the data type, variables were checked for completeness, validity, consistency, and conformity. The quality control of thermal comfort data checked that all the values were within an acceptable range (qualitative data) limits and corresponding response options (quantitative data). In case of missing data, the register was filled as NA. The dataset corresponding to the thermal comfort survey consists of 398 observations and 179 variables.

The indoor environmental spot measurements annotated during the thermal comfort survey were processed for further analysis. Inconsistencies of readings from the indoor environment were checked, and missing values were coded as NA. An averaged value for each variable was used for all further analyses. Besides, other calculated indoor environmental variables included radiant temperature, operative temperature, humidity and barometric pressure. Humidity and barometric pressure followed the procedure detailed in Section 3.3.3. The mean radiant temperature (t_r) was derived from the globe temperature (t_g), v_a, t_{in}, globe diameter (D) and globe emissivity (ε) as in Equation 3.3, where the ε for the black globe is 0.95 (ASHRAE, 2009).

$$t_r = \left[(t_g + 273.15)^4 + \frac{1.10 \ \cdot 10^8 \cdot v_a^{0.6}}{\varepsilon \cdot D^{0.4}} \cdot (t_g - t_a) \right]^{\frac{1}{4}} - 237.15 \tag{3.3}$$

The operative temperature (t_o) is usually calculated as the average of the air temperature and the mean radiant temperature weighted respectively by the convective heat transfer coefficient and the linearised radiant heat transfer coefficient for the occupants. However, in this research, the t_o was calculated as described in Equation 3.4 to account for the significant elevation difference compared to the standard value ($101.33kPa$) (ASHRAE, 2009). t_o is the average of the air temperature and the mean radiant temperature weighted respectively by the convective heat transfer coefficient (h_c) and the linearised radiant heat transfer coefficient for the occupants. The effect of altitude is accounted for in t_o when replacing h_c in Equation 3.4 with h_{cc} from Equation 3.5. Where h_{cc} is the corrected convective heat transfer coefficient (W/m^2K), h_c is the heat transfer coefficient for standard atmospheric pressure, and P_a is the local atmospheric pressure (kPa). The h_{cc} was also used for the PMV calculation PMV as described in Section 6.2.1.

$$t_o = \frac{h_r \cdot t_r + h_c \cdot t_a}{h_r + h_c} \tag{3.4}$$

$$h_{cc} = h_c \; (p_t \; 101.33)^{0.55} \tag{3.5}$$

Throughout the analysis, the operative temperature and subjective votes are statistically compared in order to identify significant differences between two or more groups. Significant difference in the mean operative temperature when participants voted for the three central categories (TSV = +1, 0, -1) was explored between contextual and individuals groups. The neutral temperature, at which the average person will be thermally neutral, was estimated from the indoor operative temperature binned into half-degree increments (t_{o-bin}) regressed against the bin's mean thermal sensation responses ($mTSV$) (de Dear and Brager, 1998). Equation 3.6 correspond to the weighted linear regression model between $mTSV$ and t_{o-bin}) for calculating t_n when $mTSV$is neutral. Thus, solving Equation 3.6 when $mTSV = 0$, the t_n is calculated from Equation 3.7.

$$mTSV = a + b \cdot t_{o-bin} \tag{3.6}$$

$$t_n = -\frac{a}{b} \tag{3.7}$$

The central tendency of t_o, t_n, t_{o-mean} and t_{comf} was statistically compared against reference values (i.e. thermal comfort standards), or to different groups (i.e. location, demographics). Table 3.11 summarises the different tests employed to analyse significant differences between groups. Differences between central tendency (means and medians) were explored for two, three and more independent groups. The general goal was to use the estimate of the mean, assess the variation, and use this information to provide the amount of evidence of a difference in means or central tendency. T-tests were used for comparing two groups mean when the data complied with the assumption for normality and variance; when unequal variance was observed, the Welch t.test was used to compare the groups. In the case of three or more groups, One-way ANOVA test or Kruskal-Wallis were used to identify significant differences between the studied groups. Kruskal-Wallis $(k-s)$ test was used to determine whether there was significant variation among n groups, where n<2. The test applied the Bonferroni rank to minimise the overall type I error due to multiple simultaneous tests. The null hypothesis states that the subjective votes come from an identical population and is accepted at a significant $p<0.05$. Whenever p value results are significant, a Wilcoxon test was used to test whether there was a statistically significant difference between pairs of groups $p<0.05$). In case the data did not comply with the assumptions of normality and variance, alternative tests were used as described in Table 3.11. Whenever evidence determines that at least one groups' mean differ from the others, follow-up multiple comparison tests (Tukey's Honestly-Significant Difference or Pairwise Wilcox test) were used to determine where the differences occur. The p values were adjusted with Bonferroni, and the hypothesis was accepted at the $p<0.05$ level. In all cases, the tests' hypotheses were confirmed or rejected for a p.value of 0.05. The statistics for each analyses, including variables, number of groups, normality, variance and statistical significance of means are described in detail in Appendix E in Table E.1.

Table 3.11: Summary of statistical tests for comparing variables central tendency

n Groups	Normality	Variance	Central tendency	Pairwise comparison
2	Normal	Equal	t.test	
2	Normal	Unequal	Welch t.test	
2	Not normal	Equal	One-sample Wilcoxon rank test	
3 or more	Normal	Equal	ANOVA	Tukey (HSD)
3 or more	Normal	Unequal	ANOVA test with no assumption of equal variance	Tukey (HSD)
3 or more	Not normal	Equal	Kruskal-Wallis rank sum test $(k-w)$	Pairwise.wilcox.test
3 or more	Not normal	Unequal	Kruskal-Wallis rank sum test $(k-w)$	Pairwise.wilcox.test

In addition to evaluating differences in central tendency, significant differences in the the cumulative distribution of data were explored through Kolmogorov–Smirnov test $(k-s)$. The scales used for collecting subjective votes related to the indoor environment are by nature categorical data. Despite the use of the scales have been challenge by several authors, the subjective votes are analysed as continuous data under the assumption of being equidistant and linear (Schweiker et al., 2017). In order to allow consistency of the data throughout the thesis, the subjective scales have been considered as continuous.

3.5 Thermal performance assessment of archetypes

The evaluation of performance aims to assess how well the dwellings archetypes provide comfort to residents compared to a reference value. Among the more than seventy indices reported for buildings' thermal performance assessment, the majority developed for assessing overheating, and only a few for assessing winter discomfort. The evaluation's indices depend on the thermal comfort model used for the evaluation and have been broadly classified as percentages, cumulative and risk indices. The criteria used in this research is the percentage index, which reports the percentage of likely discomfort hours concerning the total number of occupied hours. The index was selected because a) it can be applied to both Fanger's heat balance and adaptive comfort models and b) allows the evaluation of upper and lower exceedances from comfort temperature (Carlucci and Pagliano, 2012).

Buildings' performance is mainly done by monitoring, simulation, expert's evaluation, subjective assessments, or a combination of techniques. On the one hand, monitoring allows measuring physical parameters in buildings; however, these campaigns are costly, time-consuming, invasive, and require professional expertise (Guerra-Santin and Tweed, 2015b). On the other hand, building performance simulation (BPS) is widely applied for energy and environmental performance assessments due to the flexibility to investigate the potential impact of specific phenomena or buildings alterations through computer-based simulation software. However, uncertainty emerges during the transition from reality to simulation, undermining the model's precision, hence, the validity of the outcomes. Simulation inaccuracies result from the misuse of energy analysis methods, deficient selection of input criteria, software limitations, and external factors.

A combined approach was used in this research for the thermal performance assessment of dwelling archetypes. A well-established approach to achieve reliable results is the calibration of the model. The calibration process focuses on reducing the uncertainty of a model by comparing a predicted indoor temperature with the actual monitored temperature in dwellings. The analysis's objective was to identify the magnitude and the sources of model prediction uncertainties and the characterisation of acceptable model properties (Saltelli et al., 2004). For this purpose, a four-step procedure was defined for this research a) data collection and processing, b) evidence-based modelling, c) sensitivity analysis, and d) iterative model improvement. Further description of the modelling and calibration procedure is detailed in Chapter 7; the definition of dwellings archetypes and archetypes' audit is described below.

3.5.1 Definition of low-cost dwellings archetypes

The selection of dwellings archetypes in the Ecuadorean Andes followed a purposive sampling technique based on the last census of housing and population and low-cost housing criteria defined by the Ministry of Urban Development and Housing (MIDUVI) for funding the construction of minimum dwellings (Acosta Paredes, 2003; INEC, 2010). Census data reported the predominant envelope materials, while low-cost housing criteria defined the house type and habitable area, as described below:

- The predominant construction materials are asbestos or zinc (59.8%), cast concrete (29.7%), and clay tiles (3.1%) in the roof. The walls built of clay bricks, or hollow concrete blocks, account for 78.5% of the existing stock, 6.7% wood walls and only 5.7% for adobe (INEC, 2010). The main difference of envelope materials is observed in roof materials and is aligned with the country's housing typologies.
- Detached single-storey houses are the predominant housing type and around $40m^2$ is the minimum habitable area of low-cost housing based on MIDUVI requirements (Gallardo et al., 2016a).

Detached single-storey houses, built with the predominant constructions' materials, which habitable is around $40m^2$, were the defined archetypes of low-cost housing for this research. According to roof and wall' predominant materials, three combinations of materials were defined archetypes representing the study locations' predominant construction typologies (Figure 3.8). Typology 1 corresponds to those dwellings with asbestos/zinc in the roof and hollow concrete blocks in walls; that is the main typology used to construct low-cost housing in Ecuador. Typology 2 combines cast-concrete roof and hollow concrete blocks. Typology 3 predominant roof's material is clay tiles, used almost exclusively in vernacular or traditional architecture in the highlands, combined with adobe walls. Based on archetypes' relative thermal mass, for further analyses, Typology 1 is considered as a light, Typology 2 as medium and Typology 3 as high-thermal mass construction.

3.5.2 Archetypes data collection

Data from nine archetypes were collected through a archetypes' audit used a buildings' survey (see survey in Appendix B.2) and monitoring campaign. The collected data included physical characteristics, envelope thermal insulation, internal gains, operation schedules, and indoor environment monitoring. Besides, measurements from the dwellings were taken to produce layout,

Figure 3.8: Dwellings' construction typologies

sections, and facade drawings. Monitoring of the indoor conditions was conducted in two stages between September 2017 and January 2018, as shown in Figure 3.7. The building survey included the collection of the following variables:

a. Site and dwellings physical characteristics:

Due to being informal construction, which means dwellings have not been subject to buildings standards or official checks, most dwellings did not have architectural drawings. Thus, on-site measurements were collected to produce floor plans, sections, and facades. The information collected also included orientation and any significant source of shading. Detailed dwellings drawings are available in Appendix F.1.

b. Envelope and materials properties:

The constructions and layers for the different envelope elements are relatively standard in the studied area. Besides, householders are usually involved in the construction process. Thus, details on the constructions were collected from users and observations. Whenever possible, the thickness of the overall envelope elements was measured. The different constructions and layers of materials for each dwelling are described in Appendix F.2.

c. Internal gains and occupant behaviour:

Primary information was collected regarding internal loads and schedule of occupancy by asking occupants about their regular practices. In the same way, open questions were used for gathering information about appliances' operation, cooking, lighting, and ventilation.

During the fieldwork, the studied areas were explored to identify archetypes meeting the monitoring and location requirements defined in Section 3.3. In case an identified dwelling matched the defined characteristics, the research team approached the householders and provided a quick overview of the project and a short explanation of the research objectives and the reasons for selecting their dwellings. The monitoring equipment to be used was introduced to the potential participants, and enough time was allowed for clarifications and questions. Once participants agreed to collaborate in the research, the data loggers were installed in one or more rooms in a dwelling, and the building was conducted. Further visits were done to download data or remove the dataloggers to reduce disturbance to the residents.

3.5.3 Archetypes indoor environmental monitoring

A small data-logger (Tinytag) was installed in one or two rooms per dwelling during the monitoring campaign. The data-loggers collected air temperature (t_{in}) and relative humidity (RH) data in five-minute intervals for a minimum of 10 consecutive days as recommended by EN ISO (2007c) but also according to participants' availability and preferences. The sensors' precise location was decided based on the room geometry and layout, avoiding direct sunlight, draught and heated or cooled surfaces (EN ISO, 2007c). Table 3.12 provides details on the specifications of the sensor.

Table 3.12: Technical specifications of the monitoring equipment - Monitoring campaign

Instrument	Variable	Unit	Instrument description	Range	Accuracy
Tinytag Ultra 2	t_{in}	°C	TGU-4500 self-contained sensors Sensor type - 10K NTC Thermistor	-40 to 85	±0.5
	RH	%	Sensor type - Capacitive	0 to 95	±3 at 25 °C

3.5.4 Archetypes data processing

Data collected from dwellings archetypes were used as input for dwellings thermal modelling, as described in Section 7.3.1. The data were processed to generate the archetypes drawings and models for thermal performance simulation. Besides, archetypes data served as a reference for the definition of materials database, internal loads, and occupancy and operation schedules (Section 7.3.4).

Monitoring data were processed and tidied for indoor performance analysis and calibration purposes. Sensors data were compared against measurements from a controlled environmental chamber. The process included two reference setpoints, 10.0 °C and 20.0 °C. The mean error for the lower calibration setpoint was 0.45 °C (± 0.2 °C) and for the higher calibration setpoint was 0.45 °C (±0.23 °C). The observed error varies between the lower and higher calibration points; thus, one cannot assume a linear trend. Two points were not sufficient for applying any correction to the measurements. Nevertheless, the overall observed measurement error is relatively small for all the data loggers to produce significant output discrepancies.

3.6 Ethics, risk assessment and data protection

The nature of thermal comfort research is predominantly fieldwork studies seeking to explore occupant's interaction in real conditions. Besides the methodological challenges, fieldwork raises practical and ethical issues. On the one hand, the main practical concerns when conducting fieldwork are contact and access, participants recruitment, and health and safety. On the other hand, the main ethical issues identified are informed consent, privacy and confidentiality, risk and benefits, and power relations.

Ethics considerations were integrated into the research project by considering all the necessary steps to minimise fieldwork hazards and comply with data protection requirements. All relevant forms and approvals are attached in Appendix D, risk assessment and data protection. The overall approach toward ethics implications was assessed and approved by the Bartlett School of Environment, Energy and Resources (BSEER). Ethical approval in Ecuador is only required when human participants are involved in medical research. Nevertheless, general ethical principles applied such as respect for life dignity and biodiversity, informed consent, confidentiality and human rights respect and protection (Secretaría de Educación Superior Ciencia Tecnología e Innovación and Instituto Ecuatoriano de la Propiedad Intelectual, 2017).

3.6.1 Inform consent

The designed informed consent gave enough information about the research and guaranteed no explicit or implicit coercion. In other words, to guarantee that prospective participants can make an informed and free decision on their possible involvement. Information to participants was provided in a comprehensible written form. Enough time was allowed for them to consider their choices and discuss their decision with others if appropriate.

The choice for consent differed according to the research method; active consent was used for the surveys and signed consent for archetypes audits. Active consent was considered appropriate for surveys due to the socio-cultural background; signing a document would generate insecurity, thus reducing respondents' involvement. A signed document was used for archetypes' audit as participants' collaboration was required for a more extended period, and monitoring equipment was installed in their dwellings.

Besides, the hierarchy roles in the family were considered. For both surveys and archetypes audit, a senior family member's agreement was always obtained before any participation. As far as possible, the archetype's audit was conducted only with the responsible adult's involvement.

3.6.2 Privacy and confidentiality

Information collected by researchers were treated as confidential and were not disclosed to third parties. All personal data collected during the fieldwork were anonymised according to the principles of the UK Data Protection Act 1998. Anonymised raw data collected from participants were discussed and analysed within the fieldwork supporting team, and no personal data have been included in the diffusion of results.

3.6.3 Risk and benefits

There was no potential risk identified for the participants associated with this research. The installation of sensors (Tinytag) on the walls had a small risk of property damage. The risk was minimised using adhesives or fasteners that do not damage the walls finishing or painting.

Participants were informed about the potential benefits of the research. Special attention was paid to explain that the research outcomes may not benefit them as individuals so that they do not participate in the false expectation. No monetary reward was used in the research. Instead of monetary incentives, participants received non-monetary compensation, such as sweets and biscuits, at the end of the survey.

In terms of the risk assessment for fieldwork, one of the potentials hazards identified was alone work. For this reason, the coordination of teamwork was imperative so that a second person always accompanied the research. Besides, the research itinerary and contact details were shared with the supporting research team. Furthermore, the fieldwork activities followed the university's approved code of practice, and the corresponding approval was obtained (Appendix D.3).

3.6.4 Relation of power

It was emphasised during the data collection process that the participation was voluntary, the option of non-replying questions and withdrawal at any moment.

3.6.5 Data storage and security

The collected data, particularly any personal data, were stored following UCL's recommendations and procedures (Data protection number Z6364106 2017 07 84 - Appendix D.4). Personal data, dwellings' pictures, dwellings measurements and survey responses were stored in a secure cloud (UCL drive) and accessed through a remote connection to UCL. Personal data, such as participants names, telephone number and address, were kept according to the Data Protection Act 1998 (DPA) in a separate encrypted file. Once the fieldwork activities finished, personal data were securely destroyed following the computer security team's guidance (UCL Library Service, 2020).

Whenever pictures were taken, special attention was paid to avoid revealing any personal or dwellings identifiers. The pictures were kept for the data analysis and were used for the presentation of results. Hard copies of the buildings surveys and thermal comfort surveys were stored in a secure place and adequately disposed of once the research activities were concluded.

Chapter 4

Effect of high-altitude contextual factors on human thermal comfort

4.1 Overview

Occupants' thermal perception is a combined response to fundamental buildings' physical conditions and the interaction between behavioural, physiological, and psychological adaptive processes. Understanding the factors that lead to differences in high-altitude residents' thermal comfort responses could allow the identification of different mechanisms to restore comfort. Besides, incorporating those factors of diversity in thermal comfort models could enhance the prediction of comfort responses. The adaptive comfort approach estimate the optimal indoor temperature according to the prevailing outdoor temperature. One of this study's objectives is to extend the understanding of contextual and individual factors leading to diversity in thermal comfort in the study locations. Therefore, besides exploring the drivers already incorporated in the adaptive comfort model, additional contextual and individual factors were analysed to inform thermal comfort predictions in high-altitude regions. This chapter investigated differences in subjective votes and operative temperature (to) for contextual factors (Figure 4.1), such as outdoor and indoor conditions and dwellings physical conditions. The individual factors are explored in Chapter 5.

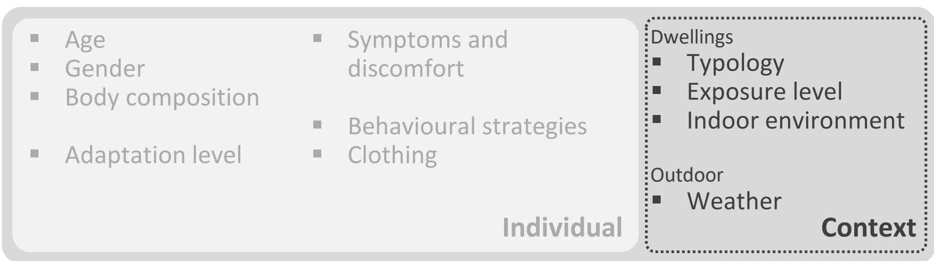


Figure 4.1: Contextual factors of diversity in thermal comfort

In order to identify significant differences between the study locations, objective (i.e. environmental measurements) and subjective data (i.e. subjective votes) were analysed. The investigation first seeks to understand the main discrepancies between the study locations regarding outdoor and indoor environments and their interaction. In terms of dwellings physical conditions, rooms' construction typologies (thermal mass) and rooms' position within the dwellings were the attributes investigated to evaluate the effect of the surveyed rooms' physical conditions in the indoor environment. Lastly, the distribution of the subjective votes and each interval of the corresponding environmental variable were explored to identify differences across the study high-altitude locations.

4.2 Methods

A combination of graphical and statistical methods was used to analyse the differences between objective indoor and outdoor environmental parameters and subjective environmental votes (thermal, humidity and air movement).

4.2.1 Analysis of indoor and outdoor environment

The analysis of indoor and outdoor environmental variables seeks to provide insight into physical variables' main differences across the studied locations. The methods used for this purpose are descriptive statistics, graphical analysis (box plots and cumulative distribution plots), and regression analysis. The differences between the cumulative distribution of observations were compared using a non-parametric test, Kolmogorov-Smirnov ($k-s$), to identify differences in the distributions' dispersion and shape.

4.2.2 Evaluating relation between objective and subjective votes

The distribution and mean sensation and perception votes were analysed for each location. Besides, the relation between subjective votes and objective measurements was investigated by looking at the votes' distribution and correlation analysis. Graphical analyses (boxplots) allowed the comparison of the votes' distribution and the corresponding indoor environmental variable.

The correlation analysis explores the relations between sensation votes and preference votes, as well as the relation between subjective votes and objective measurements.In social science, outcomes may have several causes; thus, the precision and reliability of measurement tend to be lower than those for objective measurements. Therefore, two variables are likely to be very strongly related at a correlation coefficient of 0.30 when it is statistically significant ($p<0.05$). Furthermore, the distribution of subjective votes (temperature, humidity and air movement) according to the corresponding indoor environmental variables was explored to identify any patterns and differences across locations.

4.2.3 Categorisation of surveyed rooms by typology and levels of exposure

Building properties, such as construction materials, infiltration, orientation, among other factors, affect the indoor environment, which has repercussions on thermal comfort. In order to analyse the potential effect of rooms' thermal mass and direct exposure to the outdoor environment, the collected data were coded into two new variables room typology and exposure condition. Based on the rooms' construction materials and the rooms' position within the dwelling, the surveyed rooms were categorised according to the thermal mass (medium and light) and the level of exposure to the outdoors (exposed and non-exposed) summarised in Table 4.1. The proposed categorisation does not account for over-shaded surveyed rooms despite located on the top floor of the dwelling (i.e. trees or other buildings shading the property).

Table 4.1: Categorisation of surveyed rooms based on construction typology and level of exposure to outdoor conditions

Variable	Description	Level	Descriptor
Room typology	Thermal mass of the room according to the predominant materials	1. Light	Light roof (i.e. zinc, asbestos)
		2. Medium	Roof with thermal mass (i.e. cast concrete)
Room condition	Exposure of the room's roof/ceiling to the outdoor conditions	1. Exposed 2. Non-exposed	

In terms of thermal mass, the rooms were classified based only on the ceiling and roof materials because 97% of rooms walls material is hollow concrete blocks, as presented in Table 4.8. The second variable, the level of exposure, accounts for whether the room's roof is directly exposed to the outdoors. In other words, consider whether the rooms were either the ground floor, a room located in between two stories or the top roof. This variable was investigated based on previous studies highlighting a significant impact of the outdoor environment in the indoor environment for spaces with direct roof's exposure. The effect is evident both during the day and night due to solar radiation and air temperature (Mino-Rodriguez et al., 2016; Ordóñez et al., 2019).

4.3 Weather conditions in the study locations

Understanding the differences in weather conditions might provide an insight into one of the main factors affecting thermal comfort and thermal performance assessment. A comprehensive summary of each location's outdoor environmental variables' annual descriptive statistics is presented in Table 4.2. As previously explained in the literature (Section 2.2.1), dry-bulb temperature, atmospheric pressure and humidity should decrease with the corresponding increase in altitude above sea level. In contrast, higher levels of precipitation and incident solar radiation are expected at higher locations. As seen in Table 4.2, the outdoor environmental variables in locations A and C follow the expected pattern. However, the annual solar radiation in Location B is the highest between the three locations, which reflects the prevailing arid climate in that area of the city. Location C's unusual behaviour could be attributed to the differences in sky conditions and prevailing wind directions that shift pollution from Quito towards the South-East; however, it is not possible to corroborate with the available data.

Table 4.2: Annual descriptive statistics of weather parameters by location (Secretary of Environment of the Municipality of Quito, 2019)

Location	Weather variable	unit	mean	*sd*	max	min
A	dry-bulb temperature	°C	16.4	3.8	27.2	7.5
	Humidity	kg/kg	0.01	0.00	0.02	0.00
	Relative humidity	%	71.8	20.2	99.6	13.4
	Wind speed	m/s	1.27	1.09	6.45	0.01
	Atmospheric pressure	*kPa*	77.3	0.1	77.5	77.2
	Precipitation	*mm*	0.13	0.97	30.60	0.00
	Global horizontal radiation	W/m^2	213	304	1191	0.0
	Altitude[1]	*m*	2330			
B	dry-bulb temperature	°C	14.8	3.2	23.8	8.9
	Humidity	kg/kg	0.01	0.00	0.01	0.00
	Relative humidity	%	73.3	19.2	99.5	14.8
	Wind speed	m/s	1.65	1.25	8.52	0.01
	Atmospheric pressure	*kPa*	74.4	0.0	74.5	74.3
	Precipitation	*mm*	0.1	0.7	18.3	0.0
	Global horizontal radiation	W/m^2	219	308	1183	0.0
	Altitude[1]	*m*	2660			
C	dry-bulb temperature	°C	12.2	2.9	21.4	6.2
	Humidity	kg/kg	0.01	0.00	0.01	0.00
	Relative humidity	%	73.2	17.3	99.9	19.3
	Wind speed	m/s	1.64	1.06	6.44	0.02
	Atmospheric pressure	*kPa*	70.7	0.0	70.8	70.6
	Precipitation	*mm*	0.21	1.19	43.20	0.00
	Global horizontal radiation	W/m^2	191	279	1107	0.0
	Altitude[1]	*m*	3070			

[1] Altitude of the meteorological weather station

Although the data was collected between September 2017 and January 2018, annual data was described to provide a general overview of the environmental conditions. The monthly comparison and the annual average value of the daily maximum, mean and minimum values of the dry-bulb temperature and other main weather parameters are plotted in Figure 4.2 and Figure 4.3, correspondingly. A small variation of the monthly mean outdoor temperature (boxplots) and the high oscillation (dash-dotted lines) between locations can be seen in Figure 1.2. The narrowing section ('notch') of the boxplots around the median offers an estimation of the medians' difference. As one can notice, the boxes' notches overlap across monthly values and the locations. Thus, there is a difference between the temperature median across locations and, in some cases, between the monthly means. The higher the altitude, the lower the mean temperature and the narrower the daily oscillation. The daily mean dry-bulb temperature drops from 16.4 °C (±3.8 °C) in Location A, to 14.8 °C (±3.2 °C) in Location B and 12.2 °C (±2.9 °C) in Location C. Besides, the daily oscillation decreased from 10.8 °C in Location A, to 8.7 °C in Location B and 7.9 °C in Location C.

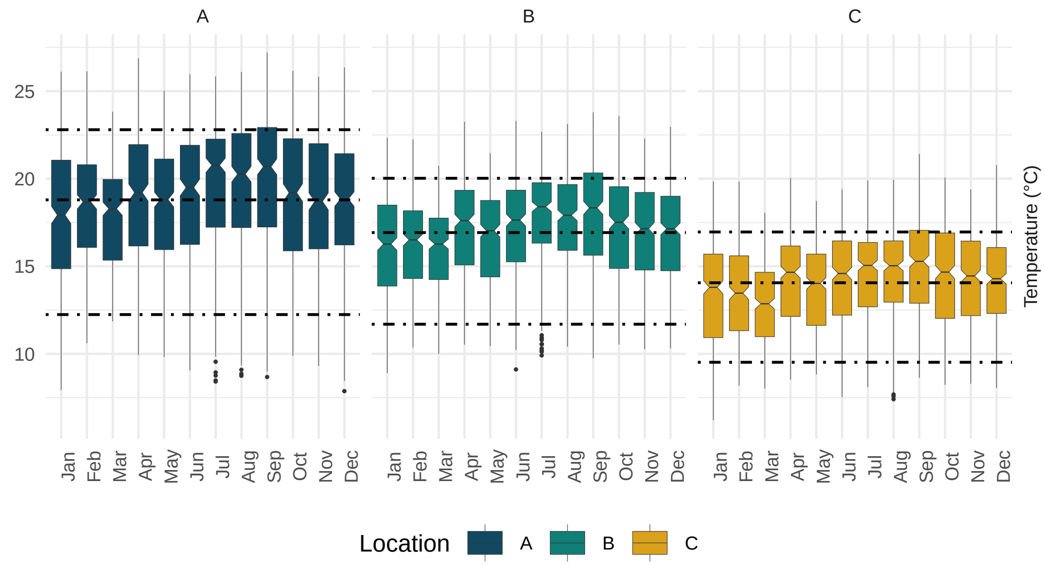


Figure 4.2: Monthly temperature (boxplots) and the maximum, mean and minimum annual daily average variation (dash-dot lines)

The weather conditions differences are evident in the outdoor temperature and humidity levels, solar radiation, and wind speed. Figure 4.3 reports the monthly (boxplots) and the maximum, mean and minimum annual average daily variation (dash-dot lines) for the other weather variables by location. There is a significant variation observed on humidity levels; the monthly variation denotes higher humidity between March and May and lower humidity levels from July to September. The latter corresponds to the warmer season, which also has higher global horizontal radiation levels and higher wind speed.

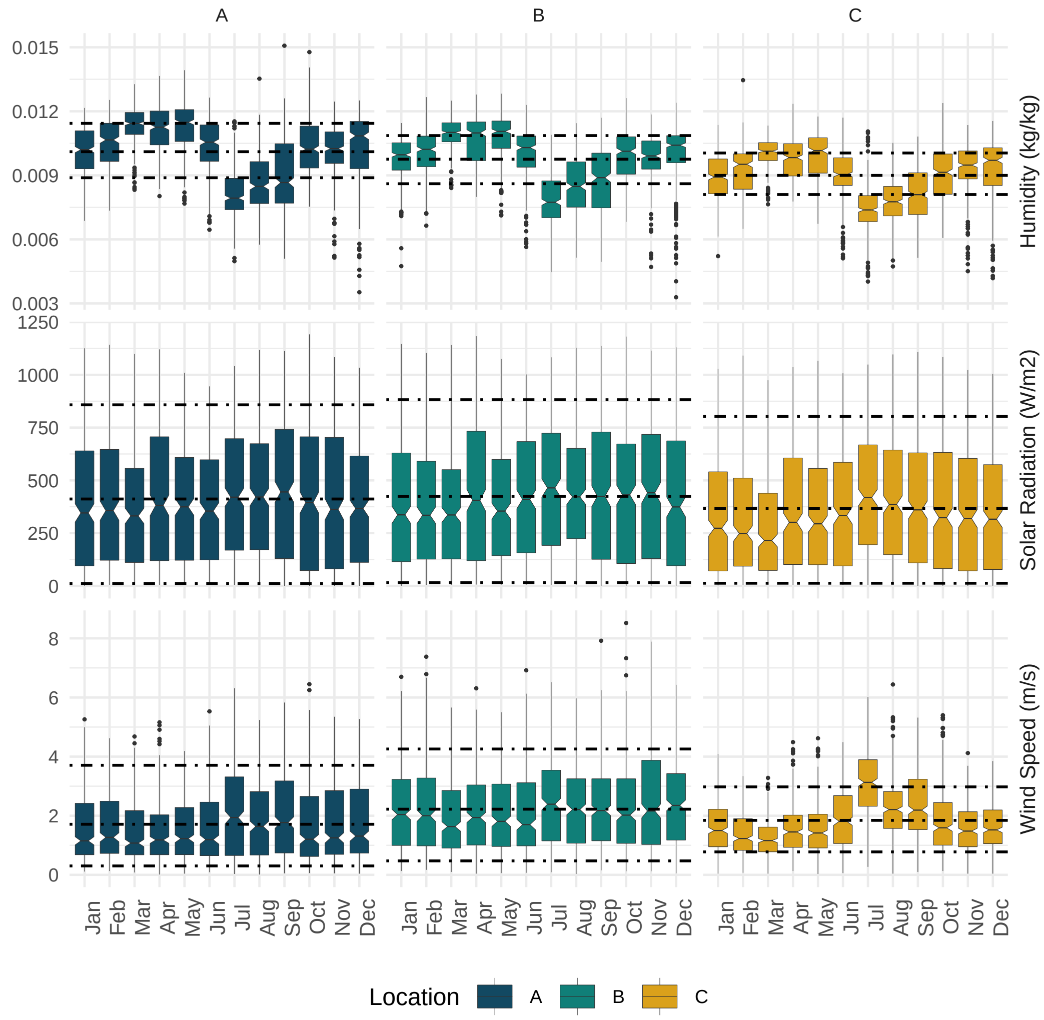


Figure 4.3: Monthly (boxplot) and the maximum, mean and minimum annual daily average variation (dash-dot lines) of weather variables by location

The difference across locations could be better appreciated in the cumulative distribution functions in Figure 4.4. A $k-s$ test was used to identify the differences in the distributions' dispersion and shape of the weather variables. Except for precipitation and global horizontal solar radiation between locations A and B; hence the mean, shape and distribution of humidity, atmospheric pressure, and wind speed vary across the three locations. For further analysis, the unusual pattern observed in the precipitation and global horizontal radiation in Location B should be considered. Temperature and wind speed directly affects the occupants' subjective response to the environment. Nevertheless, it is not clear to which extent the observed differences in humidity and atmospheric pressure could affect subjects' thermal comfort and dwellings' thermal performance.

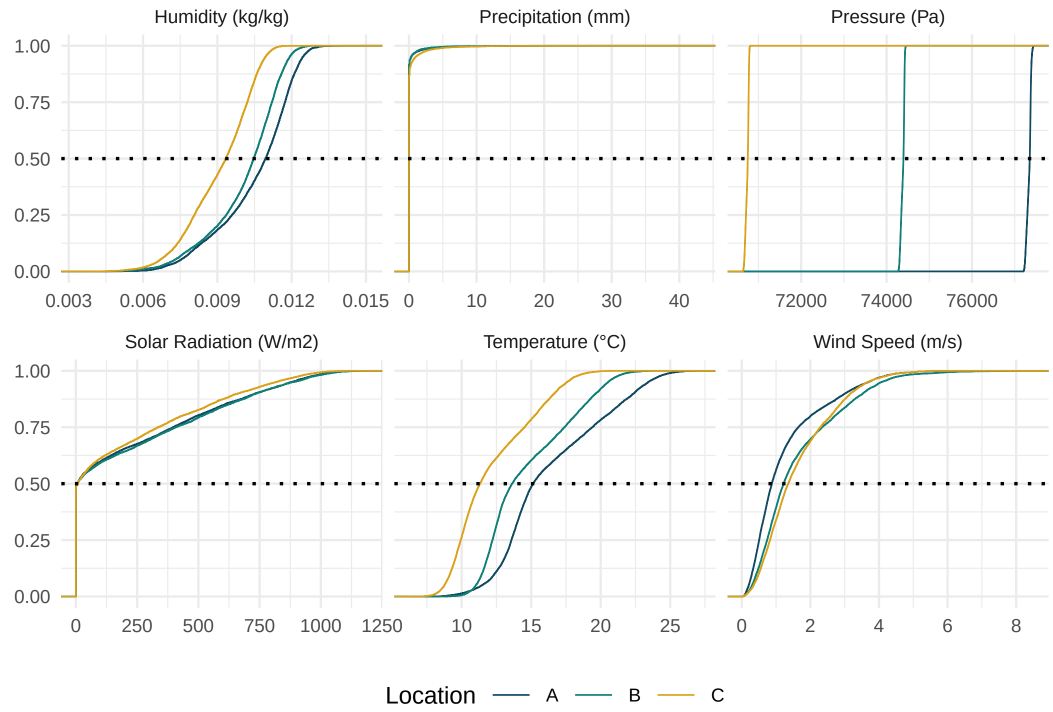


Figure 4.4: Cumulative distribution of outdoor environmental variables

4.4 Indoor environment in the surveyed dwellings

The central tendency and dispersion of the indoor environmental variables of the 287 surveyed dwellings are summarised in Table 4.3. The described indoor environmental variables are air temperature (t_{in}), globe temperature (t_g), relative humidity (RH), airspeed (v_a), CO_2 concentration levels, atmospheric pressure (P_a) and altitude above sea level. The analysed data correspond to spot measurements during the thermal comfort survey at 'time-t'; hence, the data correspond to the specific circumstances only (Guerra-Santin and Tweed, 2015b).

The indoor temperature follows a similar oscillation pattern as observed in the outdoor temperature, a higher oscillation in Location A (11.4 °C) and the narrower oscillation in Location C (8.1 °C). The temperature distribution (Figure 4.5) in Location C is concentrated at 20.0 °C, in Location B at 22.0 °C, and in Location A at 24.0 °C. It is necessary to emphasise that the minimum temperature at which subjects are exposed are not registered in the data set as the thermal surveys were collected during the daytime only. Besides, when comparing the medians across locations, the mean indoor temperature of the surveyed dwellings is significantly different across locations A, B and C (Figure 4.5). t_g is highly correlated with t_{in}, highlighting that if the measurements are truly representative of the participants' location, there is no immediate direct radiation source

Table 4.3: Descriptive statistics of indoor environmental conditions in the surveyed rooms at 'time-t' by location

Location	Variable	Unit	mean	*sd*	max	min
A	Air temperature	°C	23.9	2.1	28.6	17.2
	Globe temperature	°C	23.9	2.1	29.3	17.4
	Relative humidity	%	44.8	8.6	64.0	27.5
	Humidity	kg/kg	0.011	0.002	0.015	0.007
	Air speed	m/s	0.287	0.075	0.650	0.100
	CO_2	ppm	629	211	1683	379
	Altitude	m	2353	26	2462	2324
B	Air temperature	°C	22.1	1.8	27.6	18.6
	Globe temperature	°C	22.1	1.8	28.0	18.2
	Relative humidity	%	46.7	7.0	61.5	29.5
	Humidity	kg/kg	0.011	0.001	0.014	0.007
	Air speed	m/s	0.312	0.059	0.450	0.100
	CO_2	ppm	643	190	1340	420
	Altitude	m	2672	50	2784	2609
C	Air temperature	°C	19.6	1.6	24.2	16.1
	Globe temperature	°C	19.7	1.6	24.8	16.1
	Relative humidity	%	53.3	8.7	73.5	35.0
	Humidity	kg/kg	0.011	0.001	0.015	0.008
	Air speed	m/s	0.311	0.084	0.600	0.100
	CO_2	ppm	730	345	2023	394
	Altitude	m	3073	21	3126	3020

affecting the participants (r^2=0.96, df = 285, $p< 0.001$). Besides, the mean altitude of surveyed dwellings is 2353m (±26m) in Location A, 2672m (±50m) in Location B and 3073m (±21m) in Location C.

The indoor environmental variables differ across the three locations, not only the mean values but also the distribution. Based on Figure 4.6, a clear difference in the medians is only observed for t_{in}. The indoor airspeed is similar for the three locations. A higher rate of CO_2 concentration is observed in Location C than locations A and B. Unfortunately, outdoor values of CO_2 are not available to check if the higher concentration is due to the pollutant concentration in the outdoor environment or a proxy of reduced ventilation. Regarding humidity, the mean values are similar across locations; still, a slightly narrow distribution is observed in Location C. The cumulative distribution (Figure 4.6) and the k-s test results confirm a significant difference in the distributions' dispersion and shape for air temperature across the three locations.

Therefore, one can conclude that the difference in indoor air temperature between the three locations is significantly different in their means, shape and distribution. The mean indoor airspeed differs significantly across the locations, while the humidity ratio difference is not significant. The

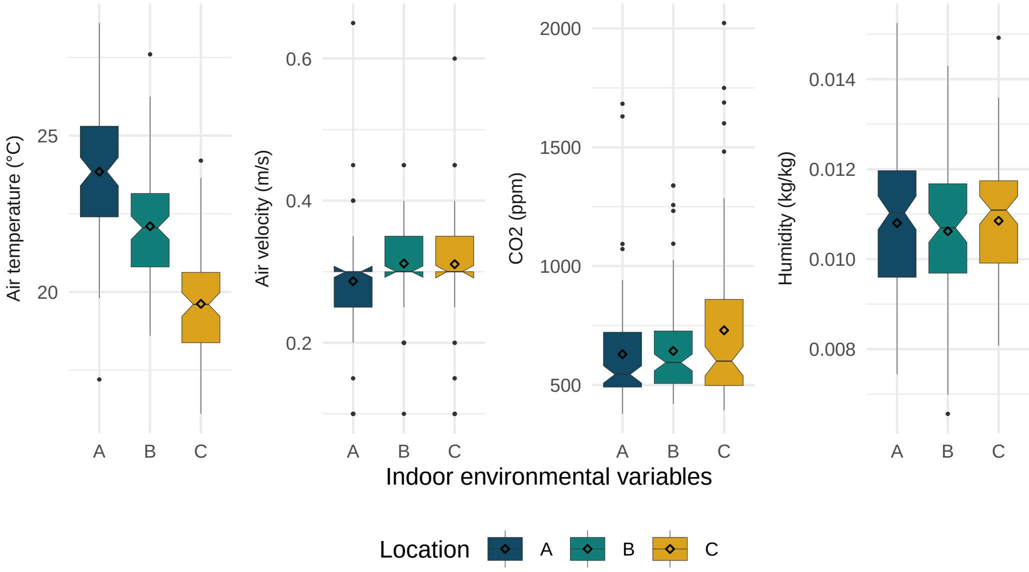


Figure 4.5: Variation of indoor variables at survey at 'time-t' by location

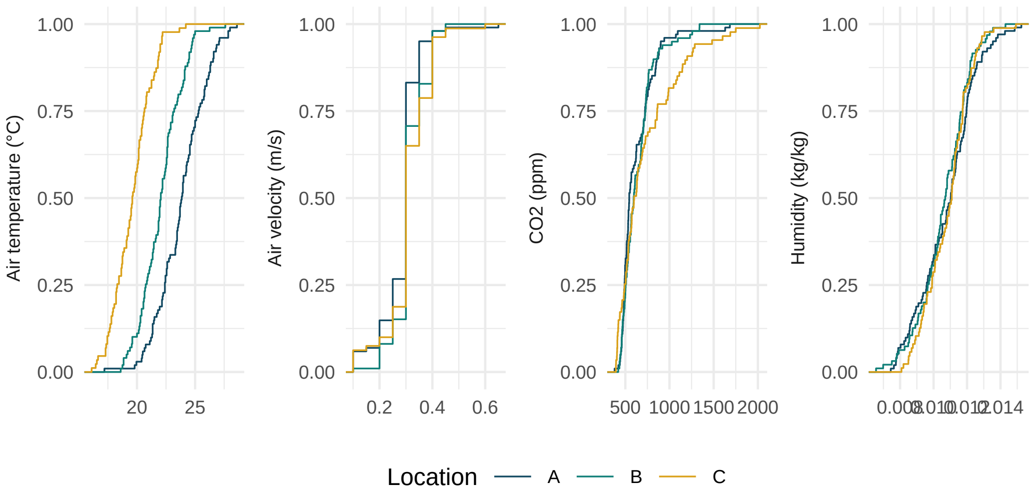


Figure 4.6: Cumulative distribution of indoor environmental variables by location

higher levels of CO_2 in Location C suggest reduced ventilation in those dwellings. That coincides with the lower rate of windows and doors opening reported by residents at Location C than the reported at locations A and B (Figure 5.15).

4.5 Effect of the outdoor conditions in the indoor environment

The indoor environmental variables at survey 'time-t' were regressed against the corresponding outdoor environmental variable at the survey 'time-t'. A summary of the regression coefficients are described in Table 4.4. Based on the coefficient of determination (r^2) and the significance (sig), there is no apparent effect of the outdoor wind speed on the indoor airspeed. Regarding humidity and air temperature, a low and moderate percentage of the indoor humidity variance could be explained by the outdoor humidity in locations A and B, same as for temperature in Location A. The upward slope of the regression line (*b*) of temperature and humidity, between 0.47 and 0.62, follow a similar progression at the three locations. In Location C, both variables' regression coefficient (humidity and temperature) are lower than those at locations A and B. The lower correlation in this location could partially be explained by the number of permanent modifications performed in these dwellings in order to reduce infiltration and increase heat gain (Figure 5.14), as well as higher use of other heating sources such as fire, turning on stoves and ovens (5.15).

Table 4.4: Summary of the regression analysis of indoor and outdoor environmental conditions at survey 'time-t'

Variable	Location	n	a	b	r.squared	df	statistic	p.value	sig
Air speed	A	101	0.26	0.01	0.05	(1,99)	5.60	0.020	*
	B	99	0.30	0.00	0.01	(1,97)	1.24	0.268	
	C	87	0.31	0.00	0.00	(1,78)	0.01	0.905	
Humidity	A	101	0.00	0.62	0.33	(1,99)	49.00	0.000	***
	B	99	0.01	0.47	0.32	(1,93)	43.80	0.000	***
	C	87	0.01	0.47	0.17	(1,85)	16.90	0.000	***
Temperature	A	101	14.20	0.46	0.28	(1,99)	39.30	0.000	***
	B	99	16.60	0.28	0.11	(1,97)	11.70	0.001	***
	C	87	14.70	0.30	0.12	(1,85)	11.10	0.001	**

Notes:
Significance *, **, *** at 90%, 95%, and 99% respectively

Based on the observed lag effect of the outdoor temperature on the indoor air temperature. The air temperature at survey 'time-t' t_{in} was also regressed against the t_{out-ma} (Figure 4.7) that corresponds to the moving average of the previous three hours. The three-hour interval was choose based on the observed time lag from the archetypes monitored data (Chapter 7) and further explored in 4.8. The displacement of the lines in the y-axis denotes the higher indoor temperatures at Location A, followed by Location B and finally, Location C's lower temperatures. The outdoor temperature has a higher effect on the indoor temperature in Location B (*b*=0.69). Whereas, the scattered temperatures in locations A and B could partly explain the lower correlation. Besides, the concentration of temperatures in the lower ranges might explain the low correlation at Location C. A piecewise regression was explored for a range of different breakdown points to check whether some segments would better explain any trend change of t_{in} in relation to $t_{out.ma}$. Nevertheless, neither the r-squared nor the residual standard error improve when segmenting the regression.

To summarise, the simultaneous outdoor environmental parameters could partially explain

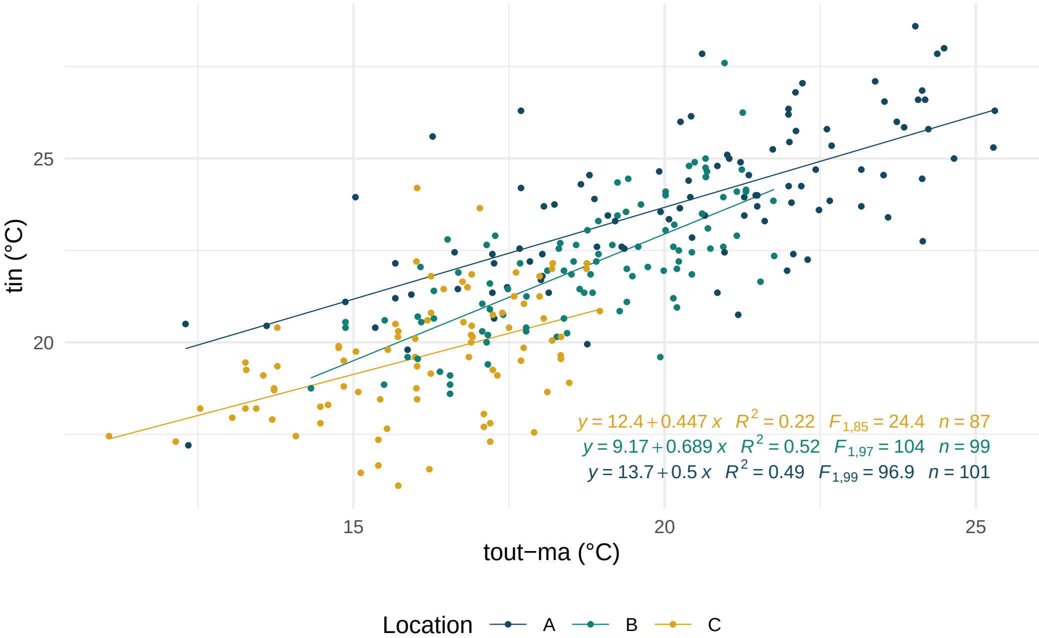


Figure 4.7: Regression of indoor air temperature at survey 'time-t' (t_{in}) and the moving average dry bulb temperature (t_{out-ma})

the variation of air temperature and humidity. Although the distance between the weather station and the surveyed dwellings is less than 5km, the wind speed and direction vary from the weather station's data due to the local urban context.

4.6 Subjective assessment of the indoor environment

Subjective votes from thermal comfort surveys are a direct method for evaluating thermal comfort under operating conditions and, thus, a mean for assessing the thermal environment's acceptability. Subjective votes regarding sensation, preference and acceptability of the main indoor thermal environmental variables were collected using different scales described in Section 3.4.3.2. The ASHRAE seven-point scale, from -3 (Cold) to 3 (Hot) with a neutral vote' 0', was used to collect thermal sensation votes (TSV). In the same way, thermal preference votes (TPV) used a seven-point scale from -3 ('much cooler') to 3 ('much warmer') and a middle point for no change. The distribution of sensation and preferences votes per point in the scale for each environmental variable are summarised in Figure 4.8 for temperature, Figure 4.9 for humidity and Figure 4.10 for air movement. The figures not only show the higher percentage of people voting for the central or no change categories but highlight the subjective differences between the studied locations. The distribution of TSV and TPV in the seven-point scale are shown in Figure 4.8. Votes for the combined dataset (all) are also included to have a reference of the overall voting pattern. Participants' seldomly voted for the extreme values of the scale (-3 and +3) when expressing their thermal sensation and preference vote.

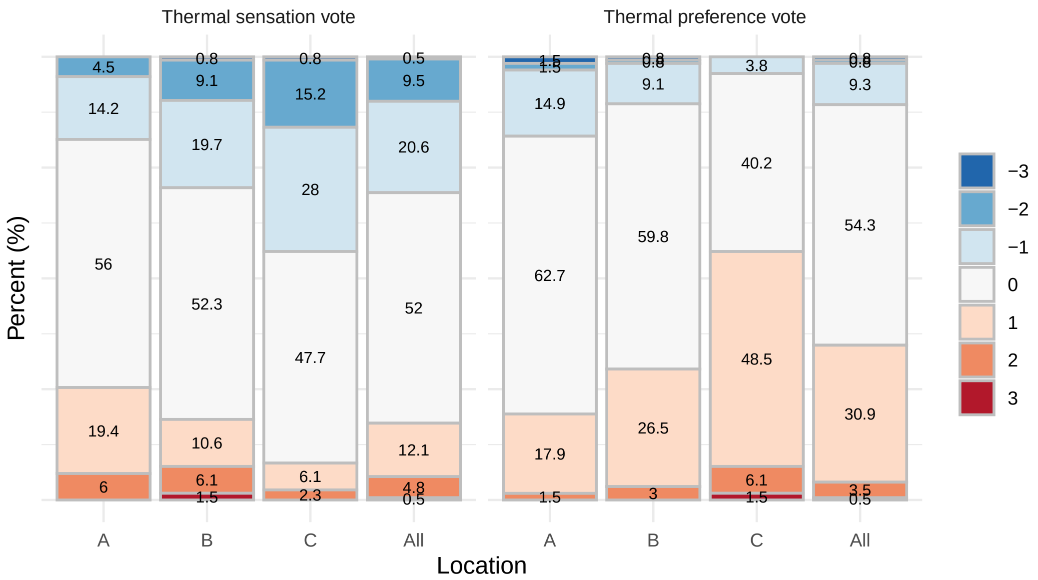


Figure 4.8: Distribution (percentage) of thermal sensation votes (TSV) and thermal preference votes (TPV) by location

The number of observed comfort votes (+1 to -1) decreased from Location A to Location C. Preference votes followed the opposite trend where the higher the location, the higher the number of participants that prefer warmer environments. In Location A, 89% of the respondents voted within the comfort range, and 63% voted for no change in the indoor temperature. A split trend is observed for a preference of either 'slightly cooler' (15%) or warmer environments (18%). As discussed in the literature, high-altitude residents show an increased threshold for cold sensation. In this research, 82% of the residents living above 3000m perceived the indoor temperature as comfortable. However, 56% of the respondents at this location would prefer warmer environments. Strong evidence supports the significant difference observed across the mean ranks of at least one pair of TSV and TPV groups ($p<0.05$, Table E.1). The mean TSV in Location C, towards 'slightly cool', is significantly different from the sensation mean vote in locations A and B (Table 4.5). The distribution of subjective votes is consistent with the measurements of the indoor environment. Considering the four-degree difference of the mean indoor temperature between Location A and Location C, a noteworthy difference in voting was expected from residents at those locations. As altitude increases, there is a small decrease in neutral votes, an increase in feeling cold, and a bigger shift from being cool to being warm. The equivalent pattern is also shown in the preference votes, except that the decrease in the proportion wanting no change is bigger than the decrease in voting neutral.

Table 4.5: Mean (Standard deviation) environmental votes by location

Variable	Vote type	A	B	C
Temperature	Sensation	0.08 (± 0.87)	-0.13 (± 1.05)	-0.50 (± 0.93)
	Preference	-0.01 (± 0.76)	0.20 (± 0.73)	0.61 (± 0.73)
Humidity	Sensation	-0.01 (± 0.97)	0.10 (± 0.74)	0.30 (± 0.89)
	Preference	-0.27 (± 0.80)	-0.34 (± 0.78)	-0.69 ± 0.85)
Air movement	Sensation	0.80 (± 0.96)	0.83 (± 0.98)	0.96 (± 0.95)
	Preference	0.55 (± 0.90)	0.55 (± 1.00)	-0.07 (± 0.93)
Overall	Acceptance	-0.23 (± 0.42)	-0.26 (± 0.44)	-0.43 (± 0.50)

Significance *, **, *** at 90%, 95%, and 99% respectively

Figure 4.9 shows the percentage distribution of humidity sensation (HSV) and preference votes (HPV). Humidity sensation and perception also used a seven-point scale where the extreme humidity is represented by +3 and extreme dry by -3. Overall, 62.8% of the participants vote neutral in terms of humidity, and 59.5% would prefer no change in the indoor relative humidity. These votes are consistent with the indoor environment measurement that shows a mean indoor relative humidity between 45% (Location A) and 53% (Location C), as seen in Table 4.3. Location B reported a higher percentage of mid-range votes (93.2%) and equally the highest rate (66.7%) for no change votes in terms of preference. Overall, around 87.4% of the respondents voted within the mid-range for humidity sensation (- 1 to 1). As observed in Table 4.5, the mean sensation vote is similar across the three locations ($p<0.05$, Table E.1). In contrast, preference votes show an increasing preference for drier environments across the three locations. In Location C, the mean HPV towards 'slightly drier' is significantly different to the one observed at the other two locations ($p<0.05$, Table E.1). Over 50% of the respondents at Location C would prefer a drier environment.

It is worth mentioning that a five-point scale from 'no movement' (0) to 'too breezy' (+4) was used to assess air movement. No votes were resister for the highest point in the scale. Meanwhile, the collected preference votes used seven-point scales as the previous variables, from much more air movement (+3) to much less (-3). In Figure 4.10, 53.3% of the participants reported feeling no air movement during the survey, 'just right' was the second most recorded response (36.9%)

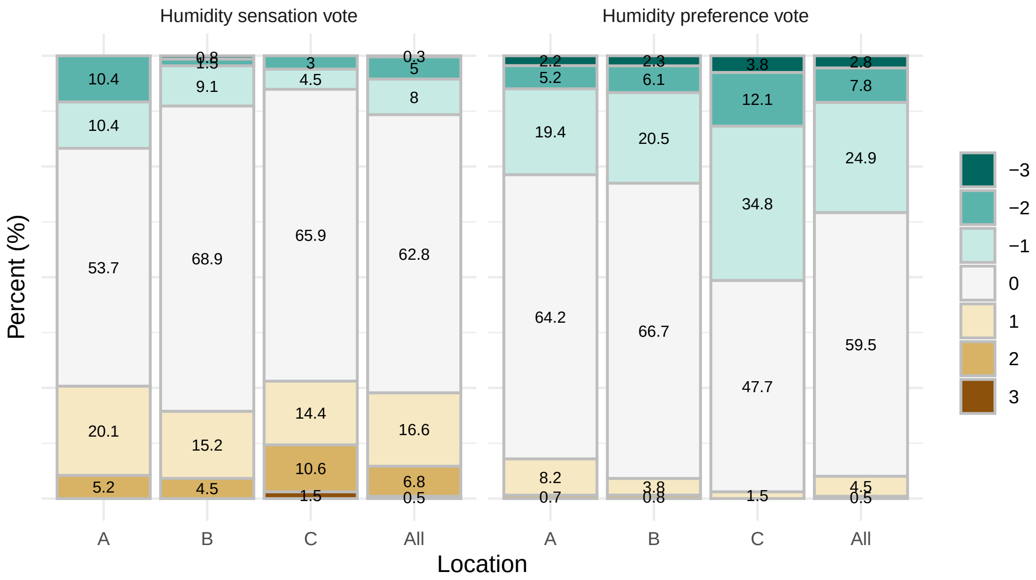


Figure 4.9: Distribution (percentage) of humidity sensation votes (HSV) and humidity preference votes (HPV) by location

of the overall votes. Considering that the mean air movement for all the locations is similar at the time of the interview (0.3m/s - $\pm$ 0.1) (Table 4.3), only participants in the higher location (Location C) would prefer lower air movement. As reported by Wang et al. (2010), in low-pressure environments, people become more sensitive to draught and prefer reduced air movement. This subjective response may be affected by the increased convective heat loss of the human body as a response to lower atmospheric pressure (ASHRAE, 2009; Ohno et al., 1991). No significant difference was observed in air movement sensation votes between locations A, B and C (Table E.1). Furthermore, the second most voted option in locations A and B showed a clear preference for 'bit more air movement'. On the contrary, Location C's second most voted option was for 'bit less air movement'. A significant different vote for no change is observed in Location C compared to the other locations (Table E.1).

Overall, the observed voting pattern for all the environmental variables is similar across the three locations. The central tendency votes for locations A and B are similar for both sensation and perception votes for temperature and humidity; sensation votes incline towards neutrality, and the preference votes centred on' no change'. In terms of air movement, participants perceived the air inside as still and showed a clear preference for a 'bit more air movement'. In Location C, the mean sensation and preference votes are significantly different from those in locations A and B. While Location C is the most different, the trend from Location A to Location C is similar.

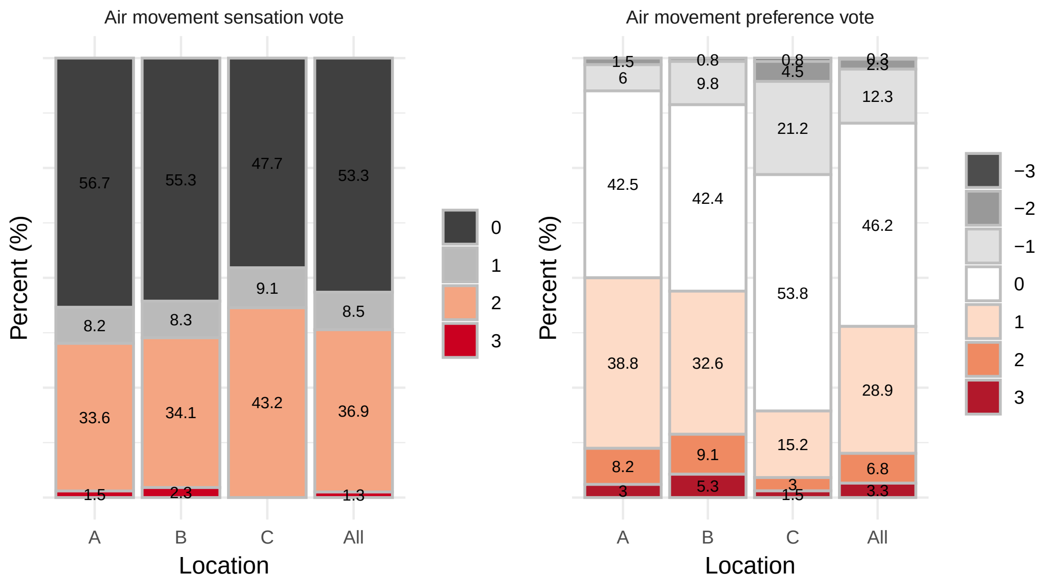


Figure 4.10: Distribution (percentage) of air movement sensation votes (ASV) and air movement preference votes (APV) by location

A significant negative correlation (p<0.05) between perception and preference votes was observed for temperature and humidity votes for all locations (Table 4.6). The correlation for air movement is significant for locations A and B. The negative correlation observed suggest that residents usually prefer an opposite environmental condition than the current one. When participants vote for high air movement sensation, the preference turns towards reducing air movement and so for temperature and humidity. A higher correlation on air movement was observed in Location C (r=-0.28); as observed previously, participants in the higher location tend to prefer less air movement. A moderate correlation was observed in terms of humidity. This variable should be examined cautiously, as most participants commented on humidity related to mould rather than the environmental one. A strong negative correlation was observed across the three locations for thermal sensation and thermal preference votes.

4.7 Relating the subjective votes and the indoor environmental variables

The figures in this section allow observing the count of sensation votes at binned time intervals of the corresponding indoor environmental variables. The operative temperature at survey 'time-t' was binned into half-degree increments (t_{o-bin}), humidity ratio 'time-t' was binned into 0.001 kg/kg increments (h_{bin}) and air movement at survey 'time-t' into 0.05 m/s increments (air_{bin}). The

Table 4.6: Summary of correlation analysis between environmental sensation and preference vote

Location	Variable	n	r	statistic	conf.low	conf.high	p.value	sig
A	Air Movement	132	-0.20	-2.35	-0.358	-0.032	0.020	*
	Humidity	132	-0.46	-5.87	-0.580	-0.309	0.000	***
	Temperature	132	-0.59	-8.32	-0.688	-0.463	0.000	***
B	Air Movement	130	-0.05	-0.607	-0.222	0.119	0.545	
	Humidity	130	-0.22	-2.56	-0.376	-0.050	0.012	*
	Temperature	130	-0.54	-7.3	-0.650	-0.406	0.000	***
C	Air Movement	130	-0.28	-3.29	-0.428	-0.111	0.001	**
	Humidity	130	-0.33	-3.92	-0.470	-0.163	0.000	***
	Temperature	130	-0.42	-5.33	-0.554	-0.273	0.000	***

Significance *, **, *** at 90%, 95%, and 99% respectively

figures aim to highlight (the shaded grey area) differences in the distribution of sensation votes across the different point scale for the same range of the corresponding indoor environmental variable. The defined shaded grey area is no more than an environmental variable range where votes for the three locations were observed. For instance, t_{o-bin} between 20.0 °C and 21.0 °C is one of the few temperatures ranges transverse to the three locations.

Figure 4.11 shows the thermal sensation votes count per each t_{o-bin} increment. As highlighted in the shaded grey area, at the same t_{o-bin} range between 20.0 °C and 21.0 °C, the sensation votes differ by location. Respondents at Location A voted between 'slightly cool' (-1) and 'cool' (-2). Respondents at Location A voted between 'slightly cool' (-1) and 'cool' (-2). In contrast, participants at Location C reported a sensation ranging from 'cool' (-2) sensation up to 'slightly warm' (+1) sensation, with the highest sensation votes count for neutral sensation. At the same time, Location B residents voted something between 'neutral' ($\pm$ 0) and 'cool'(-2). Even though the indoor temperature's range is the same, the thermal sensation differs across the three locations. Considering that an indoor environment between 21.0 and 22.0 °C is perceived as 'slightly warm' (+1) only at the higher location (Location C), one can presume that at the same indoor temperature, residents at a higher altitude perceived the indoor environment as warmer than their counterparts at a lower location.

A similar approach was used to explore humidity ratio (Figure 4.12) and air movement votes (Figure 4.13) in relation to the corresponding environment variable. At a h_{bin} range between 0.010 and 0.011 kg/kg, the votes are distributed across five out of the seven-point scale from 'humid' (+2) to 'dry' (-2). In Location A, the votes' distribution is between 'humid' (+2) and 'dry' (-2). Votes are slightly displacement towards drier sensation in Location B where the reported votes

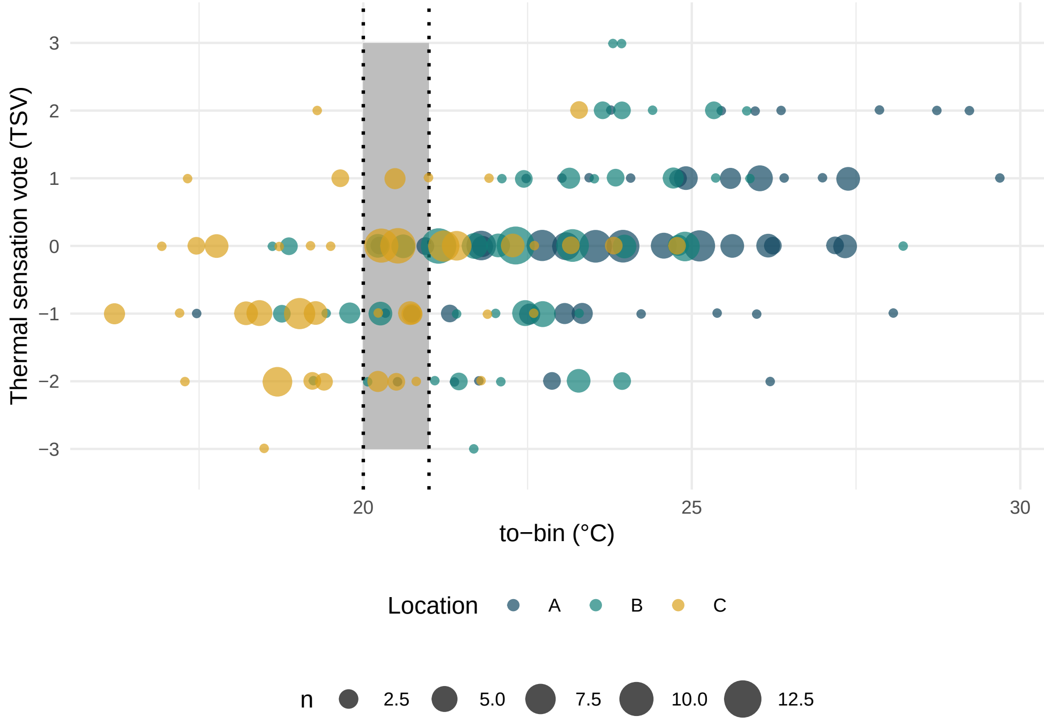


Figure 4.11: Count of thermal sensation votes at each increment of the binned operative temperature (t_{o-bin})

ranged between 'humid' (+2) and 'slightly dry' (-1). Lastly at Location C, most votes are between 'neutral' (± 0) and 'humid' (+2). Worth noting that the indoor environment variables are measured and evaluated independently; one should not discard a combined effect across them, affecting participants' subjective response.

In Figure 4.13 the highlighted air_{bin} range taking place at the three locations is $0.25m/s$ to $0.35m/s$. Most of the respondents at the lower location stated perceiving the air movement as 'just right' (+2). Meanwhile, the air movement votes at Location B and C are distributed across four-points of the scale from 'no movement' (0) to breezy (+3) and too breezy (+4). Based on the figure's data, there is no evident difference in the air movement's voting trend at the same airspeed range.

Finally, the correlation between perception votes with the corresponding environmental variable was explored and the main statistics are summarised in Table 4.7. The thermal sensation is the only subjective vote strongly correlated with indoor operative temperature at survey 'time-t'. In terms of airspeed, a moderately significant correlation between ASV and airspeed is observed in Location C. These results are aligned to the ones discussed by Wang et al. (2010), that reported

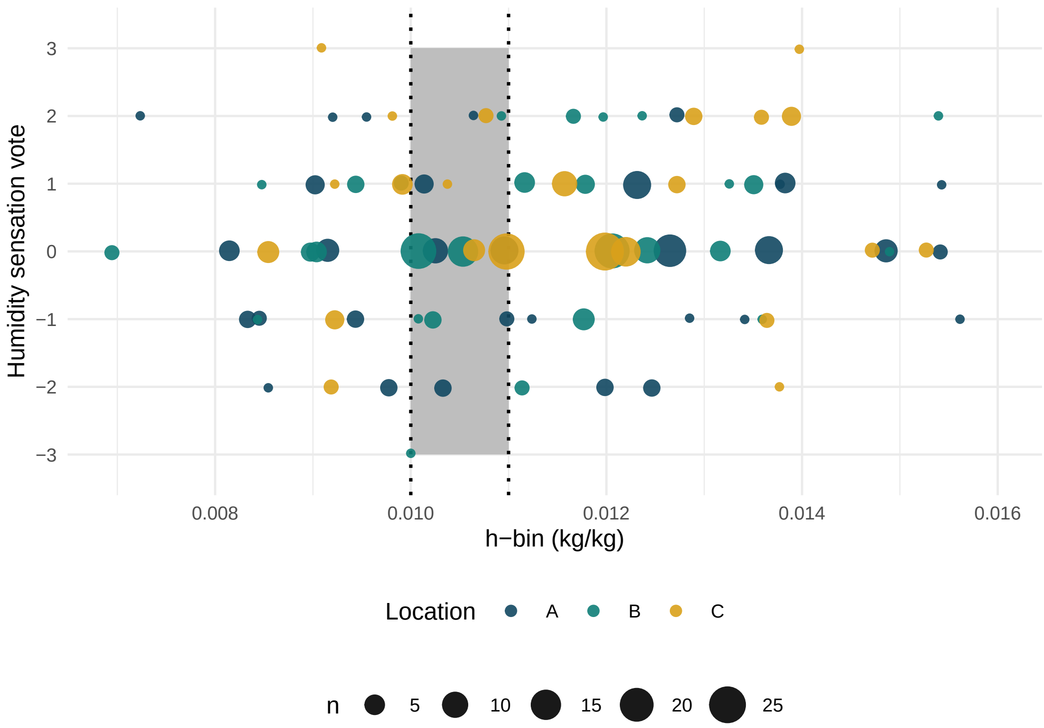


Figure 4.12: Count of humidity sensation votes at each increment of the binned indoor humidity ratio h_{bin}

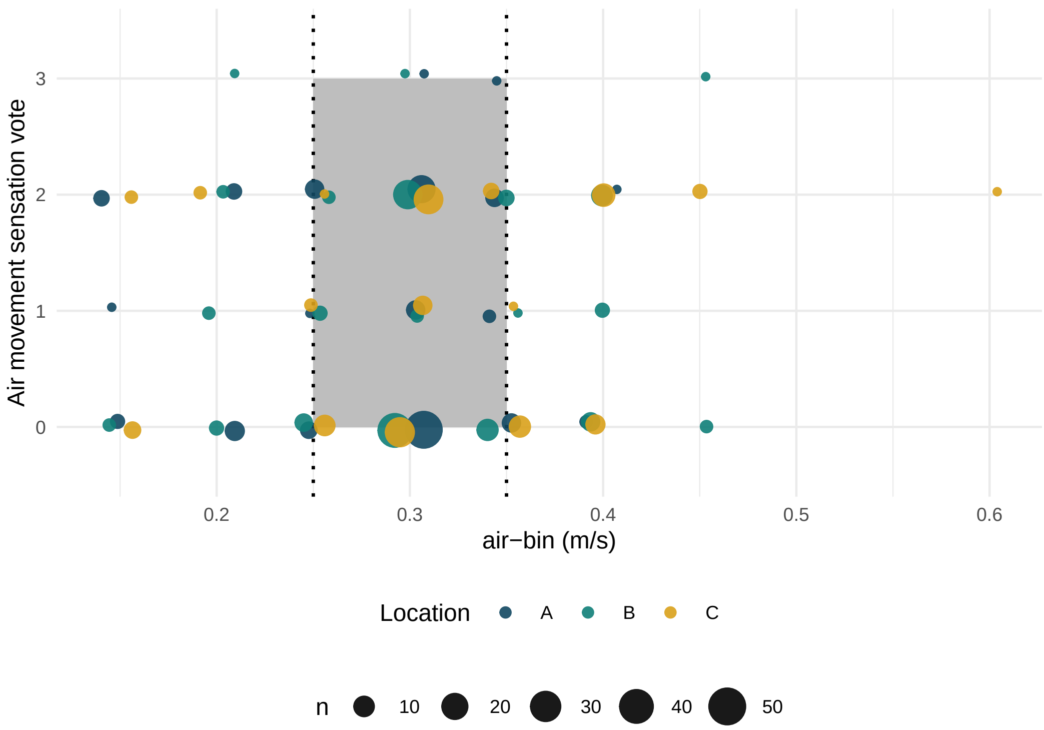


Figure 4.13: Count of air movement sensation votes at each increment of the binned indoor air speed (air_{bin})

participants being more sensitive to draught at 2300m. Finally, there is no significant correlation between HSV and humidity ratio for each location independently. Therefore, the participants' subjective votes in this research may be considered a response to the current environmental conditions only for temperature (all locations) and airspeed (Location C).

Table 4.7: Regression summary of perception votes and objective measurements at survey 'time-t'

Vote	Location	n	r.squared	df	statistic	p.value	Sig
ASV	A	132	0.00	(1,130)	0.30	0.583	
	B	128	0.01	(1,126)	1.09	0.298	
	C	123	0.05	(1,121)	5.81	0.017	*
	All	383	0.01	(1,381)	3.71	0.055	
HSV	A	132	0.05	(1,130)	7.32	0.008	**
	B	128	0.02	(1,126)	3.03	0.084	
	C	123	0.03	(1,121)	3.76	0.055	
	All	383	0.05	(1,381)	21.90	0.000	***
TSV	A	132	0.22	(1,130)	36.70	0.000	***
	B	128	0.11	(1,126)	15.00	0.000	***
	C	123	0.17	(1,121)	24.40	0.000	***
	All	383	0.19	(1,381)	91.80	0.000	***

Significance *, **, *** at 90%, 95%, and 99% respectively

4.8 Effect of surveyed dwellings physical conditions in the indoor environment

The thermal comfort survey took place in 287 surveyed rooms across the three studied locations. The predominant construction materials are hollow concrete blocks walls (97% of the sample) and cast concrete slabs roofs (73%), as seen in (Table 4.8). The second most common dwelling typology is hollow concrete blocks with a light roof (zinc/asbestos). It should be noted that the use of insulation materials and ceilings is not a common practice in the region, even when the roofs are zinc or asbestos. Finally, the traditional or vernacular dwellings build from clay tiles and adobe walls were scarcely found. Across the three locations, the few surveyed rooms in vernacular dwellings belong to Location A, the ones observed at locations B and C were currently unoccupied.

The distribution of surveyed rooms according to dwellings typology and room exposure condition are summarised in Table 4.9. Based on the proposed categorisation, over 70% of the surveyed rooms are medium thermal mass constructions and half of the rooms are non-exposed to the

Table 4.8: Surveyed dwellings by construction materials of roof, ceiling and walls

Location		**A**			**B**	**C**	**All locations**		
Construction materials									
Roof	**Ceiling / Wall**	**Adobe**	**Block[1]**	**Brick[2]**	**Block[1]**	**Block[1]**	**Adobe**	**Block[1]**	**Brick[2]**
Asbestos/zinc	No ceiling	-	15	-	9	9	-	33	-
Asbestos/zinc	Ceiling	1	16	2	14	3	1	33	2
Cast concrete	No ceiling	-	57	2	76	72	-	205	2
Clay tiles	Ceiling	3	2	3	-	3	3	5	3

Block[1] = Hollow concrete blocks
Brick[2] = Clay bricks

outdoor environment. In other words, most of the surveyed rooms were either in the ground floor or a room located in between two storeys.

Table 4.9: Typology and exposure condition of surveyed rooms by location

Room typology	**Room exposure condition**	**A**	**B**	**C**	**All locations**
Light	Exposed	36	16	14	66
	Non-exposed	2	7	1	10
Medium	Exposed	33	15	33	81
	Non-exposed	30	61	39	130

As discussed previously, the indoor temperature at survey 'time-t' (t_{in}) has the highest correlation with the outdoor temperature (t_{out-ma}) among the studied environmental parameters. The regression analyses of temperature were further evaluated by construction typology (Figure 4.14) and exposure level (Figure 4.15) of the surveyed dwellings. In Figure 4.14, the higher regression coefficient of light mass construction materials (b = 0.74) showed a considerable effect of the t_{out-ma} on the t_{in}. Besides, the regression line's shift shows a higher t_{in} in light dwellings compared to the medium thermal mass rooms. The mean t_{in} for medium thermal rooms is 21.4 °C ($\pm$ 2.2), and the one for lightweight rooms is 23.4 °C ($\pm$ 2.6); the means difference between these two groups is significant (p <.000, Table E.1). The higher relation or t_{in} on t_{out-ma} in addition to the known higher solar radiation suggest that these typology of dwellings is prone to extreme indoor conditions like overcooling and overheating. Besides, the mean t_{in} is also significantly different (p <.000, Table E.1) between the exposed (22.6 °C, $\pm$ 2.8) and non-exposed rooms (21.3 °C, $\pm$ 1.8). However, there was no difference observed in the t_{in} when evaluating the combined effect of exposed and non-exposed for light or medium thermal mass constructions.

Figure 4.15 plot the regression between t_{in} and the t_{out-ma} according to the exposure level. The higher correlation and regression slope in the exposed rooms indicate a higher rate of change

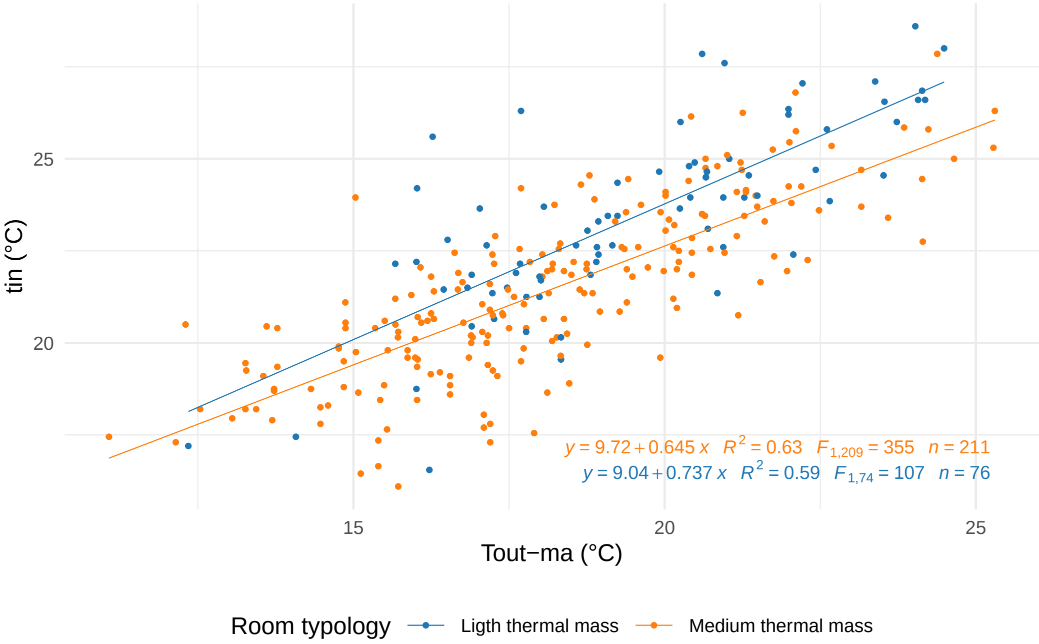


Figure 4.14: Regression of the indoor air temperature at survey 'time-t' (t_{in}) in the moving average dry bulb temperature (t_{out-ma}) by rooms' exposure

in the indoor environment due to changes in the outdoor conditions (solar radiation and dry-bulb temperature). Thus, some of the dwellings are running warmer than others at the same prevailing outdoor conditions and the t_{in} increases at a higher rate with outdoor temperature. This is relevant because any difference in mean thermal sensation votes between typologies or exposure levels could result from residents being adapted to this increased t_{in}.

4.9 Summary of the chapter

This chapter centred on identifying some of the numerous contextual factors influencing high-altitude residents' thermal comfort. For this purpose, weather data, indoor environment and dwellings physical conditions were explored and analysed based on the difference in altitude intrinsic at each location. Evidence from this section confirms the effect of high-altitude weather in the indoor environment of dwellings and differences in the subjective assessment of the environment.

A significant difference is observed in the main weather parameters: humidity, atmospheric pressure, temperature, and wind speed. Besides the expected variation due to altitude change, other parameters might also affect weather behaviour as in the case of Location B. The significant difference observed in the dry-bulb temperature relates to a decrease in temperature as altitude increases

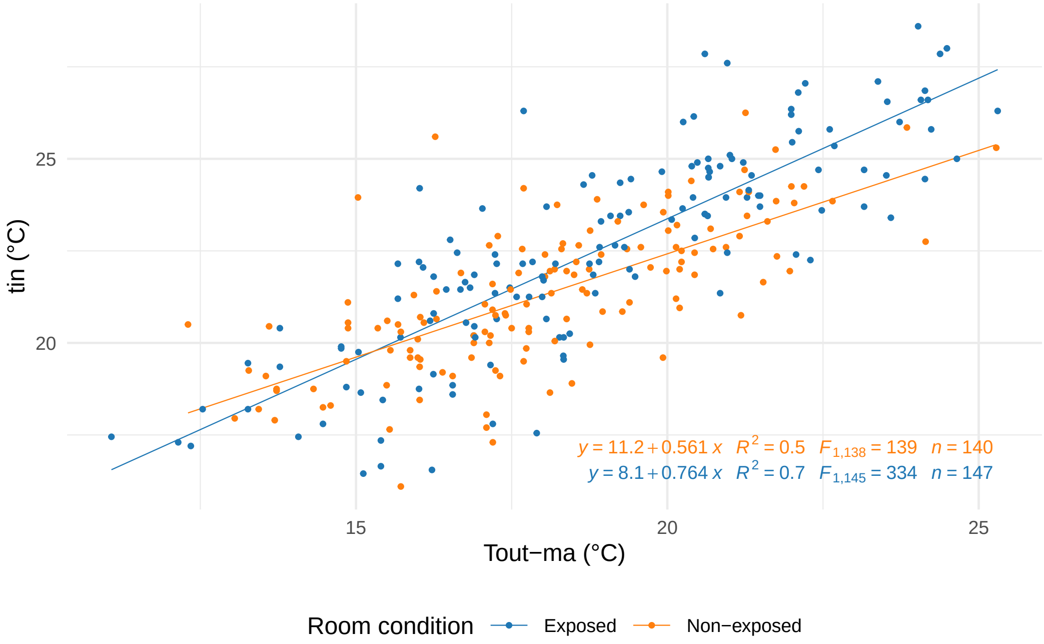


Figure 4.15: Regression of the indoor air temperature at survey 'time-t' (t_{in}) in the moving average dry bulb temperature (t_{out-ma}) by rooms' exposure

and a narrow oscillation at higher locations (Location C), contrary to Location A. Weather difference affects not only the dwellings thermal performance but also the subject's thermal perception. For instance, indoor air temperature is significantly different between the studied locations, same as the thermal sensation and preferences.

Among the indoor environmental variables, the one that presents a significant difference across locations in terms of means, shape and distribution is the air temperature. The observed difference in airspeed is related to the mean value. In contrast, no significant difference is observed in the humidity ratio. Therefore, for further analyses, the air temperature will be considered for assessing the differences between locations. Regarding humidity and air temperature, a low and moderate percentage of the indoor environment variance could be explained by the outdoor conditions in locations A and B. In contrast, there is no correlation between airspeed (indoor) and wind speed (outdoor). In Location C, the observed correlation is even low for airspeed, humidity, and air temperature. The low or non-existent correlation between indoor airspeed and wind speed could be attributed to the fact that the data was collected at the nearest weather stations; still, it does not represent the dwellings' local urban context.

Overall, the reported voting trend is similar for all the environmental variables at the three studied locations. The mean votes for Location A and B are similar for both sensation (neutral) and preference votes (no change) for temperature and humidity. In terms of air movement, most participants perceived the environment as still and reported a marked preference for higher air movement. While Location C is the most different, the mean sensation and preference votes are significantly different from those of locations A and B, there is a similar trend from A to C. After analysing the subjective votes, the researcher would recommend a couple of improvements on the scales' wording, both for humidity and air movement, for future work. The word humidity is usually associated with mould rather than environmental variable; thus, a different approach should be considered. Regarding air movement, the number of points on the sensation scale could be reduced. It was difficult for participants to differentiate between the different response options.

Moreover, a significant difference in the indoor temperature (t_{in}) regressed on the outdoor temperature (t_{out-ma}) is observed when comparing rooms' construction typology and room roof exposure level. The higher solar radiation levels significantly affect the operative temperature of light construction dwellings with roof/ceilings directly exposed to the outdoor ambient. Differences between sensation and preference votes were not explored due to a small number of observations resulting when splitting by construction typology and room location on participants. However, the t_{in} is significantly different between rooms typology (lightweight and medium thermal mass) and exposure level (exposed and non-exposed), revealing the direction for further and future research.

The investigated contextual factors have a significant impact in the subjective response of occupants, and the consistent differences were observed across the study locations. Once concluded the analysis of contextual differences, the following step, investigated in the next chapter, explores the effect of factors such as demographics, adaptation, and behavioural adjustments in thermal comfort.

Chapter 5

Effect of individuals factors on thermal comfort

5.1 Overview

Chapter 4 has shown that the environment's subjective assessment depends on the physical indoor environment. At the same time, the indoor environment depends on the outdoor environment. These dependencies are not simple, linear or perfect. Therefore, this chapter extends the investigation to the individual factors that need to be considered in the prediction of comfort in the studied locations. The analysis centred on the individual differences in the subjective assessment and the mean indoor operative temperature when participants voted between -1 to 1 (t_{o-mean}) due to demographics, adaptation factors and behavioural adjustments (Figure 5.1).

Figure 5.1: Individual factors of diversity in thermal comfort

Demographics analysis focused on differences in thermal comfort due to occupants' gender, age, and body composition. Residents' acclimatisation or adaptation to high-altitude regions investigated the effect of peoples' mobility and exposure to different environments in thermal comfort. For this purpose, an adaptation index is proposed to classify respondents into different adaptation levels to the prevailing conditions. Furthermore, the research was extended to understand the primary causes of discomfort at home and any symptoms related to the indoor environment's quality. Lastly, the predominant behavioural adjustments undertaken to restore comfort at dwellings or individuals' level were analysed. One of the primary means of adaptation reported in the literature is clothing insulation; thus, a detailed analysis is included in a separate section.

5.2 Methods

This section describes data processing used to create new variables such as body surface area (BSA) for demographics analysis; and climate classification and altitude for different locations for the definition of adaptation factors. Moreover, an explanation of the adaptation index criteria and classification of behavioural adjustments is provided. The data sets used for these analyses correspond to the one collected in sections A-Participants, B-Adaptation, C-Symptoms and discomfort at home, and D-Control strategies, from the thermal comfort surveys.

5.2.1 Body surface area

In physiology, the body surface area (BSA) refer to the nude body surface area and corresponds to the relation between mass in *kg* (W) and height in m (H), commonly calculate following the DuBois Equation 5.1 (ASHRAE, 2009).

$$BSA = 0.202W^{0.425}H^{0.725} \tag{5.1}$$

5.2.2 Recoding variables for adaptation index

The data collected from Section B-Adaptation in the questionnaire was assembly into some proxies for whether people are likely to be adapted. The variables used for creating the index are a) birthplace, b) period living in the current environment, c) weekly exposure to different weather conditions, and d) weekly exposure to buildings with air conditioning systems. However, before recoding the collected data, two new variables necessaries for this analysis were calculated: climate classification and altitude for every reported location such as the current residence, a previous residence, birthplace, or places visited during weekly commuting.

The four factors of adaptation defined in this research correspond to: a) Birthplace, b) Acclimatisation, c) Weather exposure, and d) HVAC exposure. The last factor of adaptation e) Overall adaptation is a combined factor that intends to aggregate effects of the previous four factors in a single index of adaptation. The first factor of adaptation is birthplace, focusing mainly on the altitude above sea level of the birth reported place. Acclimatisation, the second factor, considered the period living under similar weather conditions classified according to the collected data in three levels: a) $<$one year b) between 1 - 3 years and c) $>$three years. The third factor, Weather exposure, aimed to reflect the exposure to different weather conditions due to personal or work-related commuting. Participants commute around the city and across the country, and therefore they are exposed to different climate conditions. Participants reported the average number of days and the most common places visited weekly. Similarly, the HVAC exposure factor aims to reflect the average number of days a subject is exposed to mechanically conditioned spaces. In both cases, the exposition level to either different climates or HVAC was derived based on the registered number of days exposed to different conditions. Lastly, a single overall index based on weights was calculated to combine the various adaptation factors' effect. The new variables resulting from recoding answers were used to analyse the indoor environment's subjective responses and evaluate any potential difference between adaptation groups.

5.2.2.1 Climate classification for individual locations

The Köeppen-Geiger (KG) climate classification for each reported town or city was geocoded using the Köppen-Geiger world map. The high-resolution map used data from 1980 to 2016 with a 1km resolution and was derived from four high-resolution, topographically corrected climate map. Each location's latitude and longitude were converted to pixel numbers to obtain the corresponding KG class (Beck et al., 2018).

5.2.2.2 Altitude for individual locations

The altitude for each reported location was extracted from a high-resolution digital elevation model of the Earth based on the geographic coordinates (Farr et al., 2007).. Latitude and longitude were geocoded using Open Street Map Nominatim tmaptools geocode_OSM). The generated coordinates correspond to the polygon's centroid, defined by the canton's administrative limits and not necessarily the inhabited area. Therefore, manual corrections were applied whenever the geographic coordinates were located far from the inhabited area and relocated to the administrative centre; in other words, the location's main square.

5.2.3 Classification of control strategies

The control strategies to restore comfort were differentiated between environmental and individual adjustments and classified according to the action's purpose, increase or reduce heat gains and losses. Table 5.1 summarises the main strategies or systems used to adjust the dwellings' environment, using general categories from the British home survey (Raw et al., 2016)..

Following the same process, the most recurrent actions undertaken by people at home to keep themselves warm or cool were classified as shown in Table 5.2 (Gauthier, 2016; Raw et al., 2016).

Table 5.1: Environmental adjustment levels and strategies

Level 1	Level 2	Level 3	Level 4
Environment	Control heat gain	Shading	Internal shading
			External shading
	Remove heat	Natural ventilation	External doors
			External windows
			Fans
		Mechanical ventilation	Not applicable
		Air-conditioning	Not applicable
	Increase heat gain	Heating	Portable heater
			Others (i.e. cookers, open fires)

Table 5.2: Individual adjustment levels and strategies

Level 1	Level 2	Level 3
Individual	Change location	Indoors
		Outdoors
	Cooling or heating	Drinks
		Food
		Shower
	Insulation	Bedding
		Clothing
	Metabolic rate	
		Increase activity

5.2.4 Estimation of clothing insulation

Clothing insulation (Clo) is the insulation layer's resistance covering the human body expressed in m^2K/W. The effective thermal clothing insulation (I_{cl}) was estimated from the summation of individual garments, as described in Equation 5.2 (EN ISO, 2009).

$$I_{cl} = 0.161 + 0.835 \sum I_{clu} \tag{5.2}$$

I_{clu} (m^2K/W) is the effective thermal insulation of an individual garment making up the ensemble. The individual garments insulation values selected from Appendix B (EN ISO, 2009) are summarised in Table 5.3. Clo was further corrected due to the effect of posture and seats. Due to the human body's contact with a padded chair or bed, the effective heat transfer is substantially reduced; thus, corrections on posture and effect of seats are applied. Corrections to air movement were not used due to the low indoor airspeed recorded, on average below $0.2m/s$.

Table 5.3: Insulation values of typical garments (I_{cl})

Garment	Description	Icl_u (Clo)
None	None	0.00
Underwear	Underpants / Panties and bra	0.03
Shirt, blouses	Sleeveless	0.13
Shirt, blouses	Short sleeves	0.15
Shirt, blouses	Lightweight, long sleeves	0.20
Shirt, blouses	Normal, long sleeves	0.25
Vest	Vest	0.12
Sweater	Thin sweater	0.20
Sweater	Sweater	0.28
Sweater	Thick sweater	0.35
Jacket	Light jacket	0.25
Jacket	Jacket	0.35
Dress	Light dress, short sleeves	0.20
Dress	Heavy dress, long sleeves	0.40
Skirt	Light skirt	0.15
Skirt	Heavy skirt	0.25
Trousers	Walking shorts	0.11
Trousers	Lightweight	0.20
Trousers	Normal	0.25
Trousers	Flannel	0.28
Socks	Stocking	0.03
Socks	Ankle-length socks	0.02
Socks	Calf-length socks	0.03
Shoes	Shoes (Thin sole) / Sandals	0.02
Shoes	Shoes (Thick sole) / Slippers	0.04
Shoes	Boots	0.10
Accessories	Cap	0.01
Accessories	Wool hat	0.02

5.3 Demographics of surveyed occupants

A total of 398 complete thermal comfort surveys were collected from residents ageing between 18 years-old and 65 years-old. The sample of participants across the locations and the main demographics, including gender, weight and body surface area (BSA), are detailed in Table 5.4 and age ranges in Table 5.6.

Although keeping a proportional male-to-female responses ratio was desired, a higher number of female participants was surveyed. During the fieldwork, it was observed that women are more likely to be at home. A t-test was used to compare the mean BSA for males and females from residents in the highlands against the reference values defined in the comfort international standards (male = $1.84m^2$ and female = $1.69m^2$) (EN ISO, 2004). The results confirmed that the av-

Table 5.4: Participants demographics by location and gender

Location	Participants	N	Weight in kg (*sd*)	Height in cm (*sd*)	BSA m^2 (*sd*)
A	Female	68	65 (±11)	155 (±8)	1.6 (±0.1)
	Male	66	68 (±11)	166 (±9)	1.7 (±0.2)
B	Female	70	68 (±13)	157 (±6)	1.7 (±0.2)
	Male	62	71 (±13)	168 (±8)	1.8 (±0.2)
C	Female	74	64 (±13)	153 (±7)	1.6 (±0.2)
	Male	58	66 (±14)	165 (±7)	1.7 (±0.2)
All	Female	212	65 (±12)	155 (±7)	1.6 (±0.2)
	Male	186	68 (±13)	166 (±8)	1.8 (±0.2)

erage BSA for males (1.75m^2, ±0.17) and females (1.63m^2, ±0.16) are statistically different from the reference BSA for males ($t(185) = -7.22, p<.000$) and females ($t(211) = -5.49, p<.000$). One could conclude that the studied sample's BSA is significantly lower than the one established on the international standards. However, considering that most participants estimated their weight (*kg*) and height (*cm*), the reported BSA values are a rough approximation. A single BSA value is not appropriate for all adults; differences due to demographics anthropometric might adhere error to the traditional Met value (McMurray et al., 2014). The importance of an accurate estimation of the Met is related to calculating the predicted mean vote.

A comparison of the mean and standard deviation of the mean indoor operative temperature when the thermal sensation votes are between -1 to 1 (t_{o-mean}) was used to explore differences between demographics such as gender, age and BSA (Table 5.5). The t_{o-mean} for males is 22.0 °C (±2.4 °C) and for females is 22.1 °C (±2.5 °C), as seen in Figure 5.2. A t.test and Levene confirmed there is no significant difference in either the mean t_{comf} ($t(321) = 0.50, p = .613$) and equal variances ($F(322) = 2.28, p = .132$), respectively, between males and females (Table 5.5). The mean t_{o-mean} for the subjects with a BSA below the standard value is 0.4 °C higher than the one for subjects with a BSA above the reference value. However, the observed difference on the mean t_{o-mean} is no significantly different, same as for the standard deviation (Futher details in Table E.1). Besides, the central tendency of subjective votes was also explored by no significant difference was observed between males and females groups. No significant difference was observed when evaluating the indoor environment between males and females in this research, opposite to findings from previous studies (Thapa et al., 2018a,c; Yan and Yang, 2014).

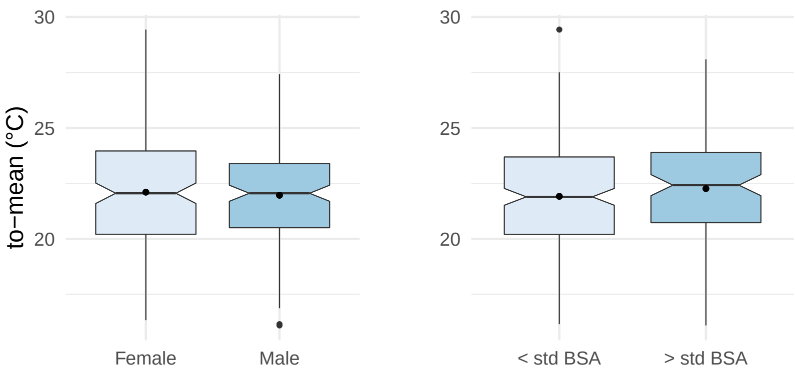
Table 5.6 summarised the distribution of participants by groups of age and gender. In Figure 5.3, one can observe that the mean t_{o-mean} vary within a narrow range (21.5 °C to 22.6 °C) across age groups, and no significant difference was identified (significance values in Table 5.5

Table 5.5: Mean operative temperature t_{o-mean}, standard deviation (sd) by demographics and p for means and variance

Variable	Level	Participants(n)[1]	mean	sd	$p(mean)$	$p(variance)$
Gender	Female	165	22.1	2.54	0.613	0.1613
	Male	159	22.0	2.42		
Age	>20	25	21.5	2.44	0.160	0.013
	20-29	67	22.6	2.34		
	30-39	81	21.9	2.25		
	40-49	62	21.5	2.82		
	50-59	46	22.2	2.19		
	60-65	34	22.2	2.35		
	<65	9	22.6	4.03		
BSA	>std BSA*	111	22.3	2.43	0.228	0.465
BSA	<std BSA*	231	21.9	2.49		

* std BSA = Standard reference value (male = 1.84m^2 and female = 1.69m^2)

[1] number of participants reporting thermal sensation votes between -1 and +1



(a) Gender **(b)** BSA index

Figure 5.2: Distribution of the mean operative temperature (t_{o-mean}) by gender and BSA

further statistics in Table E.1).

After the independent analysis of each demographic group (gender, age groups and BSA), results denote no significant difference in the mean t_{o-mean} or the standard deviation. Despite not being statistically significant, subjects with a lower BSA seems to prefer a warmer environment based on the small difference observed in the mean t_{o-mean} (0.4 °C).

5.4 Adaptation level

A key concept to be investigated in this research is occupants' acclimatisation or adaptation to high-altitude regions. This concept cannot be directly estimated or measured mainly due to peoples' mobility. Therefore, an adaptation index was proposed to assess the effect of mobility and

Table 5.6: Distribution of all participants by age group and gender

Age range	<20	20-29	30-39	40-49	50-59	60-65	<65	Total by Gender
Female	14	45	58	43	29	19	4	212
Male	14	45	41	32	25	23	6	186
Total by age	28	90	99	75	54	42	10	398

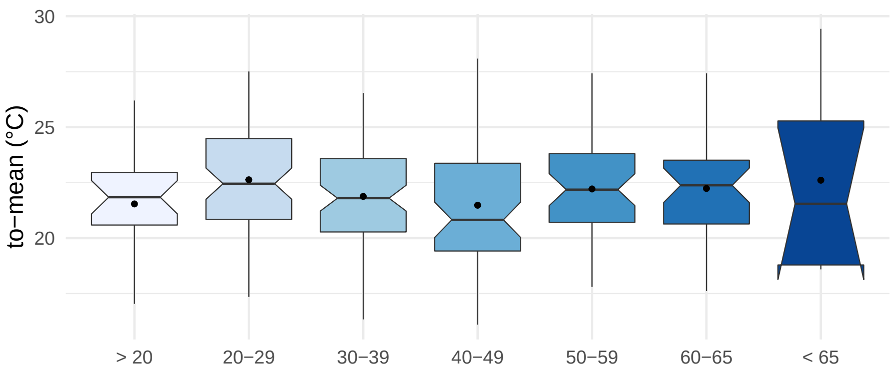


Figure 5.3: Mean operative temperature (t_{o-mean}) by age group

exposure to a different environment in operative temperature and comfort votes. The section covers a description of the original variables and levels of data collected, an explanation of the criteria used to define each adaptation factor's levels and describing the observed differences in thermal comfort votes and mean operative temperature when participants voted between -1 and +1 (t_{o-mean}).

5.4.1 Description of collected data

The number of observations for each level and factors of adaptation are summarised in Figure 5.4. The surveyed participants came mainly from either locations below 2000m or places similar to Quito's elevation (2800m). As far as possible, the sampling of participants seeks to be a representation of the population, and it is reflected in the participant's diversity of origin. Participants are native of Germany (n = 1), Venezuela (n = 1), Colombia (n = 5), and Ecuador (n = 391). About 85% of the participants have lived in the current location or locations with a similar weather condition for more than three years. Therefore, it could be assumed that most respondents are moderately acclimatised to the current environmental conditions. In terms of weekly exposure to a different context, 87% of participants commute to locations with different weather, such as locations in the coast or the amazon region, and less than 10% are exposed to mechanically conditioned spaces on a weekly basis.

When looking at the difference in t_{o-mean} across the adaptation factors' levels, no significant

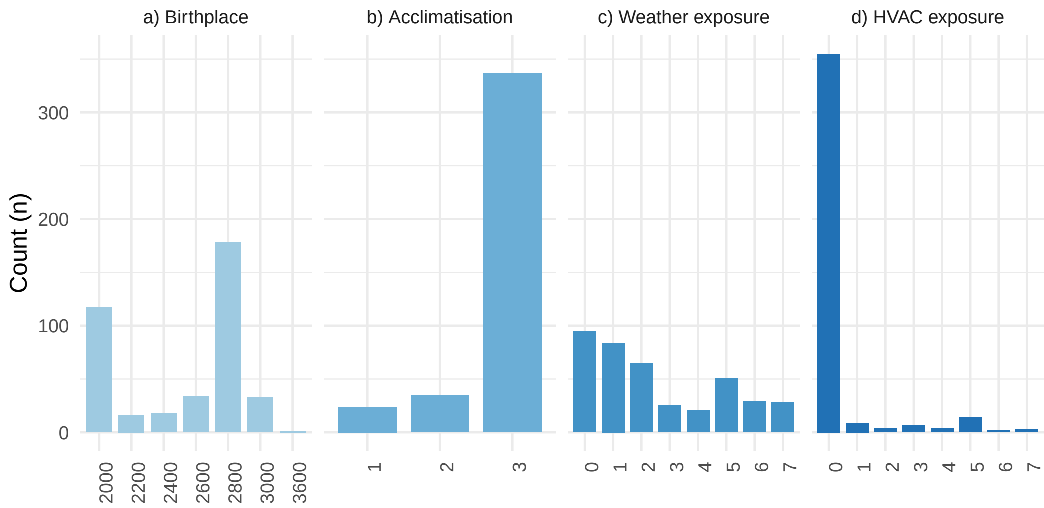


Figure 5.4: Number of participants for each adaptation factors and levels of retrieved data

differences were observed (Figure 5.5), as the diverse number of levels resulted in groups with few observations (<14). Moreover, a comparison of the collected data is not possible due to the different levels and units of analysis (i.e. meters above sea level, days and years). Therefore, the proposed index standardise the data for further analysis as described in the following section.

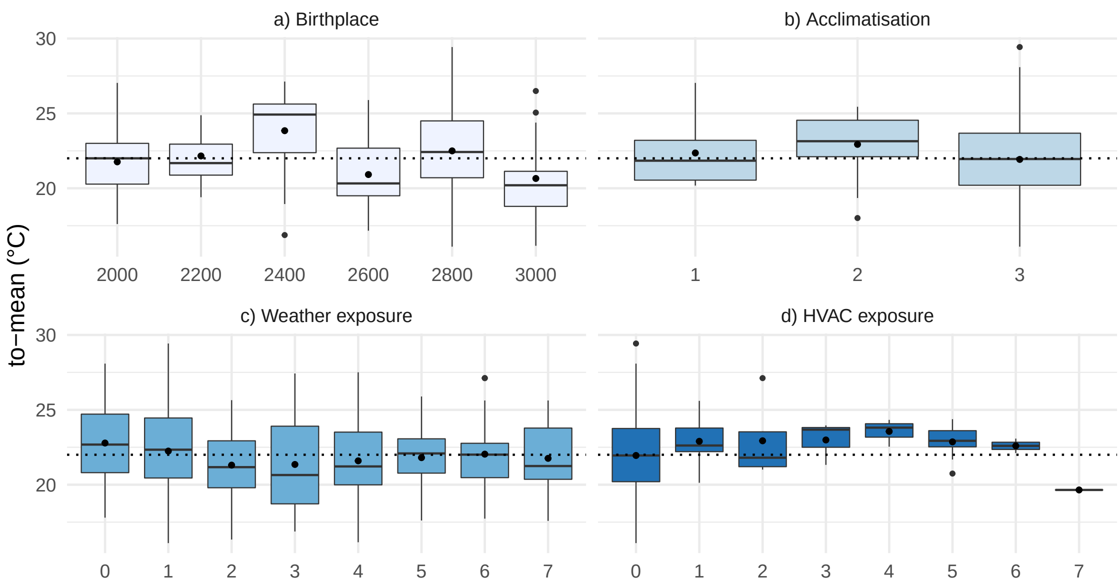


Figure 5.5: Mean operative temperature (t_{o-mean}) per adaptation factor and level

5.4.2 Definition of adaptation factors' levels and the overall index

In order to standardise the units of analysis and reduce the number of levels, the adaptations factors were recoded into 'low',' mid' and 'high', as described in Table 5.7. According to the altitude of the birthplace, participants were differentiated between high and low-altitude natives. In this research, all the respondents born in locations below 2000m in the Ecuadorian Highlands are categorised as low-altitude inhabitants. The lower boundary is aligned high altitude definition in the literature (Johnson and Luks, 2016).

Table 5.7: Acclimatisation factors to a different context and environmental exposure

Variable name	Description	Levels and descriptor	Weight
a) Birthplace	Birthplace in the Ecuadorian highlands	1: Low (<2000m) 2: Mid (2000 - 3000m) 3: High (>2000m)	1 2 3
b) Acclimatisation	Long term adaptation to current climate (Numbers of years living under the same climate conditions)	1: Low (Living <1 year) 2: Mid (1 - 3 years) 3: High (>3 years)	1 2 3
c) Weather exposure	Weekly exposure to different climate (Numbers of days a week exposed to different weather conditions)	1: Low (Exposed>1) 2: Mid (2 - 4 days) 3: High (>5 days)	3 2 1
d) HVAV exposure	Weekly exposure to HVAC systems (Numbers of days a week exposed to buildings with mechanical systems)	1: Low (Exposed >1 days) 2: Mid (2 - 4 days) 3: High (>5 days)	3 2 1
e) Overall adaptation	Level of adaptation to the current environment based on weight from the previous categories	1: Low 2: Mid 3: High	<= 6 points 7 - 10 points >= 10 points

In terms of acclimatisation, the three levels correspond low (<1 year), mid (1 - 3 years), and high (>3 years). Worth noting that there is no consensus regarding the period for considered people adapted to an environment. Thus, in this research, participants adapted to their current environment would be regarded as living in locations with similar climate for at least three years. Due to the significant difference in t_{o-mean} (Figure 5.5), the minimum threshold for classifying the level of exposure to different climate conditions is two days. Nevertheless, to differentiate individuals exposed for more than five days a week, a third level (high) was included. Despite the small number of observations and non-significant difference in t_{o-mean}, three levels were also defined for HVAC exposure. High exposure to different climate, such as cities in the Coast where the weather is classified as 'Aw'. (Tropical Savanna Climate), is scored as low as participants might have different expectations due to previous recurrent experiences. The threshold for the three levels of HVAC exposure followed the same criteria specified for the exposure to weather conditions. Once the levels were standardised in the three categories, the t_{o-mean} and subjective votes were analysed for each adaptation factor to identify any significant difference.

The weights attributed to the level of each adaptation factor, a) Birthplace, b) Acclimatisation, c) Weather exposure, and d) HVAC exposure and e) Overall adaptation, are summarised in Table 5.7. Overall adaptation index range from 4 to 12 points where the higher weights were assigned to the proxies that describe whether people are more likely to be adapted to the prevailing environmental conditions. For instance, the higher weight (3) was assigned to the higher levels of birthplace and acclimatisation, same as the lower levels of exposure to different climate and mechanically conditioned spaces. Thus, a high level of overall adaptation (Overall adaptation index = 12 or 3/3/3/3) would correspond to born at high-altitude (+3), high acclimatisation (+3), low exposure to different climate conditions (+3) and low exposure to buildings with HVAC (+3). A couple of weight combinations (e.g. 0, 1, 2) were also tested. Still, no significant difference was observed when reporting differences in t_{o-mean}.

Figure 5.6 summarises the percentage (y-axis) and the number of participants (count number inside the bar) at each adaptation factor's level. According to the reported birthplace's place, 75% of the participants are subcategorised as high-altitude residents (birthplace above 2000m), while only 25% of the respondents are from low altitude regions. 85% of the participants have lived more than three years in their current location or a different one but with the same weather conditions. Participants highly exposed to different weather due to weekly commuting reach 27% of the sample, and the ones exposed to building with HVAC systems is only 4.7%. Based on the overall adaptation index, 80% belong to the higher level and less than 1% to the lower level.

5.4.3 Evaluation of mean operative temperature per adaptation factors

The t_{o-mean} and the subjective environmental votes distribution were analysed to identify any potential pattern or difference due to adaptation factors. t_{o-mean} per adaptation factor's level are plotted in Figure 5.7. As seen in the figure, the mean t_{o-mean} across the different factors and adaptation levels is 22.0 °C (±0.4 °C) (Table 5.8). The comparison of means between the adaptation factors' levels revealed no statistical significance between the t_{o-mean} (Stats summary in Table 5.8). The probability distribution of the t_{o-mean} between mid and high adaptation level for each factor compared with a two-sample $k-w$ test was significantly different except for acclimatisation (p<0.05); hence, the observed variance of t_{o-mean} distribution across adaptation factors' levels is significantly different. These results highlight that the mean t_{o-mean} is similar across all the studied adaptation factors. However, there is difference in the range of acceptability of the indoor conditions. Low overall adapted subjects are likely to feel comfortable when t_{o-mean} is 22.3 °C (±0.24). In contrast, high overall adapted subjects have endured tolerance or are likely to

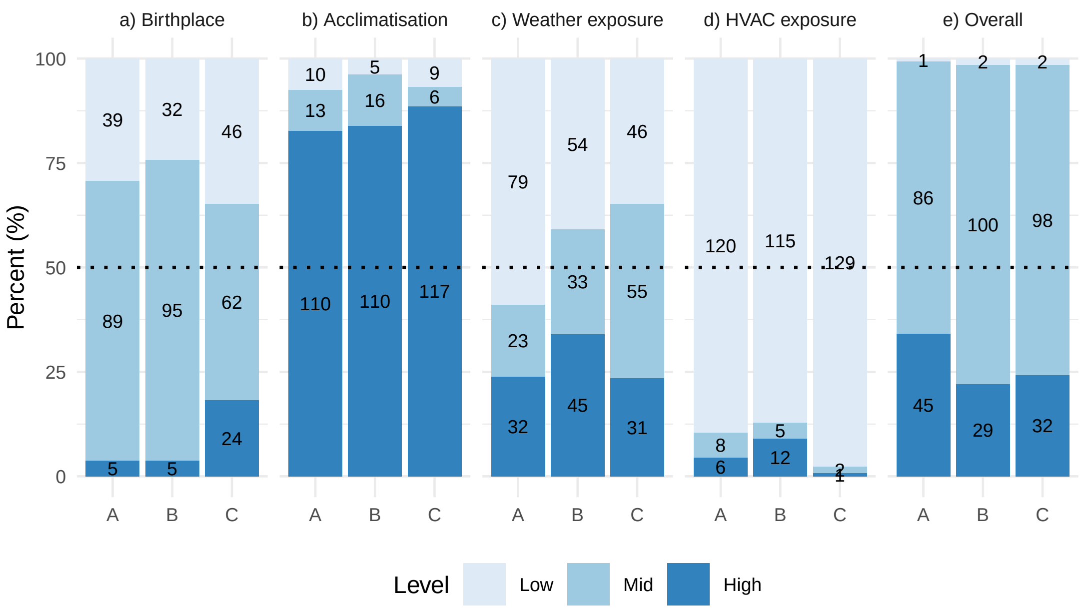


Figure 5.6: Percentage and count of acclimatisation level to different environments and conditions

feel comfortable at a broader range of t_{o-mean} is 22.0 °C (±2.6).

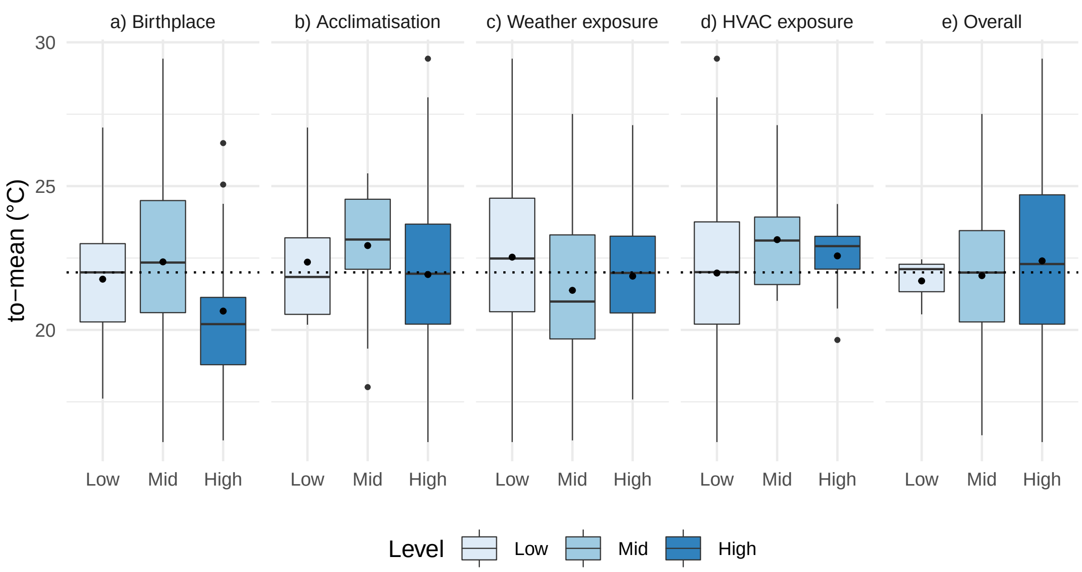


Figure 5.7: Mean operative temperature t_{o-mean} for each factor and level of adaptation

The overall index results that combine the different adaptation factors' effect are consistent with the expected outcomes. That means a narrow range of acceptable indoor temperature in low-adapted subjects (non-acclimatised) opposite to a broader range in highly adapted participants (acclimatised), as seen in Figure 5.7. On one hand, the broader range of acceptable temperature

Table 5.8: Mean operative temperature (t_{o-mean}) by adaptation factor and levels, and p for means and variance comparison

Factors	Level	n	mean	sd	df	p (means)	p (Variance)
a) Birthplace	Low	92	21.8	2.180	2	0.001	0.121
	Mid	202	22.4	2.550			
	High	29	20.7	2.350			
b) Acclimatisation	Low	17	22.4	2.290	2	0.064	0.128
	Mid	26	22.9	1.880			
	High	280	21.9	2.520			
c) Weather exposure	Low	148	22.5	2.500	2	0.002	0.064
	Mid	88	21.4	2.600			
	High	88	21.9	2.130			
d) HVAC exposure	Low	301	22.0	2.520	2	0.052	0.009
	Mid	10	23.1	1.860			
	High	13	22.6	1.290			
e) Overall	Low	3	21.7	1.020	2	0.088	0.017
	Mid	226	21.9	2.340			
	High	93	22.4	2.790			

suggest high adapted subjects are more permissible with the indoor environment. And on the other hand, the results provide insight that the used proxies offer an acceptable definition of the adaptation index.

5.4.4 Evaluation of environmental votes adaptation factors

Besides analysing the mean operative temperature (t_{o-mean}), the analysis was extended to the distribution of environmental votes for the overall adaptation index, for a detailed summary of test refer to Table E.1.

Figure 5.8 highlight the differences between the distribution of thermal sensation votes (TSV) and thermal preference votes (TPV). For the mid overall adaptation level, a lower percentage of comfort votes (TSV = -1 to +1) was observed and was higher the reported preference for warmer (Location C) and cooler (Location A) environments. The increasing trend in the number of comfort votes from the mid-adapted subjects to the high-adapted ones remains the same for the three locations in terms of thermal sensation and thermal preference. Consequently, the increased comfort votes denote a reduction in observations in the other thermal sensation and preference scale points. A lower percentage of high-adapted respondents voted for 'slightly cool' (-1) and 'cool' (-2) sensation. Meanwhile, the same group of respondents reported a small percentage of preference votes for 'slightly warm' (1) and 'warmer' environments (2). In other words, the most high-adapted residents tend to feel less uncomfortable than those who are mid-adapted. Previous studies report similar findings, concluding that previous long-term exposure to different indoor thermal conditions also influences occupants' thermal adaptation (Luo et al., 2016).

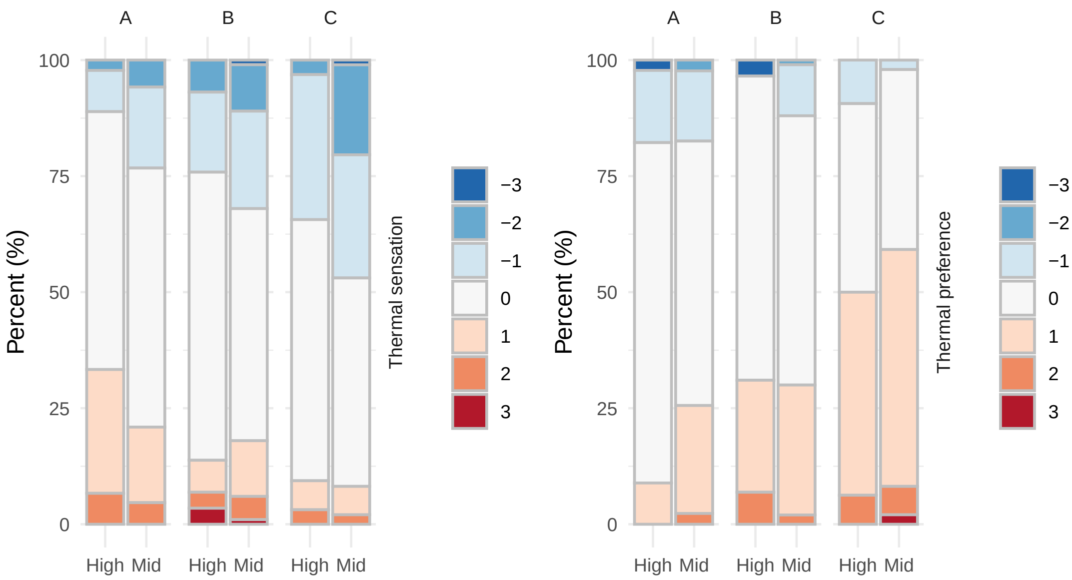


Figure 5.8: Thermal perception and thermal preference votes distribution by location and overall adaptation levels

A clear trend across locations and overall adaptation levels are not evident from the distribution of humidity votes, Figure 5.9. The random pattern in the distribution of neutral votes of humidity sensation and preference could be either explained by a non-adaptation effect to humidity or unsuitableness of the scale for assessing this concept. Particularly for mid-adapted subjects, a higher sensation of humidity (HSV from 1 to 3) is observed and a clear preference for drier (HPV from -1 to -3) environments.

Finally, participants sensation and preference for higher or lower air movement rates follow a similar trend as the figures above, but no significant difference is observed in Figure 5.10 and confirmed by statistical analyses (Table E.1). The increasing percentage of neutral votes for both sensation and preference relates to the high-adapted residents. In contrast, it is mid-adapted participants who express a greater preference for lower air movement. The air movement scale rates the degree of air movement and not directly the impact on the person sensation. Thus, it cannot be concluded that high-adapted preferred or are adapted to the prevailing air movement conditions.

About 85% of the sample are high-adapted to their context and not frequently exposed to different weather conditions or mechanically ventilated buildings. There is no significant difference

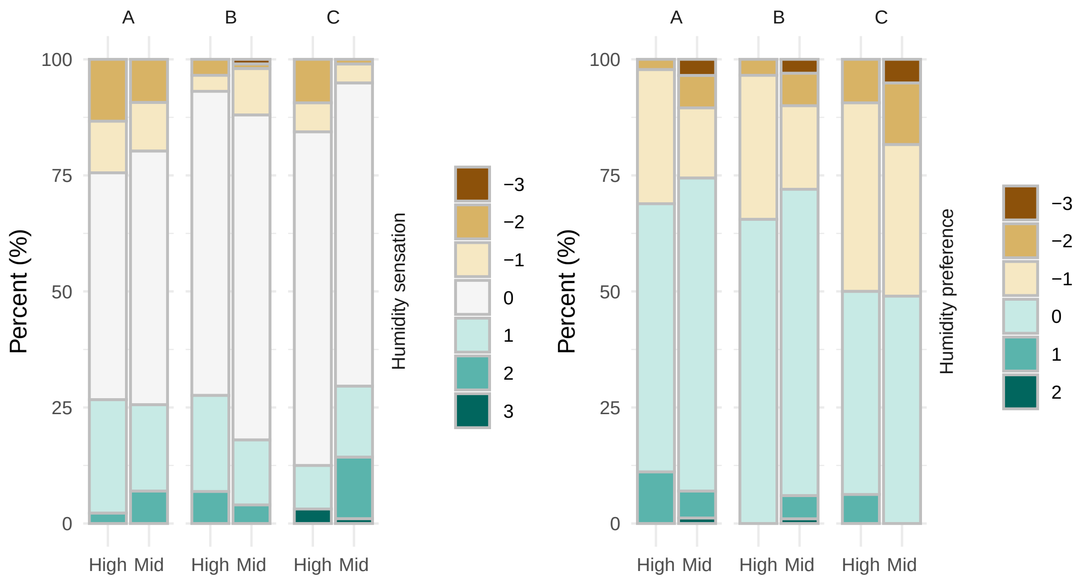


Figure 5.9: Humidity sensation and preference votes distribution by location and overall adaptation levels

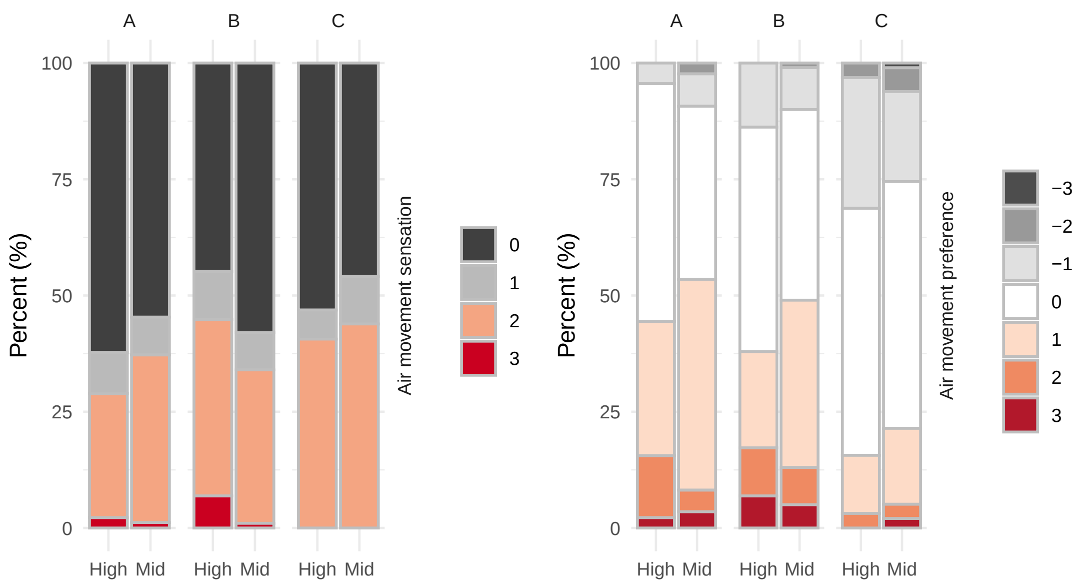


Figure 5.10: Air speed sensation and preference votes distribution by location and overall adaptation levels

in the mean t_{o-mean} between adaptation factors; however, evidence was found on the difference in t_{o-mean} distribution (Table E.1). In other words, high-adapted individuals have a broader range of comfort acceptability than those mid-adapted. Similarly, the distribution of indoor environmental votes suggests that a higher percentage of neutral votes is observed among well-acclimatised residents and a lower preference for changing the indoor conditions.

Moreover, a clear pattern of increasing comfort sensation and no-change preference votes to air temperature and air movement (preference) was observed between the mid and high adaptation levels. However, this was not the case for humidity; the random pattern could be attributed to non-adaptation to humidity or an inaccurate scale for measuring this variable. Results presented in this section confirm a certain degree of adaptation (acclimatisation) of high-altitude residents to the current conditions and the validation, to a certain extent, of the overall adaptation index to altitude.

5.5 Symptoms and discomfort at home

This section described the prevalence of symptoms and discomfort associated with the indoor environment's quality, particularly those perceived recurrently at home, based on the data reported. The health issues and difficulties at housekeeping and resting due to unpleasant temperature were analysed at participants' level (n=398). In contrast, as more than one comfort survey was collected per dwelling, discomfort issues were reported at dwellings' level (n=287) to avoid overrepresenting findings.

Around 30% of the residents experienced at least one or two health issues, and 95% of the householders' reported, on average, three causes of indoor discomfort. The overall average ratio of health problems reported is 1.7 per participant (Table 5.9). In Location C, residents experienced more health issues at home per individual (ratio of 1.8). Still, overall more participants at Location A reported complaints related to health (38%), difficulties at housekeeping (51%), and resting (68%), as well as discomfort issues at home (98%). The number of people experiencing health issues and difficulties for sleeping decrease from Location A to Location B and C (Table 5.9). Home activities' development is seriously compromised due to the indoor temperature; above 50% of the respondents have difficulties while housekeeping and resting.

Overall, the primary health issues affecting the surveyed participants are dry throat (n=39), headache (n=37), runny nose (n=32) and fatigue (n=25). The most frequent symptoms are similar across locations; however, each location's incidence is not the same. In Location A, as shown in Figure 5.11, the percentage of participants perceiving symptoms is higher than those in Location C. In Figure 5.11 and Figure 5.12, the frequency 'often' indicates symptoms experienced once or twice a week while 'sometimes' corresponds to once or twice every two weeks. Location A reports most of the symptoms and for a greater number of participants.

In terms of discomfort at home, as shown in Figure 5.12,the householders' main issues are related to temperature (high, low or diurnal oscillation) and draught. As expected, a higher percent-

Table 5.9: Health and discomfort issues reported by each participant and dwelling

Location	Participant				Dwelling	
	Issues/Subject [1]	H Issues[2] (%)	Housekeep[3] (%)	Resting[4] (%)	Issues/Dwelling[5]	Discomfort[6] (%)
A	1.6	38	51	65	2.9	98
B	1.7	26	36	55	3.2	93
C	1.8	23	46	49	3.2	95
All	1.7	29	44	56	3.1	95

[1] Issues/Subject = Average ratio of health issues reported per subject
[2] H Issues = Percentage of subjects reporting at least one health issue at home
[3] Housekeep = Percentage of subjects that report being affected by temperature when housekeeping
[4] Resting = Percentage of subjects that report being affected by temperature when resting
[5] Issues/Dwelling = Average ratio of discomfort issues reported per dwelling
[6] Percentage of dwellings that report at least one indoor discomfort issue

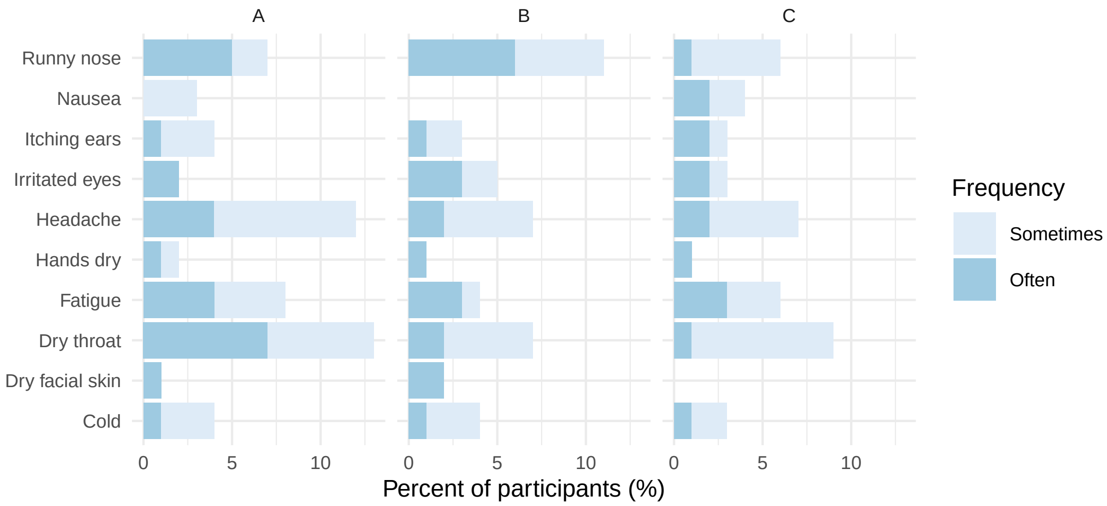


Figure 5.11: Percentage and rate of health issues reported by location

age of discomfort due to high temperature is observed at Location A. Meanwhile, in Location C, most of the complaints are due to a low temperature. Location C reports more inconveniences due to temperature oscillation than location A, even though the former is effectively the one with the broader thermal oscillation (Section 4.3 and Section 4.4). The higher rate of complaints to temperature oscillation may suggest that in locations where the temperature is lower or oscillates within a narrower range (i.e. Location C), users might be more sensitive to any temperature change. Moreover, residents in Location C complained about humidity and draught. Humidity and draught discomfort could be considered as an additive effect of low temperature, as humidity and air movement, at the moment of the survey, are not significantly different compared to the other two locations. Dense air ('stuffy air') is reported as unpleasant for 9% of the respondents.

Besides the stated options in the questionnaire, participants complained about dust (n= 37), wind (n= 15) and noise (n=10); most of these complaints belong to participants at Location B.

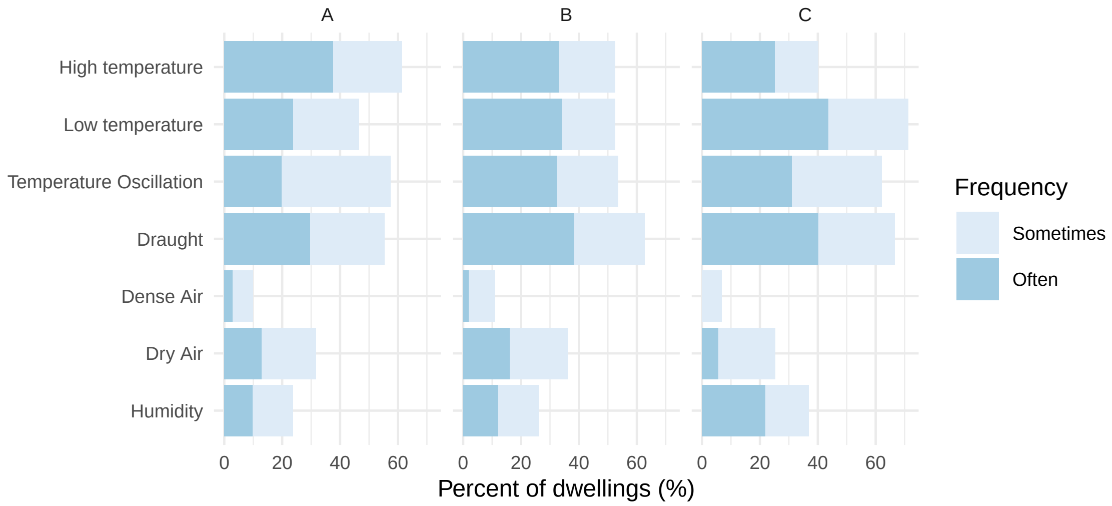


Figure 5.12: Building related discomfort by location and frequency of occurrence

Furthermore, participants were asked to report how much the indoor temperature affects resting and housekeeping based on a three-level scale (none, bit and too much), Figure 5.13. Following the trend as in symptoms, the location reporting the higher impact on indoor activities is Location A, where heat was the main concern for 43 participants when housekeeping and 46 when resting. Responses in Location B were divided between it being cold and warm for both activities. In contrast, people's major complaint relates to cold environments at Location C when housekeeping (43 participants) and resting (42 participants).

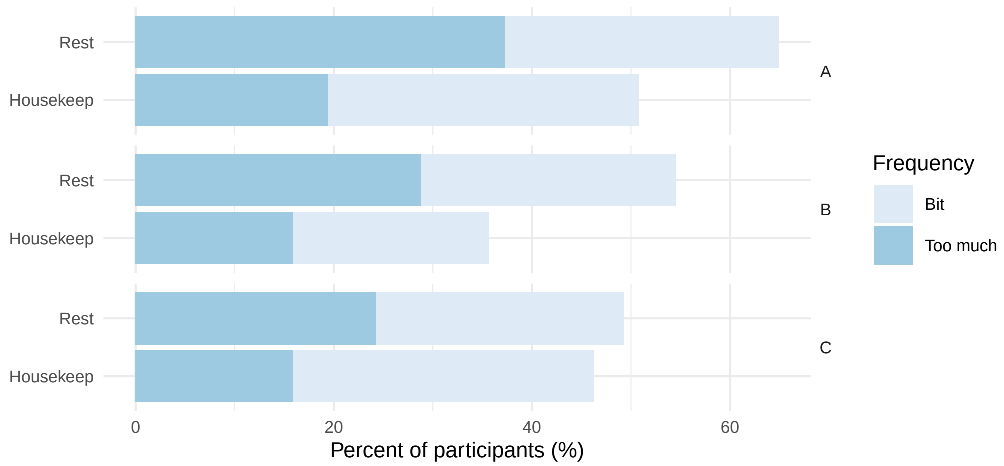


Figure 5.13: Perceived effect of temperature (combined warm and cold) at indoor activities by location

The percentage of participants reporting building-related symptoms associated with the indoor conditions at dwellings is not minor; at least 30% of the sample reported at least one symptom. Warmer conditions might increase the prevalence of perceived symptoms related to the poor indoor environment, as shown in results from Location A. Meanwhile, in a cooler location (Location C), participants are more sensitive to thermal oscillation, humidity and draught. Despite the high percentage of participants satisfied with the indoor environment at the moment of the survey, as reported in Section 4.6, draught, temperature oscillation or specific warm or cold environments were reported as constants issues by more than half of the sample. Moreover, above 50% of the participants stated that temperature is an issue when resting at home or while conducting housekeeping activities.

5.6 Control Strategies for thermal adjustment

The responses to adjust the indoor environment varies according to the availability of controls and the type of buildings. At residential buildings, it is assumed that households have available diverse coping strategies. The different control strategies reported by the participants were categorised based on two parameters. The first focused on whether the action taken is at the environmental level (context) or the participant level (individual). The second parameters considered temporality, classifying actions into permanent modifications and temporal adjustments. Therefore, the studied control strategies could either be permanent modifications to dwellings or temporary adjustment to the context or individual level. The criteria for grouping the different actions into levels is described below for permanent modifications in Table 5.10 and temporary adjustments in Table 5.11. These classifications provide a framework for assessing permanent modifications and temporal adjustment most frequently reported and the intentions behind each action or response's use. Permanent modifications classification consists of four levels according to the expected indoor effect (levels 2 and 3); the fourth level corresponds to householders' coded answer.

The answers to the questions reporting any conscious adjustment taken to keep themselves warm or cool on a typically cold or warm day were classified into environmental and individual adjustments. Similarly to permanent modifications, temporal adjustments were further divided into levels according to the intended purpose to be achieved by the reported actions. In Table 5.11, level 2 refers to the expected effect, and level 3 is the coded answer registered by the researcher during the survey.

The permanent modifications reported included more than 30 different actions. However,

Table 5.10: Permanent environmental modifications in dwellings to improve indoor temperature

Level 1	**Level 2**	**Level 3**	**Level 4**
Environmental	Control heat gain	External shading	Cover patio
		Internal shading	Add curtains
	Remove heat	Increase ventilation	Add net to windows
			Fans to increase air movement
	Increase heat gain	Heat the space	Install heaters
			Install more bulbs
		Reduce infiltration	Replace doors
			Replace windows
			Seal cracks
	Reduce heat gain	Thermal mass (ceiling)	Add ceiling
		Thermal mass (walls)	Walls insulation
		Thermal mass (floor)	Change floor finishing
		Thermal mass (roof)	Change zinc for concrete
	Other	Control humidity	Dry damp walls
		Room size and distribution	Change furniture distribution
			Enlarge rooms size
			Remove furniture
	None	None	None

Table 5.11: Temporal environmental and individual adjustments people do to improve indoor temperature

Level 1	**Level 2**	**Level 3**
Environmental	Control heat gain	Open/close external shading
		Open/close internal shading
	Increase heat gain	Turn on/off heaters
		Turn on/off other heating (e.g. fire)
	Remove heat	Open/close external doors
		Open/close external windows
Individual	Change location	Indoors
		Outdoors
	Cooling or heating themselves	Warm/cold drinks
		Warm/cold food
		Take a hot/cold shower
	Insulation	Bedding
		Adding/removing clothing
	Metabolic rate	Increase activity
None	None	None

only 26% (n=74 houses) of the surveyed dwellings reported a permanent amendment to improve the indoor temperature. Table 5.12 summarises the number of permanent modifications according to the indoor environment's expected outcome (level 2). It should be noted that the summary in Table 5.12 report one or more strategies per dwelling. The ratio represents the number of actions divided by the unit of analysis, either dwellings or participants.

In order to get a deeper understanding of the main modifications, Figure 5.14 shows the strategies reported by householders, colour-coded based on the intention behind the action. The main

Table 5.12: Environmental and individual control strategies taken to keep warm and cold reported by location

Diversity factors	Keep warm...				Keep cool...				Ratio
	A	B	C	All	A	B	C	All	
Environmental	36	35	41	112	108	59	48	215	0.8
Individual	150	156	174	480	131	109	64	304	2.0
None	17	7	5	29	15	12	25	52	0.2

modification focused on reducing infiltration by sealing cracks and replacing doors and windows. The second expected outcome seeks to balance the indoor temperature by changing floor finishing or adding ceiling. Interestingly, the third most frequent action, mainly reported in Location C, is external shading (covering internal patios). Some householders reported using translucent roofs (external shading) to increase solar radiation gains and protect the dwelling from rain and wind. Which is not a surprise considering Location C is the one with the highest precipitation level of the studied locations (Table 4.2). In contrast, in locations A and B, internal shading is more frequently used. It could be explained by the need to control glare and, in some cases, privacy.

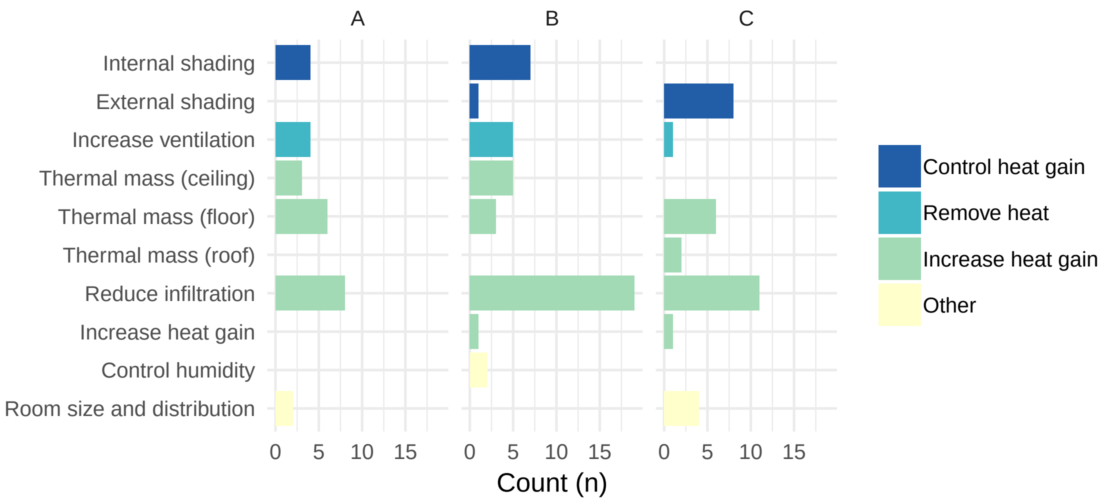


Figure 5.14: Number of dwellings permanent modifications (n) by location

The conducted permanent modifications focused on reducing heat loss by minimising the infiltration, particularly in Location C. The low number of overall reported changes could be attributed to several causes such as a) lack of knowledge on how to improve the indoor environment, b) lack of budget to conduct any modification, c) is not perceived as a need or d) occupants are not the owners of the space.

Figure 5.15 summarised the distribution of individual adjustments in the environment, and

Figure 5.16 the ones undertaken at a personal level. The main actions taken by subjects to cool down the environment correspond to opening external doors and windows. As expected, these actions are more frequent in Location A, while were very few actions were reported to warm up the indoor environment. The higher rate of responses increased heat gains are observed in Location C. Among the means used for heating, the responses include but are not limited to the use of fire, hairdryer, and turning on the cookers or ovens.

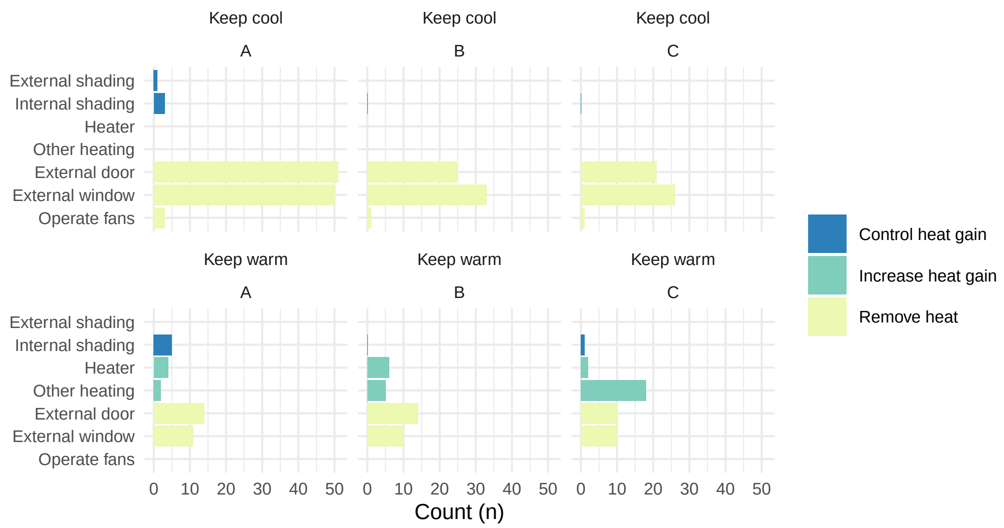


Figure 5.15: Environmental control strategies taken to keep themselves cool or warm by location

Modifying clothing is the primary mechanism used at a personal level to keep warm or cool across the three locations (Figure 5.16). In additions to using warmer clothes, the actions taken to keep warm are drinking hot beverages (n = 95) and using blankets or going to bed (n= 94). The same as for keeping warm, cold drinks correspond to the second most common strategy used to keep themselves cool (n = 71) followed by taking a shower (n = 47).

The temporal adjustments reported by respondents, as previously described in Table 5.10, were classified at the first level between environmental and individual actions. As reported in Table 5.13, personal control strategies are the primary mechanism used to restore comfort among the sample. 86% of the participants reported taking at least one individual control strategy to keep warm, and 68% take at least one action to keep cool. On average, each participant reported applying at least one action to keep warm and one to keep themselves cool. The higher percentage of responses to keep warm were observed in Location C (93%), while the higher rate of responses for keeping cool was reported at locations A and B (72%).

In terms of environmental adjustments, only 21% reported an action to increase heat gains

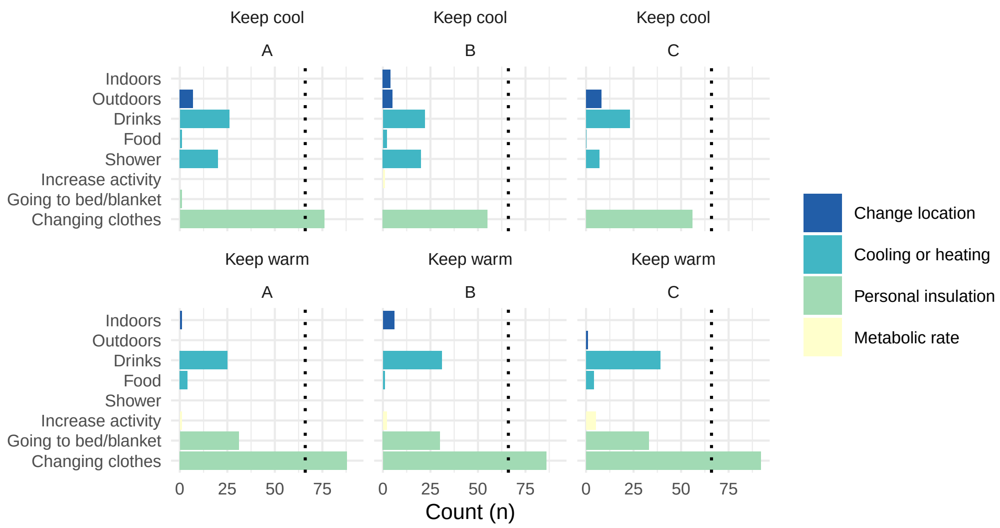


Figure 5.16: Personal control strategies taken to keep themselves cool or warm by location

at home, and 36% take at least one action to remove heat. Following the trend observed at individual adjustments, the higher location (Location C) reported more strategies to keep warm the environment (26%). Meanwhile, the lower location (Location A) take more actions to keep the environment cool (49%). A small percentage of users considered any action is needed for either keeping warm (7%) or keeping cool (13%). It is noteworthy that windows and doors' operation could be more of a habit than a strategy for increasing natural ventilation. Windows and doors are kept open regardless of being warm or not. Sometimes it is used for socialising and keeping in touch with neighbours.

Table 5.13: Temporal adjustments at environmental and individual level taken to keep participants warm or cold by location (Classification level 1)

		Keep themselves warm...				**Keep themselves cool...**			
Level 1	**Variable**	**A**	**B**	**C**	**All**	**A**	**B**	**C**	**All**
Environmental	Ratio	1.5	1.5	1.2	1.4	1.7	1.3	1.4	1.5
Individual		1.4	1.4	1.4	1.4	1.4	1.1	1.2	1.2
None		1	1	1	1	1	1	1	1
Environmental	Percentage	18	18	26	21	49	34	26	36
Individual		81	86	93	86	72	72	61	68
None		13	5	4	7	11	9	19	13

In terms of permanent and temporal adjustments, the main intentions behind the different actions are heating the space or keeping themselves warm in Location C. In contrast, in Location A, actions are mainly taken to cool down the environment or keep themselves cool. Overall, individual actions to keep warm are more frequently reported than individual actions to keep cool, which is true of all locations. In contrast, environmental actions to keep cool are more frequently reported than environmental actions to keep warm, which applies to locations A and B, while there is no difference at Location C. In all locations, individual actions are more frequent than environmental ones. This difference more evident for keeping cool than for keeping warm strategies. These could be attributed to the fact that a) varying clothing is the easiest and available to households; moreover, it offers flexibility to temperature changes, and b) there is greater flexibility in adding clothing than there is in removing clothing.

Only 26% of the surveyed dwellings reported a permanent adjustment conducted at their place. Increase natural ventilation by operating external doors and windows is the primary action used by householders to keep cool. The available control options at dwellings are limited; portable heaters or fans are not a standard practice in the regions. Instead, actions at an individual level are the most accessible ones. Around 80% of the subjects reported taking at least one individual action to restore comfort, suggesting a high interaction with the available mechanisms.

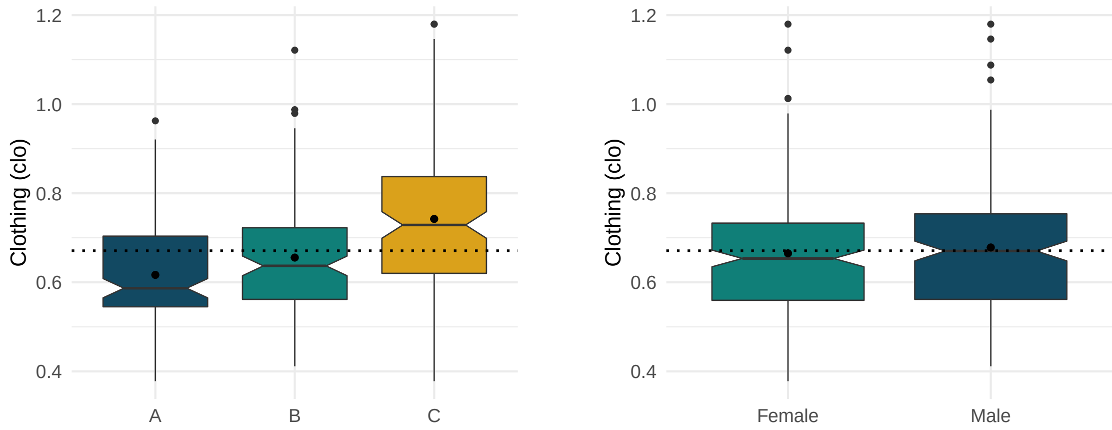
5.7 Clothing insulation

Clothing is not only one of the main inputs in the heat balance model but also one of the primary personal adjustments to discomfort to the prevailing environmental conditions. Table 5.14 summarise the mean and *sd* *Clo* by gender and location. Besides, the mean *Clo* for the whole sample not only increases with altitude, but the variance (*sd*) is broader from Location A (0.62 $\pm$0.11), to Location B (0.66 $\pm$0.13), and Location C (0.74 $\pm$0.16), where subjects are exposed to colder environments. Due to the narrow annual temperature variation, the reported clothing value varies little during the year. The estimated *Clo* are lower than those reported by Thapa et al. (2018c) from dwellings located at a similar altitude (2565m) (Thapa et al., 2018c).

Table 5.14: Mean and *sd* clothing insulation by gender and location

Location	n	Gender	mean	sd	G1	G2	p	sig
A	68	Female	0.59	0.10	A-Female	B-Female	0.003	**
	66	Male	0.65	0.12	B-Female	C-Female	0.003	**
B	70	Female	0.65	0.12	A-Female	C-Female	0.000	***
	62	Male	0.66	0.13	A-Male	B-Male	0.804	
C	74	Female	0.75	0.16	B-Female	C-Male	0.008	**
	58	Male	0.74	0.17	A-Male	C-Male	0.003	**
2565m (Thapa et al., 2018c)		Female	0.78	0.22				
		Male	0.97	0.33				

The *Clo* was compared by gender (Female and Male) and across locations (A, B and C), as seen in Figure 5.17. Results confirmed that the mean clothing insulation is significantly different across the three locations (p<0.05, Table E.1). In terms of gender, there is no evidence of a difference in *Clo* between male and female participants. Nevertheless, as observed in Figure 5.18 and Table 5.14, there is a significant difference in *Clo* when looking at the combined effect of gender and location. When comparing the clothing values between female and male subjects by location, one can notice the significant difference in *Clo* in Location A. In other words, at lower and warmer locations, one can expect a significant difference in the mean *Clo* between female and male participant. While at higher and cooler locations, there is no significant difference in the mean *Clo* due to gender.



(a) Location **(b)** Gender

Figure 5.17: Individual effect of clothing insulation by location and gender

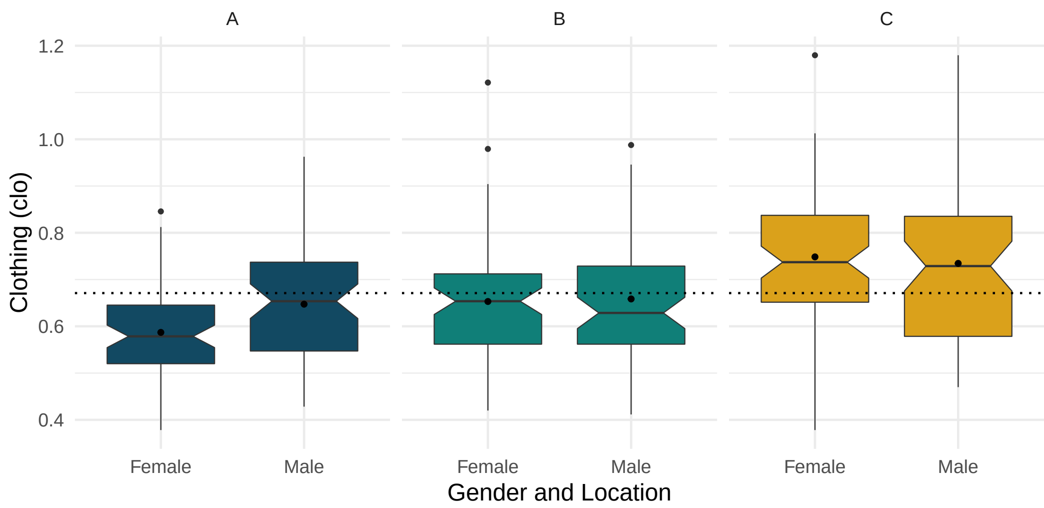


Figure 5.18: Combine effect of clothing insulation by location and gender

However, the *Clo* variation range is narrower in locations A and B, whereas the opposite is observed in Location C (Figure 5.18). This variation in *Clo* values indicates, to a certain degree, that modifications on clothing level are used in response to the changes in the indoor air temperature, as stated by Yang et al. (2013).

Subjects *Clo* was compared to both indoor and outdoor air temperature, Figure 5.19 and Figure 5.20, respectively. *Clo* level was found to be different between locations; however, one should consider that the outdoor temperature change according to the elevation. Generally, as denoted by the standard deviation, graphically presented in Figure 5.19, the *Clo* range is narrower at the lower locations A and B than Location C. That is a consistent pattern found along with the different operative temperature ranges, denoting that people respond to the change 'adaptively' as stated by Nicol and Humphreys (2010). Worth noting that clothing insulation gradually decreases at Location C when temperature increases from 18.0 °C to 20.0 °C. Once temperature reaches the range of 20.0 °C and 22.0 °C (temperature range recorded for the three locations), the mean *Clo* change not only due to temperature but also by location. For that temperature range (20.0 °C- 22.0 °C), the mean *Clo* and the variance range are broader for Location C subjects compared to those in Location A. The variation of clothing insulation could be associate with a higher adjustment opportunity (active subjects) to achieve comfort. In other words, clothing can be easily used as an individual adjustment to keep themselves warm than the other way around (keeping themselves cool).

When regressing *Clo* on the dry-bulb outdoor temperature at survey at 'time-t', one could notice the low (but significant) correlation between these variables suggesting a minor influence of outdoor conditions on the respondent's behaviour (Figure 5.20). The low regression slope and the increasing displacement in the y-axis indicate that participants' choice for lighter or heavier *Clo* is more a habitual response to overall climate than a response to the recent weather. Especially at Location A, but less so at Locations B and C. The implication is that people adopt a *Clo* level appropriate for most of the time and change it only slightly, making small changes in other ways (e.g. with shading or ventilation, or possibly by loosening or tightening clothing). Besides, the evaluation of *Clo* was extended for different times during the day, morning hours (8:00 and 12:59) and afternoon (13:00 and 18:00); still, no significant difference was found in *Clo* levels.

Clo is one of the primary mechanisms adopted to restores comfort; this is particularly true at dwellings where occupants have broader flexibility to adjust their clothing than places a particular dress code is required. Generally, people in warmer climate wear lighter clothes, while in a cold

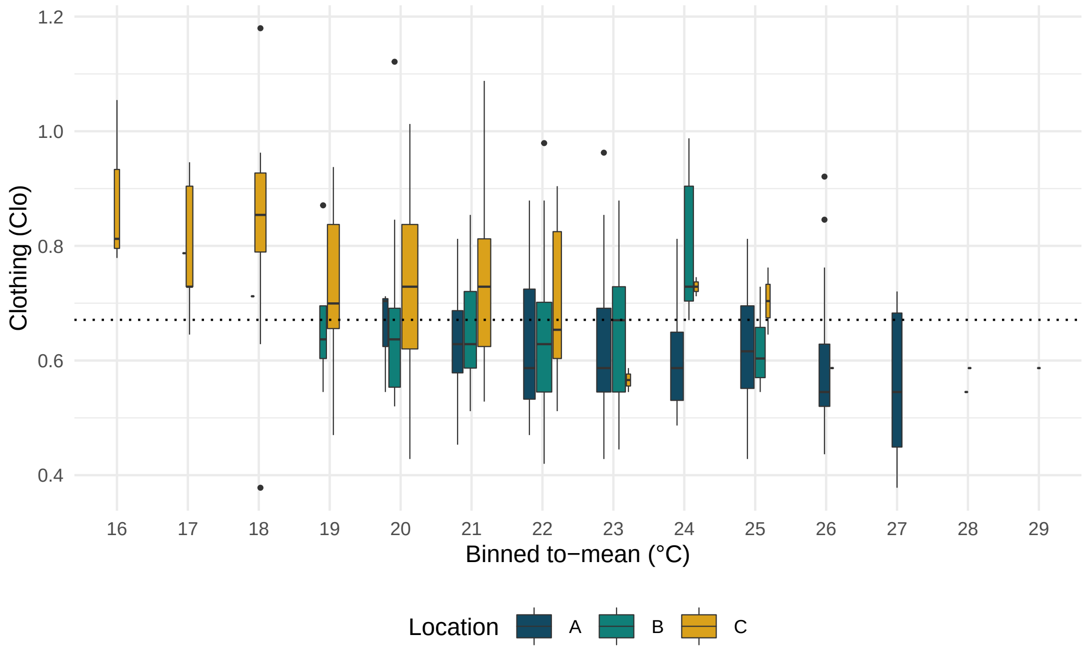


Figure 5.19: Clothing insulation variation according to indoor temperature (T_a) for each location

climate, people wear thicker clothes as an adaptive response to the prevailing conditions. However, one of the key findings from this section suggests that clothing in high-altitude locations is also a habitual response to the overall weather and not only a behavioural adjustment to the recent conditions. The findings are not conclusive, so further research is needed to explain if the observed habituation is due to the difference in altitude or due to the relatively stable annual temperature oscillation in the subtropics, or both. The second interesting finding is the robust evidence related to the interaction effect of gender and location to explain the difference between clothing levels. The results suggest that variation in gender clothing could be expected up to a certain threshold in temperature (i.e. 2400 m as in Location A). Due to the higher *Clo* levels required at higher and colder environments, no significant difference would likely be observed between genders.

5.8 Psychological

The questionnaire did not include any set of questions to explore the psychological differences between subjects. However, based on participants' comments during the survey, a couple of interpretation could be added to the analysis. Several participants commented on being used to the current environmental conditions (n=39). Some others mentioned that there is little or nothing they could do to improve the indoor conditions. Less than 8% of the participants reported being exposed to mechanically conditioned spaces, reflecting that heating or cooling systems are not

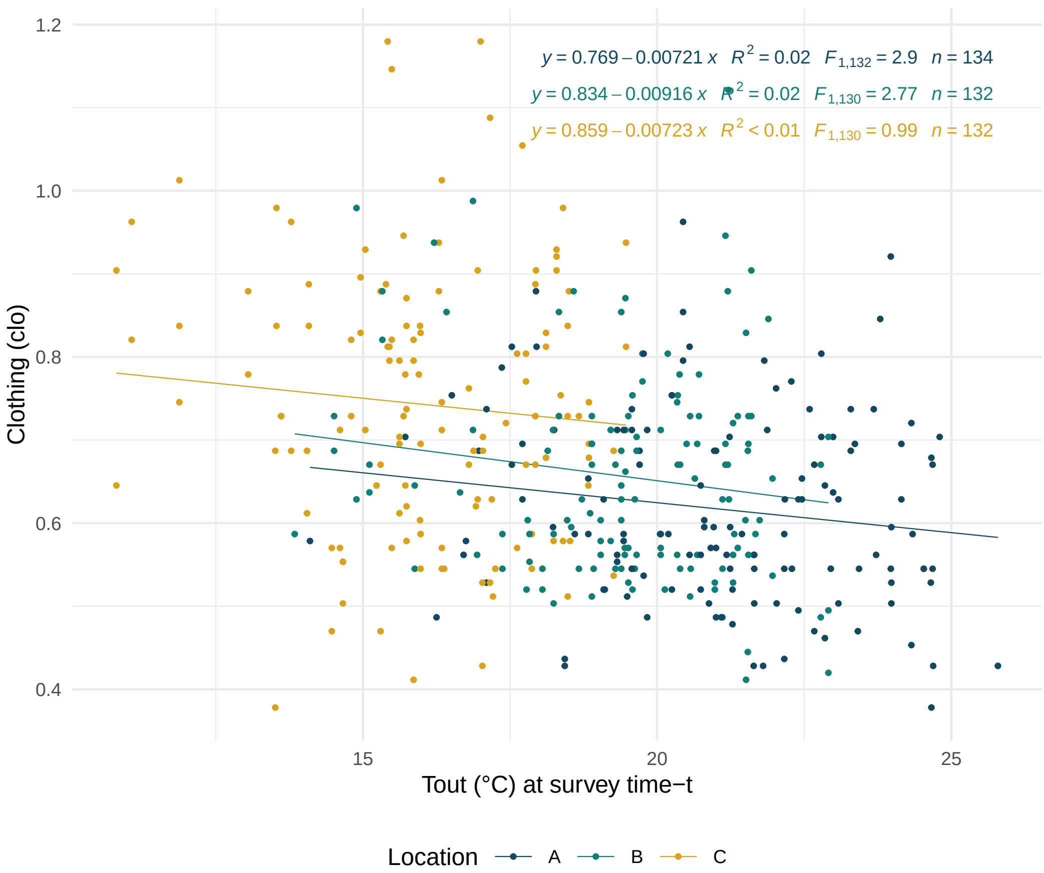


Figure 5.20: Regression of clothing insulation level on the outdoor dry-bulb temperature for each location

common in buildings in the Ecuadorian Andes. Thus, one can assume low expectations regarding the indoor environment and low perceived control over the environment.

Nevertheless, around 70% of the participants reported being overall satisfied with the indoor conditions. The higher overall satisfaction could be partly attributed to the fact thata) occupants that have lived in free-running dwellings, maybe even through generations, and b) lack of budget to conduct any modification, c) residents are more likely to be less severe when judging the indoor environment (Ole Fanger and Toftum, 2002).

5.9 Summary of the chapter

This chapter aimed to investigate the individual factors to be considered in the prediction of comfort for high-altitude residents exposed to diurnal temperature differences and hypobaric environments. Data from the thermal comfort survey were analysed to this effect, differentiating between demographics, adaptation, symptoms and discomfort at home, and behavioural adjustments. The observed results confirmed that people have adjusted to their current environment in different ways.

Firstly, 85% have lived in high-altitude regions under the same weather conditions over the last three consecutive years; hence, the studied sample is reasonably acclimatised to their environment. Moreover, only 30% are frequently exposed to a different climate or less than 5% to mechanically ventilated buildings. In terms of the mean operative temperature t_{o-mean}, the primary difference found does not rely on the mean temperature but the limits of acceptable temperature. While a narrow range was observed among short term residents, a broader one is acceptable for acclimated residents.

Secondly, the higher percentage of participants reporting symptoms related to poor indoor air quality belongs to the location with a warmer environment. Around 30% of the overall participants reported experiencing at least one building-related symptom. Half of the sample reported constant issues related to draught, temperature oscillation, and hot or cold environments. Besides, a similar percentage found it difficult to rest or to conduct households' tasks. These results seem contradictory to the high rate of participants showing satisfaction with their indoor environment. One might assume that either the participants were overall satisfied with the indoor conditions at the moment of the survey or more specific/different questions required to gain information on discomfort. However, the prevalence of symptoms and discomfort provides important results to evaluate further whether the study dwellings are currently of adequate quality.

Thirdly, improving the thermal environment is probably not the main reason for applying permanent modifications to dwellings. The few reported are intended to increase or control heat gain and solar radiation. Meanwhile, 80% of the participants reported exercising individual temporal responses to modify the indoor environment or regulate heat balance. It is worth noticing that most of the actions undertaken are at a personal level, mainly through clothing adjustments and food and drinks intake. A better understanding of the mechanism currently used by households to keep themselves cool or warm allows identifying the effectiveness of certain behavioural adjustments to minimise overheating or undercooling. A significant difference in clothing level across locations is not only an adaptation mean to the current conditions but a habituation response to the overall climate. Evidence shows that even at the same indoor temperature, a higher level of clothing insulation is observed in high-altitude residents.

Interestingly, no significant difference was observed in *Clo* when looking at gender. However, the combined effect of gender and altitude suggests that *Clo* difference could be observed in low altitude and warm weathers but not in high-altitude locations. Moreover, clothing insulation depends on participants preference as clothing patterns are not regulated by climate or social norms. Occupants will, over time, adjust their clothing so that they are comfortable at the mean indoor temperature in their dwellings; thus, the mean temperature causes the mean t_{comf}. However, occupants will control the room temperature to make themselves comfortable. As soon as the controls are available, they will adjust blinds and windows opening. In this case, t_{comf} causes the indoor temperature (Humphreys et al., 2016).

As previously explained, due to the complex interaction between individual and contextual factors affecting thermal perception, a differentiation between each particular factor's contribution in the prediction of thermal comfort remains a challenge. However, few insights on psychological adaption could be drawn from the results reported in this chapter. Based on the low percentage of people exposed to mechanically conditioned spaces, a low expectation could be expected. This statement is based on the high number of participants commenting that they considered that there is nothing they could do to improve the indoor environment. These occupants, who have been living in free-running buildings, maybe even through generations, are more likely to be less severe when judging the indoor environment (Ole Fanger and Toftum, 2002).

Chapter 4 and this chapter (Chapter 5) answer the first objective set out in this research to investigate the diverse thermal responses of subjects exposed to high-altitude environments in a subtropical highland climate. The effect of acclimatisation and/or adaptation is almost impossible or impractical to assess due to people's mobility. Moreover, due to the complex interaction between contextual (e.g. altitude) and individual (e.g. acclimatisation and/or adaptation) factors, the extent to which these factors affect thermal comfort predictions remains a challenge. Among others, the difficulty relies on eliminating the confounding effects of physiological (age and body mass) and psychological and contextual factors. Besides, unlike other studies, participants in this research could not be limited to the acclimatised ones due to regular exposure to different conditions due to their daily life activities and the geographical proximity to locations with different weather conditions.

Besides the physiological adaptations summarised in the literature, metabolic rate and clothing insulation are two of the primary adaption responses observed in long-term residents. For future studies, a better estimation of both parameters would be recommended in order to investigate the potential effect of these parameters as a mean of adaptation to high-altitude environment. As described in the literature and international standards, clothing insulation should be corrected to account for difference in the actual surface area of a clothed body and the effect of pressure (convective heat transfer). However, the collected data were not detailed enough to allow for this correction. Future research in the field is recommended in order to evaluate the reduction in convective hear transfer and consequent increase in dry insulation for the definition of clothing in high-altitude regions.

Chapter 6

Thermal comfort model for high-altitude locations

6.1 Overview

Several diversity factors affect the subjective assessment of the indoor thermal environment. In this research, one contextual (altitude) and two individual factors (adaptation factors and clothing) were found to affect the thermal environment's subjective assessment and comfort temperature. Moreover, residents in high-altitude regions have undergone several physiological adaptations to overcome the constant low-pressure stressor. Therefore, the need to develop a thermal comfort model aligned with residents' perception in the Ecuadorian Andes.

This chapter discussed the results obtained from predictions using current comfort standards and propose a novel high-altitude comfort algorithm. For this purpose, the observed thermal comfort votes and comfort temperatures (t_{comf}) were evaluated and compared with predicted values based on current comfort standards, by using the PMV model (ISO7730:2005) and adaptive comfort models (ASHRAE55:2017 and ISO15251:2007). On the one hand, the PMV model is recommended to estimate a comfortable environment for air conditioned spaces. On the other hand, the adaptive comfort model is intended for naturally ventilated spaces, particularly for warm weather, where increased ventilation could help restore comfort among occupants. In this chapter, both thermal comfort models were explored further to discuss the applicability in high-altitude regions. The comparison with current standards was conducted to identify the existing thermal comfort models' applicability in the Ecuadorian Highlands, which is one of the main aims of this research. The actual mean votes (AMV) were compared with the predicted mean vote (PMV) and the adjusted PMV for the reduced atmospheric pressure in high-altitude environments. In addition, the

t_{comf} was estimated from the collected data and compared with t_{comf} calculated from the regression equations in ASHRAE55:2017 and ISO15251:2007.

The high-altitude thermal comfort model was derived based on the observed data. The proposed thermal comfort model involved a sensible definition of the outdoor reference temperature and incorporation of diversity drivers as predictors in the t_{comf} equation. The chapter ends with a description of the high-altitude comfort model and the acceptable comfort limits for the subtropical highlands.

6.2 Methods

The methods below described the process used for calculating the PMV and adaptive comfort indexes. Both models' indexes were calculated using RStudio Team (2020) and 'comf' package (Schweiker et al., 2021). Moreover, the section described the procedure followed for deriving the high-altitude comfort model.

6.2.1 Estimation of the PMV and PPD

The PMV index is calculated from four environmental factors air temperature (t_{in}), mean radiant temperature (t_r), relative humidity (RH) and airspeed (v_a), and two personal variables clothing insulation (Clo) and metabolic rate (Met). t_{in}, RH and v_a were measured onsite. Calculated variables include t_r (Section 3.4.6), Clo (Section 5.2.4) and Met was estimated based on a weighted average of metabolic rates as explained in Section 3.4.3.2 (Table 3.4).

The PMV and PPD indexes for each set of participants data were calculated using a computer code based on the ISO 7730 standard (EN ISO, 2005; Schweiker et al., 2021). The PMV equation is applicable only when the variables are within the parameters' range stated in Table 6.1. Except for altitude, all the parameters were within the acceptable ranges emphasising the limited applicability of the PMV model in high-altitude locations. For this analysis, all locations were included to allow for comparison; only missing values (i.e. airspeed and MET) were filtered. Hence, a total of 386 rows of data from respondents out of 398 were processed for further analysis.

In order to account for the reduced atmospheric pressure in the studied locations compared to the standard reference value ($101.33kPa$), the convective heat transfer (h_c) was corrected as detailed in Section 3.4.6. The h_c was replaced for the corresponding parameter in the PMV code from the 'comf' package (parameter HL6 in the Rcode) (Schweiker et al., 2021). The PMV equation does not account for the effect of evaporation of sweat; hence, further corrections because of altitude in the PMV model were not considered [ASHRAE, 2017]. The model corrected to

Table 6.1: Constraints for the applicability of the PMV model

Parameter	Units	ASHRAE55:2017	ISO7730:2005 / ISO15251:2007
Activity	Met	1.0 to 2.0	0.8 to 4.0
Clothing	Clo	≤ 1.5	0.0 to 2.0
External temperature	°C	-	10 to 30
Radiant temperature	°C	-	10 to 40
Humidity	kg/kg	<0.012	-
Air speed	m/s	<0.2	0 to 1
Altitude (Atmospheric pressure)	m	Up to 3000	(0 to 2700)

the studied locations' atmospheric pressure will be referred to as adjusted PMV (adjPMV) and adjusted PPD (adjPPD), while the indices without correction as PMV and PPD. The comparison between indices was conducted to evaluate whether the PMV provide a good estimation of the actual mean vote (AMV). An acceptable deviation in the prediction of PMV is $\pm$ 0.25 standard deviation of the mean (Humphreys and Nicol, 2002). Besides, correlation analysis was run to determine the relationship between AMV and the PMV (PMV and adjPMV).

6.2.2 Estimation of comfort based on the adaptive comfort models

The international standards ASHRAE55:2017 and EN15251:2017 recommend using the adaptive model for design and thermal comfort assessment of free-running buildings. The prediction of t_{comf} is based on the linear regression of operative temperature on the outdoor temperature (ANSI/ASHRAE/IES, 2017). The operative temperature index was calculated as detailed in Section 3.4.6 and t_{comf} calculated by using the ASHRAE55:2017 (Equation 6.1) and ISO15251:2007 (Equation 6.2) comfort equations. The observed t_{comf} corresponded to the operative temperature when occupants voted within the three central categories in the ASHRAE scale (-1, 0, +1).

$$t_{comf} = 0.31 \cdot t_{pma_{out}} + 17.8 \tag{6.1}$$

$$t_{comf} = 0.33\theta_{rm} + 18.8 \tag{6.2}$$

The thermal comfort equations derived for international standards differ in their coefficients and outdoor reference temperature, as seen in Equation 6.1 and Equation 6.2. The prevailing mean outdoor temperature t_{pm} was calculated as in Equation 6.3. Where α is a constant ranging between 0 and 1 that corresponds to the speed at which the running mean responds to outdoor temperature changes. The recommended α values are between 0.6 and 0.9, corresponding to a fast or slow response to the outdoor temperature, respectively. ASHRAE55:2017 suggests an $\alpha = 0.90$ for tropical areas where day-to-day temperature dynamics are relatively minor and lower values for mid-latitude climates. In Equation 6.3, $t_{e(d-1)}$ represents the mean daily outdoor temperature for the previous day, $t_{e(d-2)}$ is the mean daily outdoor temperature for the day before and so on (ANSI/ASHRAE/IES, 2017).

$$t_{pm} = (1-\alpha)\cdot[t_{e(d-1)} + \alpha\cdot t_{e(d-2)} + \alpha^2\cdot t_{e(d-3)} + \alpha^3\cdot t_{e(d-4)} + \cdots] \quad (6.3)$$

ISO15251:2007 defined the outdoor reference temperature as the exponentially weighted running mean of the daily mean outdoor temperature (θ_{rm}), expressed in Equation 6.4 where α is a constant ranging from 0 to 1 and the value recommended by this standard is 0.8.

$$\theta_{rm} = (1-\alpha)\cdot[\theta_{ed-1} + \alpha\cdot\theta_{ed-2} + \alpha^2\cdot\theta_{ed-3}\cdots] \quad (6.4)$$

The adaptive comfort model is recommended for applicability when the parameters are within the ranges stated in Table 6.2. The limits of applicability would exclude Location C of the analysis due to lower prevailing outdoor conditions than the standards' limits.

Table 6.2: Constraints for the applicability of adaptive comfort model

Parameter	**Units**	**ASHRAE55:2017**	**ISO15251:2007**
Operation mode		free-running	free-running
Metabolic rate	*Met*	1.0 to 1.3	1.0 to 1.3
Clothing level	*Clo*	0.5 to 1.0*	0.5 to 1.0*
Outdoor temperature	°C	10 to 35	10 to 30 upper comfort limit 15 to 30 lower comfort limit

* Occupants are free to adapt their clothing within the stated range

6.2.3 Definition of thermal comfort model for the highlands

6.2.3.1 Derivation of neutral temperature

The neutral temperature (t_n) was calculated as described in Section 3.4.6 in Equation 3.7. Besides estimating the t_n from a weighted linear regression, t_{n-g} was estimated using a standard regression coefficient know as Griffiths ($b = 0.5$), as in Equation 6.5 (Humphreys et al., 2016).

$$t_{n-g} = t_o - TSV/b \quad (6.5)$$

6.2.3.2 Definition of the outdoor reference temperature

Several outdoor reference values have been used for the prediction of the comfort temperature. Initially, the outdoor reference temperature in the prediction of comfort temperature was defined as the monthly mean outdoor dry-bulb temperature (Humphreys and Nicol, 1998) and later substituted by the exponentially weighted running mean outdoor air temperature (θ_{rm}) (Humphreys and Nicol, 2002) and the prevailing mean outdoor temperature (t_{pm}) (ANSI/ASHRAE/IES, 2017). In this research, different outdoor reference temperature values were assessed to identify the predictor that allows a better estimation of t_{comf}. The evaluated outdoor reference predictors included the a) daily mean, b) t_{pm} and c) θ_{rm}. The daily mean was calculated as the 24-hour average (ISO Daily mean) and the simple average between the maximum and minimum (ASHRAE Daily mean). t_{pm} and θ_{rm} were calculated as described in Equation 6.3 and Equation 6.4. In both cases, the outdoor temperature value is sensible to the α value that corresponds to the degree of temperature response to the previous days. The t_{pm} was calculated for the previous 7, 15 and 30 days from now on, referred to as t_{pm07}, t_{pm15} and t_{pm30}. Besides, the running mean average temperature (θ_{rm}) was calculated to evaluate the effect of α values for a half-life of about a day (α= 0.45, $\theta_{rm0.45}$), half a week (α = 0.8, $\theta_{rm0.80}$) and 2-3 weeks (α = 0.96, $\theta_{rm0.96}$) (Nicol and Humphreys, 2010). A total of eight predictors of outdoor temperature were tested. The better predictors were identified as the ones with a higher coefficient of determination (r^2) and statistical significance (p) in the regression models.

6.2.3.3 Assessment of drivers of diversity in comfort temperature prediction

The results from the previous chapters suggest that altitude, level of adaptation and clothing are factors that might explain the diversity of thermal comfort in high-altitude locations. Thus, the need to evaluate the incorporation of these diversity factors in the prediction of comfort temperature. The regression models' fit was assessed based on the coefficient of determination (R^2 and $adj.R^2$) and the penalised-likelihood criterion for choosing the best predictors in regression. The penalised-likelihood Akaike Information Criterion (*AIC*) is used when false-negative findings would be more misleading than a false positive. In contrast, the Bayesian Information Criterion (*BIC*) is used when a false-positive result would be more misleading than a false negative. The lowest *AIC* and *BIC* values over the based model allowed to identify the pertinence of including or not an additional variable in the predictive model.

For assessing the factors altitude and clothing in the regression, the variables were binned. A total of 8 groups resulted from binning altitude above sea level into the closest hundreds (i.e.

2400m, 2500m until 3100m) and nine groups of clothing levels from 0.4 to 1.2. Before exploring the regressions that include altitude, the outdoor temperature and the barometric pressure, checked for multicollinearity, which refers to the condition when two or more of the explanatory variables are strongly correlated. Both variables are affected by elevation; thus, the effect of multicollinearity was tested through the Variance inflation factor (VIF).

6.2.3.4 Thermal comfort model for the Ecuadorian Highlands

The high-altitude comfort equation and comfort limits were derived for each location as a linear model. The comfort temperature (t_{comf}) based on the prevalent outdoor temperature is the operative temperature at which either the average person or the largest proportion of a group of people will be comfortable. t_{comf} was derived from Equation 6.6. The predictor is the outdoor reference temperature (t_{out}), b is the slope of the function proportional to the degree of adaptation to the different climatic conditions, and a is the y-intercept.

$$t_{comf} = a + b \cdot t_{out} \tag{6.6}$$

80% acceptable thermal sensations by solving the regression model for the mean thermal sensation (Equation 3.6) of ± 0.85 and 90% acceptable thermal sensations was determined similarly by solving the equation for mean thermal sensations of ± 0.5 (de Dear and Brager, 1998). Besides the standard comfort ranges, in this study ranges were also explored for each location and participants' level of acclimatisation. For this purpose, mean comfort temperature per study locations and acclimatisation levels were evaluated, and the regression models derived for each group.

6.3 Heat balance model

The mean values and standard deviation of the predicted mean vote (PMV) and the predicted percentage of dissatisfaction (PPD) based on the standard calculation and the adjusted model are summarised in Table 6.3. The adjusted PMV (adjPMV) for the whole dataset is -0.66, and the actual mean vote (AMV) is -0.18. The adjPMV overestimates the thermal sensation by almost half-point in the ASHRAE scale (-0.48). Overall, the PMV and the adjPMV overestimate the thermal sensation of participants in the three locations. However, as expected, the difference between the observed votes and the predicted mean votes is smaller for the model adjusted due to atmospheric pressure difference. On average, the standard deviation (sd) from the mean is around one-point in the ASHRAE scale (∼0.98), which suggest that the votes variance is within the three central categories (-1 to +1). The average magnitude of the errors, between the AMV, and the PMV and adjPMV, were calculated through the mean absolute error (MAE). An average error of 0.49, or a half-point in the thermal sensation scale, was observed between the adjPMV and AMV. The defined comfort categories for PMV in ISO7730:2005 (EN ISO, 2005) are ±0.2 (Category A), ±0.5 (Category B) and ±0.7 (Category C) for comfort categories. Therefore, a half-point error in the thermal sensation scale would compromise between a comfortable or uncomfortable environment.

Table 6.3: Descriptive statistics of PMV and PPD - Mean and Standard deviation by location

	AMV		**adjPMV**		**PMV**		**adjPPD**	**PPD**	**adjPMV-AMV**	**PMV-AMV**
Location	**mean**	*sd*	**mean**	*sd*	**mean**	*sd*	**mean**	**mean**	**MAE**	**MAE**
A	0.06	0.86	-0.34	0.94	-0.60	1.03	22.9	27.8	-0.41	-0.66
B	-0.11	1.06	-0.73	0.96	-1.07	1.07	27.5	36.0	-0.62	-0.96
C	-0.51	0.94	-0.94	0.98	-1.36	1.12	31.5	41.9	-0.43	-0.86
All	-0.18	0.98	-0.66	0.99	-1.00	1.12	27.2	35.0	-0.49	-0.82

By regressing AMV on the AdjPMV, one can notice the existing relationship between the observed and the predicted votes (Figure 6.1). Overall, the higher the altitude, the lower the association between the TSV and PMV. A low but significant relationship was observed at Location A and B. In contrast, a non-significant and extremely poor association was found between adjPMV and AMV at Location C (Table 6.4). The adjPMV model only explained a low range of the effects in the AMV, 16% (Location A), 7% (Location B) and 1% (Location C). Moreover, the votes' distribution highlights the non-linear relationship, especially when AdjPMV is below -1. The subjects' thermal response below zero (neutral point) does not always follow a linear pattern. Instead, even when adjPMV predicts cold sensation, participants reported a neutral vote. These neutral votes could either imply that subjects are generally satisfied with colder conditions or a combination of adaptation and coping mechanisms.

Table 6.4: Regression coefficients of thermal sensation votes (TSV) on the adjusted predicted mean vote (adjPMV) and predicted mean vote (PMV)

	adjPMV model					**PMV model**				
Location	**Intercept**	**adjPMV**	r^2	p	**sig**	**Intercept**	**PMV**	r^2	p	**sig**
A	0.19	0.37	0.16	0.000	***	0.26	0.33	0.16	0.000	***
B	0.10	0.29	0.07	0.003	**	0.16	0.25	0.06	0.004	**
C	-0.42	0.09	0.01	0.294		-0.40	0.08	0.01	0.303	
All	0.02	0.29	0.09	0.000	***	0.08	0.26	0.08	0.000	***

The equations' intercept indicates that when PMV equal to zero, the estimated AMV are 0.37

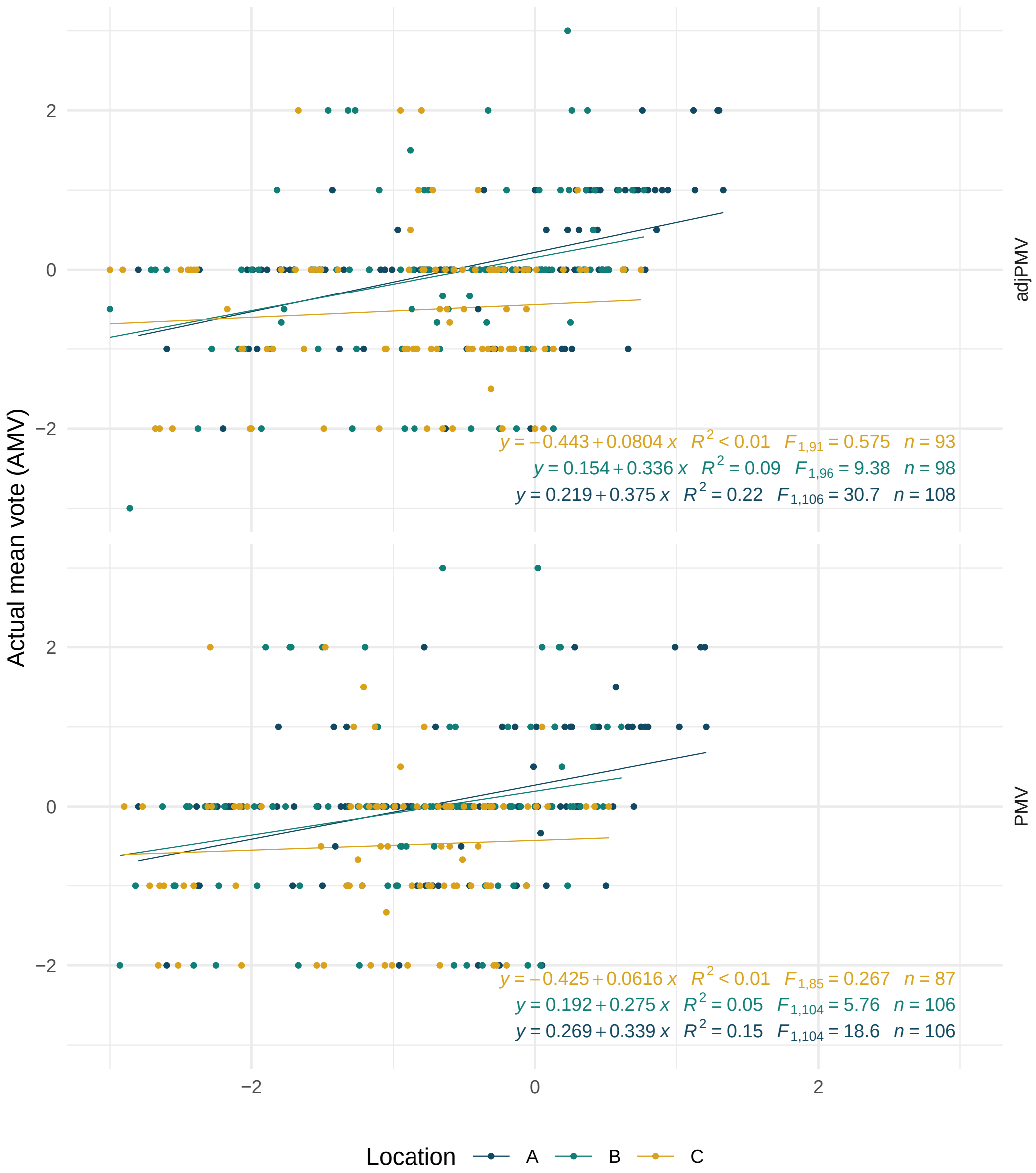


Figure 6.1: Regression of thermal sensation vote (TSV) on the adjusted predicted mean vote (adjPMV)

(Location A), 0.29 (Location B) and -0.42 (Location C). At locations A and B, the PMV underestimate the occupants' thermal sensation and predicts a cooler sensation. Contrary to Location C, where the PMV overestimates occupants' thermal sensation predicting warmer sensation than the reported ones. Moreover, Location C's nearly-flat slope suggests that occupants' thermal sensation does not change as the adjPMV. One of the limitations of predicting comfort using adjPMV in high-altitude environments is the altitude constraint (up to 3000m) stated in Table 6.1. Besides, the poor estimations of the adjPMV could be attributed to the non-steady conditions in free-running dwellings or the analyse of individuals' responses instead of a group mean thermal sensation for the same environment.

6.4 Adaptive thermal comfort models

The obtained adaptive comfort equations and the equations from ASHRAE55:2017 and ISO15251:2007 standards are plotted in Figure 6.2. The regression in the figure considered t_{comf} and the outdoor temperature at the moment of the survey. The linear equation's slope steepness indicates the t_{comf} change rate with the corresponding outdoor temperature change.

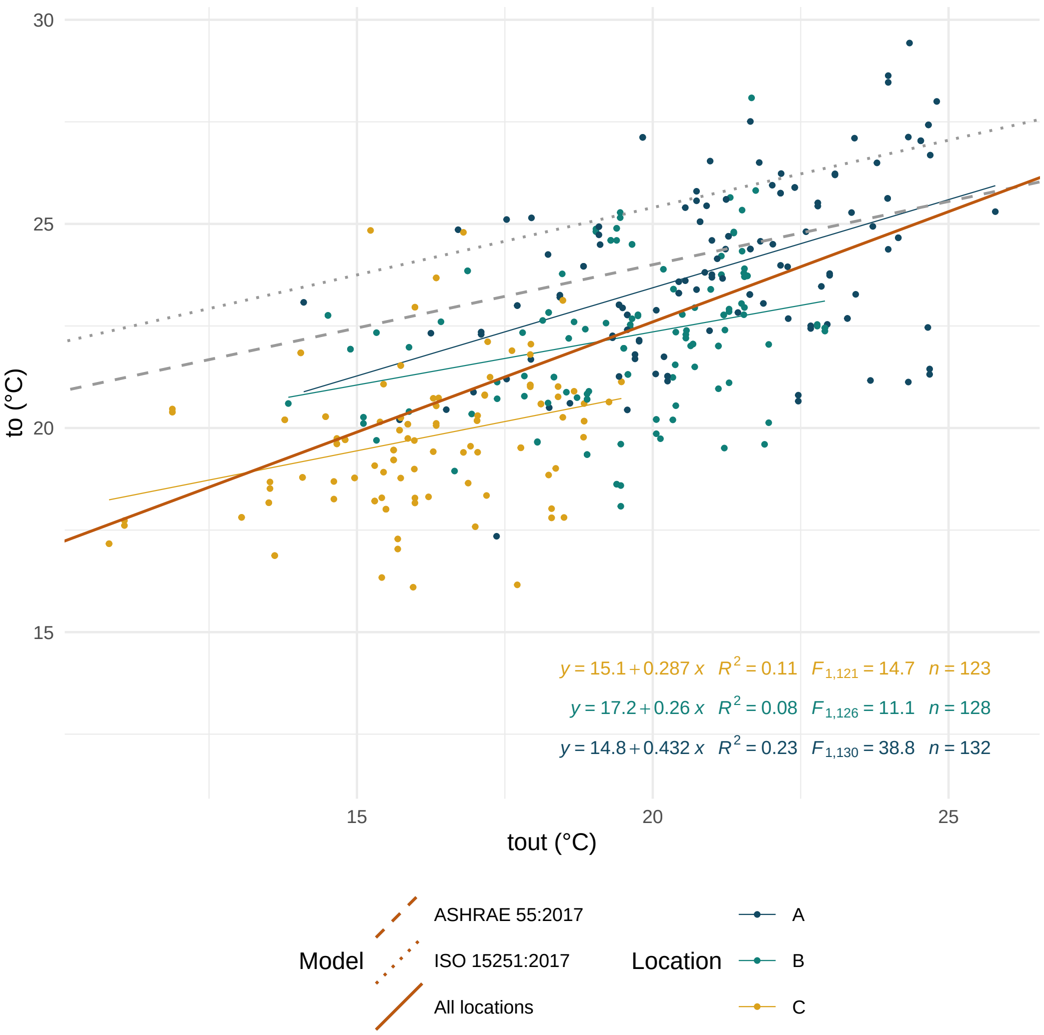


Figure 6.2: Regression of indoor operative temperature on the outdoor dry bulb temperature at survey 'time-t' and the adaptive thermal equations from standards by location

The slope of the equations for the study locations decreases as altitude increases. Hence, Location A's steeper slope implies a higher impact of t_{out} in the prediction of t_{comf} than the effect of t_{out} in the prediction of t_{comf} in Location C. In addition, the less steeped slope also denotes the small change in the comfort temperature despite changes in t_{out}. A single comfort equation for geographic proximity locations would facilitate the definition of comfort requirements in local buildings standards in practical terms. However, the comfort equation's steeper slope derived for the three locations' combined dataset (t_{comf} = 11.8 + 0.54 · t_{out}) predicts higher t_{comf} in Location A and lower t_{comf} in Location C.

Table 6.5 summarised the mean and standard deviation of t_{comf} for both predicted with ASHRAE55:2017 and ISO15251:2007 comfort equation, and the observed data. Despite the different equations' coefficients, the adaptive comfort equations in ASHRAE55:2017 and ISO15251:2007 yield similar optimal comfort temperatures (Carlucci et al., 2018). Besides, the range of t_{comf} is relatively narrow when compared to the one obtained from the observed values (*sd* in Table 6.5). However, the observed comfort temperature is significantly different from the predicted ones (ASHRAE55:2017, 15251:2017). On the one hand, in Location A, the observed mean t_{comf} (23.0 °C) is higher than the predicted from the standards, highlighting the fact that residents at a lower location are more sensitive to cold, and hence, preferred warmer environment. On the other hand, the observed mean comfort temperature in Location C (19.8 °C) is lower than the one predicted by the standards, denoting residents' adaptation to a cooler environment. Furthermore, the consistent decrease of t_{comf} as altitude increase indicates, to a certain extent, the acclimatisation of residents in the highlands. About one-degree difference was observed on the mean t_{comf} across locations, whereas the major difference lies in the mean's t_{comf} deviation. The four-degree (±2.0 °C) t_{comf} range observed in Location A decreased to 3.6 °C (±1.8 °C) in Location B and is 3.4 °C in Location C. Hence, the higher the altitude above sea level, the lower the t_{comf} and the narrower the range of acceptability. By location, the correlation between the predicted comfort temperature, ASHRAE55:2017 and ISO15251:2007, and the observed t_{comf} is not only small but non-significant in some cases. A higher correlation between t_{comf} predicted and t_{comf} observed was obtained from the observed data, as denoted by the r^2 and p in Table 6.5. The t_{comf} for the whole dataset (22.0 °C) yielded similar results to the ones predicted by the standards ASHRAE55:2017 (22.6 °C) and ISO15251:2007 (22.7 °C). The correlation between the observed and predicted t_{comf} are robust and statistically significant; nevertheless, the predicted t_{comf} are similar but inaccurate for the study locations.

The range of mean and standard deviation of the different outdoor reference temperatures are also described in Table 6.5. As detailed in Table 6.2, ISO15251:2007 lower limits of application of the θ_{rm} are 15.0 °C $<\theta_{rm}<$30.0 °C, and for the ASHRAE55:2017, the lower limit of applicability

Table 6.5: Predicted and observed t_{comf} (mean and *sd*), reference t_{out} (mean and *sd*), and correlations between observed and predicted t_{comf}

		t_{comf}		t_{out}		Cor obs vs pre		
Model	**Location**	**mean**	*sd*	**mean**	*sd*	r^2	p	**sig**
ASHRAE55:2017	A	23.3	0.09	17.8	0.29	0.002	0.656	
	B	22.7	0.09	16.0	0.30	0.030	0.077	
	C	22.0	0.18	13.5	0.58	0.069	0.008	**
	All	22.7	0.55	15.8	1.79	0.452	0.000	***
ISO15251:2007	A	23.1	0.11	13.0	0.33	0.066	0.005	**
	B	22.7	0.09	11.7	0.27	0.015	0.218	
	C	22.1	0.16	10.0	0.49	0.064	0.011	*
	All	22.6	0.42	11.6	1.29	0.464	0.000	***
Observed	A	23.8	2.00	21.1	2.34	0.196	0.000	***
	B	22.1	1.81	19.5	1.97	0.059	0.013	*
	C	19.8	1.72	16.1	1.93	0.089	0.003	**
	All	22.0	2.47	18.9	2.95	0.414	0.000	***

Significance *, **, *** at 90%, 95%, and 99% respectively

is t_{pm} is 10.0 °C. Based on these limits of applicability, the adaptive comfort standards could be applied to predict t_{comf} in locations A and B. Still, neither models should be used to predict comfort temperature in Location C.

6.5 Thermal comfort conditions for the highlands in Ecuador

Current thermal comfort models, both the PMV and adaptive comfort model, failed to predict comfort temperature for the study high-altitude locations. In practice, neither the PMV nor the adaptive model should be used in high-altitude regions. The PMV standard should not be applied to locations above 3000m, and the adaptive standards should not be used when the outdoor temperature is below 15.0 °C (ISO15251:2007) or 10.0 °C (ASHRAE55:2017). Furthermore, findings in Chapter 4 and Chapter 5 highlights the importance of contextualising thermal comfort criteria according to socio-cultural and climate factors, as does the strong evidence from existing research. Thus, an evident need to develop a high-altitude comfort model for the Ecuadorian Highlands aligned with local inhabitants' requirements and perception.

6.5.1 Prediction of the neutral temperature

The subjects' sensitivity to any change in the indoor temperature is expressed in terms of scale units of subjective warmth per degree of room temperature (Humphreys et al., 2016). Figure 6.3 shows the regression between the ASHRAE seven point-scale (TSV) and the operative temperature (t_o) for each subject by location and the combined data set. Besides the counts of observations at each bin' are also represented by the size of the dots. The regression of comfort votes on t_o explains between 15 and 25% (r^2) of the observed variance. Besides, as in most fieldwork data, TSV votes are widely scattered, revealing the diversity of thermal perception votes. On the one hand, the range of neutral temperature (TSV = 0 on the y-axis) lies between 17.0 °C and 28.0 °C. On the other hand, for the same given temperature range, one can observe TSV votes distributed between warm (+2) and cool (-2) sensation.

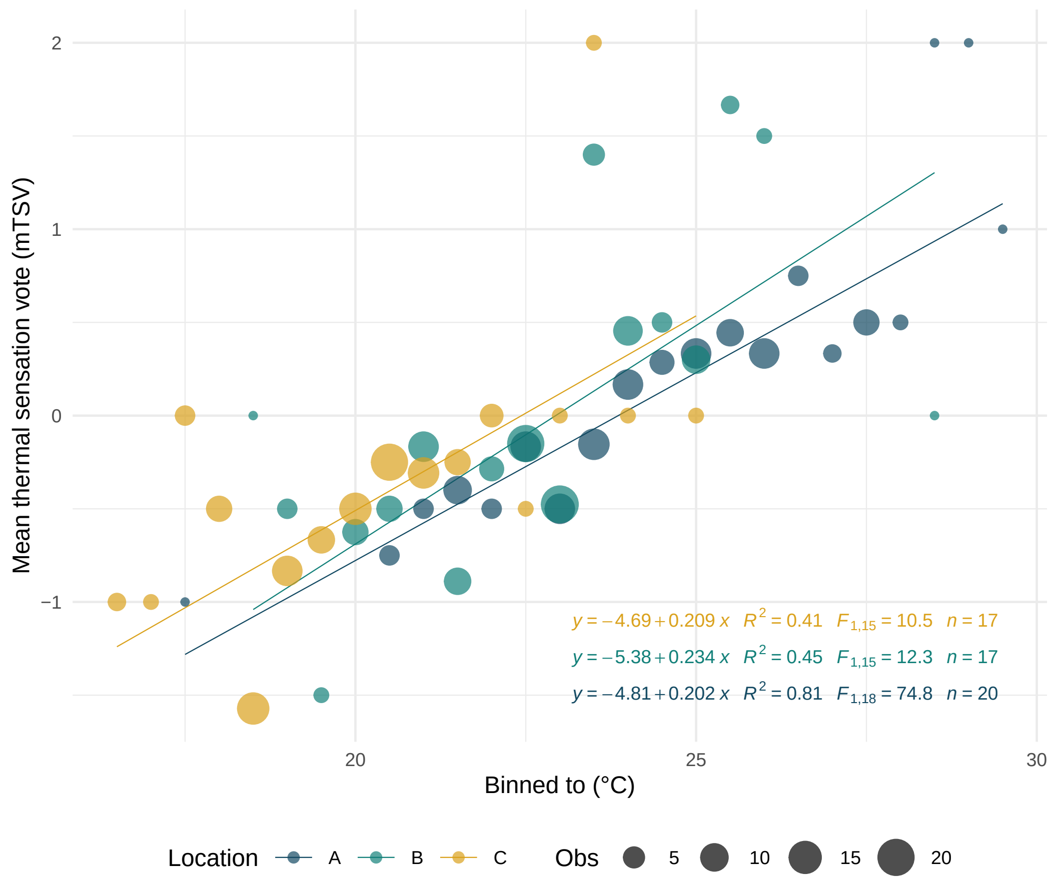


Figure 6.3: Thermal sensitivity of subjects to the operative temperature (t_o) for 0.5 °C bin by location

The slopes of the equations in Figure 6.3 reveal occupants' thermal sensitivity (unit/ °C). In this research, the coefficient's difference is not significant; however, the regression lines are consistently shifted from the lower to the higher locations. That suggests that at the same t_o, the mean thermal sensation of participants at the higher location will be slightly higher than the mean thermal sensation of participants at the lower location. Although occupants' thermal sensitivity is not significantly different across locations, calculating t_n from the whole dataset (t_n = 23.1 °C) would overestimate occupants' sensation in the higher locations.

The neutral temperatures for each location, obtained from the regression equations of mTSV on the binned t_o are 23.8 °C (Location A), 23.0 °C (Location B), and 22.4 °C (Location C), summarised in Table 6.6. A decreasing t_n observed as the altitude above sea level increases has been reported in previous studies. t_n in Location A and B are similar to those reported at 2600m, at Solukhumbu - Nepal (21.1 °C) (Rijal et al., 2010). In contrast, the t_n derived for the higher location is lower than ones reported at locations even at higher altitudes. For instance, in Lhasa (3650m), the neutral temperature for summer is 23.2 °C (Yang et al., 2013).

Table 6.6: Regression coefficient of thermal sensation vote (TSV) on operative temperature (t_o)

Location	n	Intercept	t_o	r.square	conf.low	conf.high	p.value	Sig	t_n	t_n 80%	t_n 90%
A	20	-4.81	0.202	0.81	0.153	0.251	0.000	***	23.8	± 4.2	± 2.5
B	17	-5.38	0.234	0.45	0.092	0.377	0.003	**	23.0	± 3.6	± 2.1
C	17	-4.69	0.209	0.41	0.071	0.346	0.006	**	22.4	± 4.1	± 2.4

Significance *, **, *** at 90%, 95%, and 99% respectively

Despite the regressions obtained from mTSV on the binned t_o are statistically significant, the small data sets might be insufficient to produce a reliable regression for estimating the neutral temperature (Humphreys et al., 2013). Thus, t_n was also calculated using Griffiths' standard coefficient (0.5) and two other coefficients (0.33 and 0.40) regressed against the outdoor temperature at survey 'time-t' (t_{out}). Besides, a coefficient of 0.25 was used for testing a coefficient similar to the one obtained from the observed data (t_o in Table 6.6) and 0.33 and 0.4 based on recommendations from the literature (Nicol and Humphreys, 2010).

Table 6.7: Comfort temperature predicted by Griffiths' method for different coefficients (b)

Criteria	b	n obs	mean	sd	min	max	r.squared	p.value	Sig
Tn	0.25	381	23.0	3.55	11	34.0	0.008	0.006	**
	0.33	381	22.8	2.88	12.9	32.1	0.074	0.000	***
	0.40	381	22.7	2.58	14.0	31.0	0.134	0.000	***
	0.50	381	22.6	2.38	15.0	30.0	0.214	0.000	***

n obs: Excluding NA, values not available due to lack of data in operative temperature
Significance *, **, *** at 90%, 95%, and 99% respectively

The mean t_n predicted using coefficients from 0.25 to 0.5 ranges from 22.6-23.0 °C across all locations. The mean neutral temperature predicted with Griffiths regression coefficient produced conservative estimations. Hence, underestimating or overestimating the responses of participants in the studied locations. Therefore, the t_n in this research was estimated from the regression of the mean TSV on binned t_o (Table 6.6).

6.5.2 Defining the outdoor reference temperature

The outdoor temperature reference value that better predict comfort temperature in high-altitude regions are summarised in Table 6.8. The best estimations of t_{comf} were obtained using the daily mean outdoor air temperature (ASHRAE Daily mean and ISO Daily mean) as predictors, as well as $\theta_{rm0.45}$ ($\alpha = 0.45$).

Table 6.8: Comfort temperature equation using different predictors for outdoor temperature

t_{out} **Criteria**	**Location**	**Intercept**	t_{out}	r^2	p	**sig**
Observed	A	14.8	0.43	0.23	0.000	***
air temperature	B	17.2	0.26	0.08	0.001	**
	C	15.1	0.29	0.11	0.000	***
	All	11.1	0.58	0.45	0.000	***
ASHRAE	A	10.7	0.75	0.07	0.003	**
Daily mean	B	-6.3	1.76	0.21	0.000	***
	C	8.9	0.81	0.17	0.000	***
	All	6.7	0.97	0.52	0.000	***
ISO	A	12.0	0.72	0.08	0.001	***
Daily mean	B	-0.7	1.52	0.22	0.000	***
	C	10.6	0.73	0.14	0.000	***
	All	7.1	1.01	0.52	0.000	***
ISO Trm45	A	6.2	1.08	0.11	0.000	***
($\theta_{rm0.45}$)	B	-1.4	1.59	0.11	0.000	***
	C	9.2	0.83	0.13	0.000	***
	All	5.8	1.10	0.51	0.000	***

Significance *, **, *** at 90%, 95%, and 99% respectively

The smaller the α value, the smaller the previous day temperature's effect in calculating the outdoor reference temperature. A lower and significant correlation was observed when estimating the t_{comf} following the comfort standards recommendations. For instance, using an α value of 0.9 (ASHRAE55:2017) suggested for climates where the day-to-day variation is relative minor (i.e. humid tropics), or an α value of 0.8 (ISO15251:2007), which corresponds to a half-life of approximately 3.5 days (Nicol and Humphreys, 2010).

6.5.3 Sensitivity of comfort temperature to drivers of diversity

The drivers of diversity observed to affect the subjective votes and t_{comf} were altitude (Chapter 4), adaptation factors and clothing (Chapter 5). The differences in t_{comf} were observed not only in the mean values but in t_{comf} variance (Table 6.9). The variance of t_{comf} is significantly different across the levels and adaptation factors (birthplace, acclimatisation, weather exposure, HVAC exposure and overall), as previously discussed in Section 5.4. Besides, the mean t_{comf} changes significantly between 2400m - 2500m (23.7 °C – 21.4 °C), 2500m - 2600m (22.2 °C - 21.4 °C) and 2700m – 2800m (22.7 °C – 20.6 °C). A pairwise comparison above 2800m was not possible due to the small number of observations. However, the difference in the mean t_{comf} is significant when comparing the three-study location. Furthermore, the regression of comfort temperature on altitude indicates that the comfort temperature will decrease on average 0.54 °C per 100m increase in altitude (t_{comf} = 36.5 – 0.0054 x altitude). Clothing insulation partly explains the differences in comfort temperature. The mean t_{comf} varies significantly between 0.6 to 0.7 *Clo* (22.5 – 21.9) and 0.7 to 0.8 *Clo* (21.9 °C – 21.0 °C).

Table 6.9: Variance and means differences of comfort temperature across levels of diversity factors

		Variance difference		**means difference**		**means pairwise comparison**					
						Low - Mid		**Low - High**		**Mid - High**	
Factor	**df**	*p*	**sig**	*p*	**sig**	*p*	**sig**	*p*	**sig**	*p*	**sig**
a) Birthplace	2	0.000	***	0.001	***	0.027	*	0.816		0.020	*
b) Acclimatisation	2	0.016	*	0.014	*	NE		0.135		NE	
c) Weather exposure	2	0.004	**	0.000	***	0.003	**	0.060		0.108	
d) HVAC exposure	1	0.000	***	0.007	**	NE		NE		0.937	
e) Overall	2	0.000	***	0.834		-		-		-	
						2400 - 2500		**2500 - 2600**		**2700 - 2800**	
Altitude	7	0.008	**	0.000	***	0.051	*	0.043	*	0.000	***
						0.6 - 0.7		**0.7 - 0.8**			
Clothing	8	0.315		0.000	***	0.032	*	0.007	**		

Significance *, **, *** at 90%, 95%, and 99% respectively
NE - Not enough observations

Besides analysing the differences in t_{comf} means and variance, a multiple regression was conducted using t_{out} and the different adaptation levels for each diversity factor as predictors (Table 6.10). A base model predicting t_{comf} from t_{out} was used as a reference value to assess the multiple linear regressions. Slightly higher coefficient of determination (R^2) were observed whenever including one or two additional predictors in the model. However, an $adj.R^2$ lower than R^2 for all the combinations suggested no improvement in the prediction of t_{comf}. Furthermore, the AIC and BIC values are not lower than those obtained for the base model. In conclusion, none of the diversity factors assessed would enhance comfort temperature prediction either due to data structure (variables format or the number of levels) or sufficient observations.

The adaptive model assumes, as embedded in the model, the capacity of self-regulation and the physiological, behavioural, and psychological responses of a person. Thus, regardless of the difference in t_{comf} observed between some of the diversity factors, there is not enough evidence to consider the comfort algorithm's inclusion. What is clear is that the t_{comf} is different for various

Table 6.10: Summary of multiple regression analysis or t_{comf} on t_{out} including factors of diversity

Factor	df	R^2	$adj.r^2$	p	AIC	BIC	df.residual
t_{out} (Base model)	2	0.514	0.512	0.000	1278	1289	322
a) Birthplace + t_{out}	4	0.520	0.515	0.000	1274	1293	319
b) Acclimatisation + t_{out}	4	0.514	0.510	0.000	1278	1297	319
c) Weather exposure + t_{out}	4	0.517	0.513	0.000	1280	1298	320
d) HVAC exposure + t_{out}	3	0.514	0.511	0.000	1280	1295	321
e) Overall + t_{out}	4	0.515	0.510	0.000	1281	1300	320
a + b + c + d + t_{out}	9	0.526	0.513	0.000	1277	1315	313
Altitude + t_{out}	3	0.519	0.516	0.000	1276	1291	321
Altitude	2	0.451	0.449	0.000	1317	1329	322
Clothing	10	0.533	0.520	0.000	1281	1322	314

Significance *, **, *** at 90%, 95%, and 99% respectively

groups, both in mean and variance. However, the multiple regressions results do not demonstrate a significant improvement in the prediction of t_{comf} by including an additional predictor. Furthermore, the regression predicts the mean but does not define the range and, therefore, does not capture the observed variance. In some cases, the subgroups of analysis are too small to test or yield more meaningful results.

6.5.4 High-altitude thermal comfort model

The observed mean comfort temperature and variance across diversity factors are statistically significant. However, as expected, the inclusion of these factors in a multiple linear regression does not improve the mean t_{comf} prediction because the main difference relies on t_{comf} variance across groups. In order to assess the effect of acclimatisation, t_{comf} were compared between acclimatised subjects (Overall adaptation = High) and non-acclimatised ones (Overall adaptation = Low-Mid), removing in this way other sources of the variance than the intrinsic context. Table 6.11 summarises the mean and standard deviation of t_{comf} per acclimatisation group. The mean t_{comf} slightly varies between acclimatisation groups; however, these differences are not statistically significant ($p>0.05$). Meanwhile, the standard deviation from the mean t_{comf} differs across study locations and acclimatisation. The higher the altitude, the narrower the range of acceptable comfort temperature. At lower altitudes, not only t_{comf} would be higher (Location A t_{comf} = 23.8 °C), but participants would accept a broader range of comfortable temperatures (±2.0 °C); whereas at altitudes above 3000 t_{comf} is lower (Location C t_{comf}= 19.8 °C), and the comfort range is narrow (±1.7 °C).

Similarly, the range of comfortable temperature for non-acclimatised subjects is narrower

Table 6.11: Comfort temperature (mean and *sd*) by acclimatisation groups

	All participants			Acclimatised			Non-acclimatised		
Location	**count**	**mean**	*sd*	**count**	**mean**	*sd*	**count**	**mean**	*sd*
A	119	23.8	2.00	80	24.0	2.12	39	23.4	1.69
B	105	22.1	1.81	72	22.0	1.88	33	22.2	1.66
C	100	19.8	1.72	74	19.8	1.76	26	20.1	1.61
All	324	22.0	2.47	226	22.0	2.61	98	22.1	2.12

(∼3.3 °C) than the average comfort range for acclimatised subjects (∼3.8 °C). The key conclusion is that the mean t_{comf} varies significantly across locations, as the altitude increases the t_{comf} decreases. Moreover, different comfort ranges should be considered for acclimatised and non-acclimatised subjects. Acclimatised subjects are more permissive, to a certain extent, to a broader range of comfort temperatures than non-acclimatised inhabitants. In practical terms, these distinctions between altitude and acclimatisation must not always be possible; thus, a general regression equation obtained from the entire dataset was also derived.

Based on the above mentioned, the proposed thermal comfort equations are different for each study location. Moreover, the recommended comfort limits also differ according to occupants' acclimatisation and study location. The linear comfort equations for the Ecuadorian Highlands resulted from regressing the comfort temperature (t_{comf}) over the outdoor air temperature (24-hours average outdoor air temperature) are plotted in Figure 6.4.

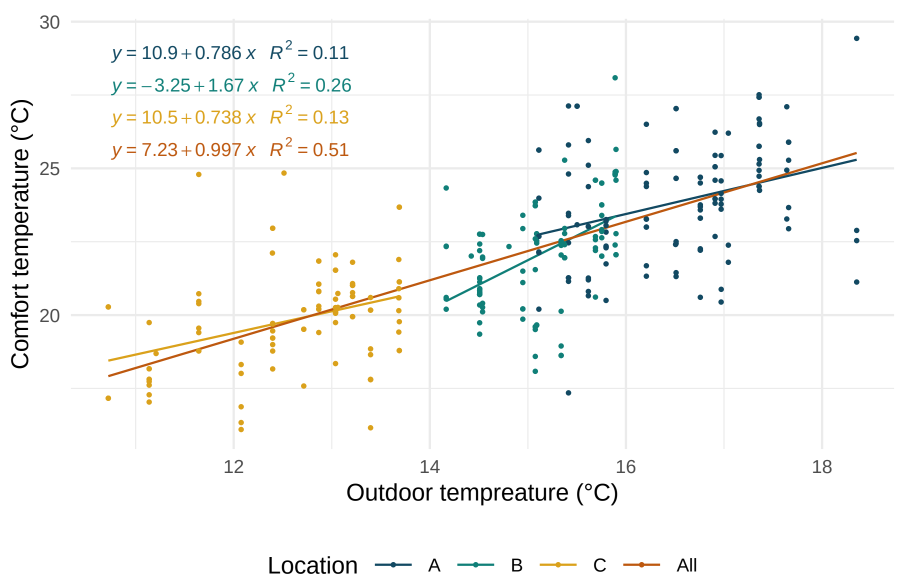


Figure 6.4: High-altitude thermal comfort models for each study location, comfort temperature on t_{out} (Daily mean dry bulb outdoor temperature $t_{out-iso}$)

The regression coefficient (b) denotes the rate of change of the mean t_{comf} given a one-unit change in the outdoor air temperature. On the one hand, a steeper slope is observed in Location B (b = 1.67), Table 6.12 indicating the higher impact of t_{out} in t_{comf}, which in turns suggests a higher adaptation of users to the prevailing environmental conditions. On the other hand, similar lower slopes were observed for Location A (b = 0.786) and Location C (b = 0.738). The lower effect of the t_{out} in the prediction of t_{comf} might also suggest a wider use of behavioural adjustments. Overall, the models' slopes are higher when compared to the ones of the international standards (ASHRAE55:2017 b = 0.31, ISO15251:2007 b = 0.33). However, when comparing the slope with the ones of the few equations derived from studies in high-altitude regions (Eastern India), the values are similar (Thapa et al., 2018c). The differences in the intercept and regression coefficient from one study to another could be attributed to variations in cultural background, climate, and other contextual factors, as reported in the literature (Section 2.3.4). The steeper slope suggests that residents in the Ecuadorian Highlands are better adapted to their environment than that suggested by ASHRAE55:2017, ISO15251:2007 or other models.

Table 6.12: Thermal comfort model regression coefficients for acclimatisation groups

Location	**Adaptation**	**Intercept**	t_{out}	r^2	p	**sig**
A	All participants	10.9	0.786	0.108	0.000	***
A	Acclimatised	8.2	0.958	0.156	0.000	***
A	Non-acclimatised	21.0	0.148	0.004	0.694	
B	All participants	-3.3	1.670	0.255	0.000	***
B	Acclimatised	-5.4	1.820	0.278	0.000	***
B	Non-acclimatised	1.7	1.360	0.204	0.008	**
C	All participants	10.5	0.738	0.135	0.000	***
C	Acclimatised	11.0	0.701	0.120	0.003	**
C	Non-acclimatised	7.5	0.967	0.175	0.033	*
All	All participants	7.2	0.997	0.514	0.000	***
All	Acclimatised	7.0	1.020	0.538	0.000	***
All	Non-acclimatised	8.1	0.934	0.434	0.000	***

Significance *, **, *** at 90%, 95%, and 99% respectively

Besides, regressions for the different acclimatisation groups were also derived and summarised in Table 6.12. A slightly higher r^2 was observed for acclimatised participants' models in locations A and B. Another interesting fact observed is the regression coefficients close to the unit, which implies that the rate of change of t_{comf} would correspond to the daily mean outdoor temperature plus the value of the intercept (~7.0 °C) for a t_{out} range between 10.7 °C and 18.4 °C.

The prescribed acceptable comfort ranges in international standards are defined as acceptability ranges and comfort categories. For instance, the ASHRAE55:2017 standard defines comfort limits for 80% (±3.5 °C) and 90% (±2.5 °C) of acceptability. Whereas the three recommended comfort categories in ISO15251:2007, according to the buildings' requirements, are category I (±2.0 °C), II (±3.0 °C), and III (±4.0 °C). Figure 6.5 illustrates an 80% (±3.5 °C) and 90% (±2.5 °C) range of acceptability for the Ecuadorian Highlands. As discussed previously, the acceptability limits of comfort for the Ecuadorian Highlands should be adjusted to the altitude and residents' acclimatisation. Thus, Location A residents' recommended range is ±2.0 °C and a narrow range of ±1.7 °C for residents in Location C, based on standard deviation in Table 6.11. Assuming that participants voting in the ASHRAE scale's central categories feel comfortable, the range of acceptability is around 85% of the surveyed residents. The comfort equation for all locations and the corresponding 80% (±3.5 °C) and 90% (±2.5 °C) limits of acceptability are plotted in Figure 6.5.

6.6 Summary of the chapter

The chapter aimed to identify a thermal comfort model that better represents residents' thermal sensation in Ecuador's high-altitude regions. For this purpose, the data from the study locations were compared against predictions from the PMV model and adaptive comfort models from cur-

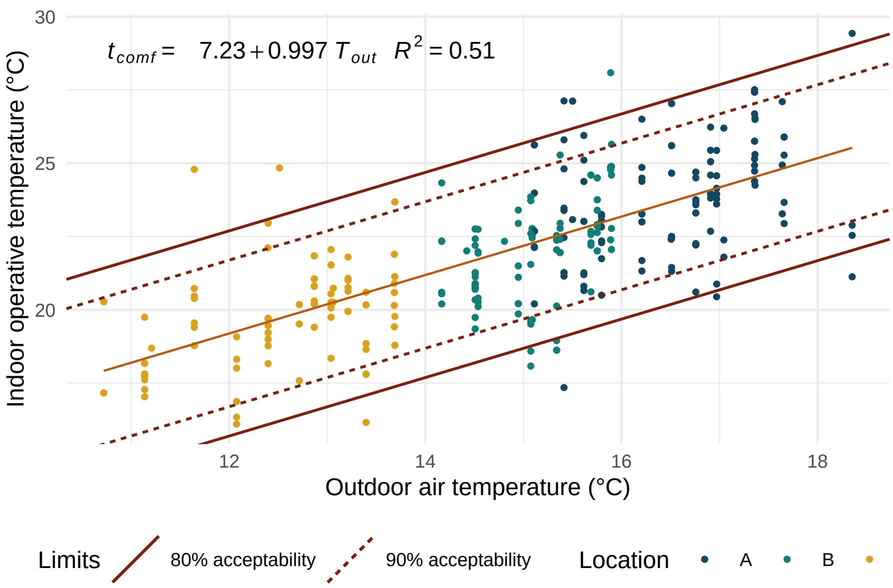


Figure 6.5: Thermal comfort range for 80% and 90% of acceptability for the high-altitude comfort model, comfort temperature on t_{out} (Daily mean dry bulb outdoor temperature $t_{out-iso}$)

rent international standards. Key findings in this chapter are that none international standard accurately predicts comfort in the study locations. The disparity increases with altitude from Location A to Location C. However, the predictions from adaptive comfort models are more accurate than the PMV model for this sample. Another interesting fact is that neither international standards should be used to predict comfort in Location C. The applicability of PMV standard limits to locations below 3000m above sea level and adaptive comfort standards are not recommended for prevailing outdoor temperatures below 10.0 °C or 15.0 °C.

In the research, altitude was accounted for in the calculation of thermal comfort indexes when replacing the convective heat transfer coefficients in the computation of PMV calculation and operative temperature. On the one hand, the mean error between the PMV and AMV is around half-point in the thermal sensation scales. On the other hand, the adaptive comfort models' predictions are only similar when considering the whole dataset. However, when looking into the predicted values by locations, a significant difference is observed in t_{comf} mean and standard deviation, particularly at Location C. As reported in the literature, regardless of the use of different equations to calculate the outdoor reference temperature and the use of different adaptive comfort equations, the predicted values yield similar optimal adaptive comfort temperatures.

The high-altitude thermal comfort model for the Ecuadorian Highlands resulted from the regression of the comfort temperature and the 24-hour mean outdoor air temperature. Although the international standards recommend a mean running temperature, a better prediction was obtained when using daily mean values. As discussed in the previous chapters, several diversity drivers might explain the scattered observed votes. For this purpose, diversity factors such as altitude, adaptation factors and clothing levels were assessed as predictors of t_{comf}. Multiple linear regressions for each factor of diversity as well as combined effects were evaluated. Although the observed t_{comf} mean and variance across some factors are statistically significant, results suggest that incorporating another variable does not improve the prediction of t_{comf}. That is not surprising, as the main difference observed relies on the variance of t_{comf} rather than the mean. Grouping participants into acclimatised and non-acclimatised further extended the overall adaptation analyses. Overall, a slightly higher correlation (r^2 = 0.54) was obtained when regressing t_{comf} on t_{out} for acclimatised subjects, as well as a higher t_{comf}. Nevertheless, the main finding relies on the consistent and significant difference in t_{comf} variance between acclimatised and non-acclimatised subjects. Acceptability comfort limits for acclimatised subjects are $\pm$2.1 °C (Location A) and $\pm$3.4 °C (Location C), whereas the range for non-acclimatised residents is $\sim \pm$1.7 °C regardless of the study location.

The derived thermal high-altitude thermal comfort model explains 51% of the observed comfort temperature for the whole data set. t_{comf} decreases consistently as the altitude above sea level increases; the same occurs with acceptability's comfort limits. Due to the significant t_{comf} difference across locations, three comfort equations have been derived for Location A (Equation 6.7), Location B (Equation 6.8) and Location C (Equation 6.9), where t_{out} is 24-hour average outdoor air temperature.

$$t_{comf_A} = 0.786 \cdot t_{out} + 10.9 \qquad (Comfort\ limits \pm 2.0\ °C) \tag{6.7}$$

$$t_{comf_B} = 1.670 \cdot t_{out} - 3.3 \qquad (Comfort\ limits \pm 1.8\ °C) \tag{6.8}$$

$$t_{comf_C} = 0.738 \cdot t_{out} + 10.5 \qquad (Comfort\ limits \pm 1.7\ °C) \tag{6.9}$$

Moreover, different acceptability comfort limits are recommended to account for altitude and acclimatisation differences. The different comfort equations and comfort limits are not of practical use; thus, a single equation and comfort limits have also been derived for practical implications.

Chapter 7

Archetypes thermal performance assessment

7.1 Overview

This chapter reports results and findings regarding the applicability assessment of the high-altitude thermal comfort model in the thermal performance evaluation of dwellings located in the Ecuadorian Highlands. The developed high-altitude comfort model, presented in the Chapter 6, is used to evaluate the thermal performance of the existing housing stock's and hypothetical dwellings in compliance with the new - Ecuadorian construction standard (NEC11) (Norma Ecuatoriana de la Construcción, 2018). On the one hand, the thermal evaluation aims to estimate the likelihood of occupants' satisfaction with the indoor conditions in high-altitude regions. On the other hand, the evaluation of hypothetical archetypes' thermal environment in compliance with NEC11 aims to assess a modified envelope's potential repercussion in the indoor thermal performance. A total of nine dwellings, three dwellings at each location, corresponding to each of the three identified dwellings archetypes. The research approach combined dwellings monitoring and building performance simulation (BPS) to estimate housing archetypes' annual indoor thermal performance in the studied region.

Building performance simulation (BPS) is widely applied for energy and environmental performance assessments. However, uncertainty emerges during the transition from reality to simulation, undermining the model's precision and outcomes validity. In order to tackle the inherent inaccuracy of the building model, uncertainty and sensitivity analysis of the input data was conducted and serve as the base of the iterative calibration process. Each of the four steps of the proposed methodological approach is thoroughly described and justified. Once the simulation models reached the standard criteria for calibration, the last step was to quantify the number of hours of comfort and discomfort for both the existing archetypes and the hypothetical archetypes in compliance with NEC11. The comfort limits of acceptability were defined based on thermal comfort models from current international standards (ASHRAE55:2017 and ISO15251:2007) and the proposed high-altitude thermal comfort model.

7.2 Review of calibration methods and limitations

Building energy simulation (BES) models are mainly used to inform architectural design, HVAC design and operation, retrofit analysis, building optimisation, among others. However, there is an increasing concern about the model's credibility due to significant discrepancies between simulated and measured data. A BES model is regarded as 'good' if it accurately predicts performance while accounting for most complex physical interactions and interrelations. Due to the assumptions used in defining the inputs, some variability in simulation outputs is expected. However, the scale of the discrepancy is often too wide to be acceptable and inadvertently reduces confidence levels in the results of simulation calculations (de Wilde, 2019).

The leading causes of discrepancies between predicted and actual performance stem from a) uncertainty arising from assumptions due to lack of information; b) model inadequacy associated with oversimplification of physical building elements; c) minimum feedback regarding actual use and operation of buildings; d) scenario uncertainty related to operating conditions such as occupancy or weather (Chong et al., 2021).

The process of using BES models and 'tuning' the various inputs to the simulation computer program to match the observed variable with that predicted one is known as calibration. The primary reasons for calibrating a BES model are that it allows more reliable performance outputs identification and increases confidence in the monitoring and verification process (Reddy, 2005; Sun and Reddy, 2011). The calibration process has been considered an art as it used to rely on user knowledge and plenty of trial and error. However, nowadays increased proliferation of devices and sensors makes high-resolution data readily available and computerised processes have increased the automated calibration approaches. The existing literature provides an overview of the current calibration methodologies. However, BES models' calibration remains a challenge due to the lack of clear guidelines and best practices. Besides, there is little documentation detailing models' inputs and outputs, calibration procedures, simulation reproducibility and the criteria for evaluating calibration performance.

BES calibration methodologies from the literature have been classified into four classes a) calibration based on manual, iterative, and pragmatic intervention; b) calibration based on a suite of comparative graphical displays; c) calibration based on analytical procedures; d) calibration based on analytical or mathematical methods (Reddy, 2005; Sun and Reddy, 2011). Coakley et al. (2014) further include Bayesian calibration and meta-modelling. Finding from recent overviews highlight the growing evidence towards the implementation of automated approaches. The main analytical techniques used to assist or complete the calibration process include but are not limited to sensitivity analysis (SA), high-resolution data, uncertainty quantification (UQ), and building audits (Chong et al., 2021).

Global methods, such as global sensitivity analysis, allow an overall view of the importance of different inputs while considering their interaction (Macdonald, 2002). This approach is commonly used to calibrate building envelope (material properties and infiltration rate), internal gains and schedules (occupant, lighting, and equipment power density). Electricity and dry-bulb temperature are among the outputs most frequently used to calibrate BES models at building scale. BES calibration using dry-bulb temperature is often carried out during free-floating periods to investigate the relative changes in building envelope performance (Chong et al., 2021).

Interestingly, several studies used measured indoor environmental conditions as inputs to the model to obtain a better-calibrated model at the zone level. For instance, the indoor air temperature has been used to get more accurate predictions of zone airflow rates (Mihai and Zmeureanu, 2017), thermostat setpoint and variable air volume (VAV) box minimum/maximum airflow, respectively (Yin et al., 2016), and thermophysical parameters of the building envelope and infiltration rate (Li et al., 2018). Li et al. (2018) assess the building thermal performance disregarding the effect of occupant's behaviour by considering a period where occupants sleep, hence assuming no variation on internal loads and ventilation.

Despite the growing number of calibration studies, the different approaches used are difficult to replicate due to the complexity of BES models and poorly reported calibration parameters, observed inputs and outputs, and set of assumptions made during pre and post-processing.

This research proposes a simplified methodology for calibrating free-running dwellings with high-resolution data. The calibration objective is hourly indoor air temperature; therefore, the most influential parameters selected for fine-tuning are building envelope and infiltration rate. The primary calibration objective is to minimise the hourly indoor temperature for thermal comfort assessment. Therefore, the minimum and maximum indoor air temperature values must be accurately predicted to quantify discomfort in the studied dwellings. In contrast to most of the methodologies in the literature that describes processes mainly focused on average values. Besides, the novel calibration methodology describes a suitable process for defining a suitable and valid range of inputs values when no data regarding materials thermal properties are available. The process focuses on quantifying and ordering by importance, the strength and relevance of the inputs in determining the value of the output through sensitivity analysis. Due to the characteristic of sensitivity analysis, the model calibration does not offer a unique and best solution but rather a small set plausible solution.

7.3 Methods

This chapter's methods centred on quantifying the comfort and discomfort of hours in the selected dwellings archetypes. For this purpose, audit and monitoring of dwellings archetypes were used for creating and validating simulation models. An inverse uncertainty approach was used for the calibration that estimates the unknown variables using mathematical models and measured data (Tian et al., 2018). The thermal environment of the archetypes was evaluated through dynamic thermal simulation (annual assessment). Archetypes annual thermal performance was then compared against the comfort criteria from international standards and the high-altitude thermal comfort model.

This research proposes a simplified methodology for the calibration of free-running dwelling models based on hourly indoor air temperature. The four-steps proposed in the calibration and simulation methodology are a) data processing, b) evidence-based modelling, c) sensitivity analysis, and d) iterative model improvement. Data from nine single-story dwellings with different building constructions, medium-exposed thermal mass and uninsulated lightweight construction, were used as test buildings. The simulation data include indoor environmental data (air temperature and relative humidity), weather data from a local meteorological network and building survey data (drawings and occupancy patterns). The simulation process initiates by processing the dwellings data for preliminary simulation model creation and building uncertainty qualification.

Sensitivity and uncertainty analyses were used to identify the building elements that significantly impact dwellings thermal performance. The outputs of the sensitivity analysis, list of influential parameters and variation range, were used as the parameter to be adjusted in the calibration process. The model's accuracy was validated by comparing measured and simulated indoor temperature by the mean Bias Error (MBE) and the Coefficient of Variation of the RMSE (CvRMSE) based on the limits of ASHRAE 14 (Ramos-Ruiz and Fernández-Bandera, 2017). Estimations of indoor environmental data obtained from the calibrated models were used to assess the thermal performance (hours of comfort and discomfort) of archetypes based on the adaptive models from international comfort standards and the developed high-altitude comfort model (Chapter 6).

7.3.1 Definition of archetypes input parameters and sampling

On-site data collection and references from the literature were considered as input parameters for the modelling. The input data for archetypes models were categorised as follows a) site and dwellings physical characteristics, b) envelope and materials properties, c) and internal gains and occupant behaviour. Some relevant simulation data were collected from the dwellings' audit and indoor environmental monitoring. However, detailed and accurate data for all the simulation input parameters cannot be collected by simple observation or are unknown. The data source and uncertainty rank due to detail and accuracy are presented in Table 7.1.

Table 7.1: Sources of uncertainty in dwellings thermal performance analysis

	Category	Model factors	Descriptor	Data source	Source rank*
a)	Site and dwellings physical characteristics	Weather data	Known	Local weather station	2
		Latitude and longitude	Known	Collected on-site	2
		Altitude		Collected on-site	2
		Exposure index	Known	Collected on-site	2
		Ground temperature	Uncertain	Calculated EPlus	2
		Orientation	Known	Collected on-site	2
		Geometry and layout	Known	Collected on-site	2
b)	Envelope and materials properties	Thickness	Uncertain	Collected on-site/± variation	3
		Density	Uncertain	Guidelines and standards	4
		Specific heat capacity	Uncertain	Guidelines and standards	4
		U-value (Glazing)	Uncertain	Lack of information	5
		Infiltration rate	Uncertain	Guidelines and standards	4
		Ventilation rate	Uncertain	Lack of information	5
c)	Internal gains and occupant behaviour	Occupancy	Uncertain	Assumption**	5
		Equipment	Uncertain	Assumption**	5
		Lighting	Uncertain	Assumption**	5
		Windows operation	Uncertain	Assumption**	5

* The smaller the number of source rank, the higher the data reliability
** Assumption based on the data from dwellings' audit

Once the uncertainty factors were identified, the following step consisted of defining the magnitude of uncertainty of the input data based on the range of variation and the probability distribution. According to the purpose of this research, the probability distribution for all factors was regarded as uniform distributions as there are no reference values neither from local guidelines nor as-built information. The definition for the range of variations for each dwelling factor are described below:

a. Site and dwellings physical characteristics:

Archetypes geometry was well defined based on the measurements taken during the fieldwork (Appendix F.1). In the same way, the archetypes' geographical location, altitude and orientation were retrieved from satellite views and they are summarised in Table 7.2.

Table 7.2: Archetypes' geographical location, altitude, orientation and occupancy

Arch	Rooms [n]	Surface [m^2]	Volume [m^3]	Occupancy Male [n]	Female [n]	Children [n]	Lat	Lon	Site Elevation [m]	North [°]
A1	4	65.8	168.6	1	2	1	-0.1	-78.5	2340	315
A2	2	20.6	41.2	0	1	1	-0.1	-78.5	2340	315
A3	6	64.5	138.6	4	0	0	-0.2	-78.4	2347	140
B1	2	38.9	83.3	0	0	0	-0.1	-78.4	2608	325
B2	4	66.5	153.0	1	1	2	-0.1	-78.4	2751	355
B3	3	32.0	77.4	1	2	1	-0.1	-78.4	2732	350
C1	2	33.7	67.4	0	0	0	-0.4	-78.6	3056	280
C2	4	57.9	132.9	0	1	1	-0.4	-78.6	3030	310
C3	5	47.5	114.0	1	3	2	-0.4	-78.6	3105	295

The site factors such as weather data, location, altitude, and exposure index, were well-known based on the fieldwork's information, except for the ground temperature. For this case, the ground initial temperature profiles were produced through an iterative process using the Slab program in EnergyPlus (U.S. Department of Energy, 2019). The iterative process concluded when a maximum difference of 0.1 °C is achieved between the last two floor's simulated values (ASHRAE, 2009). Once defined the baseline values, a range of ±1.0 °C was used for the minimum and maximum iteration values for the sensitivity analysis.

b. Envelope and materials properties:

There is a lack of reference and technical specifications of local constructions materials. Therefore thermal properties and U-values for all the archetypes are uncertain parameters in this research. The sensitivity analysis was carried out for all the dwellings' materials, including thermal properties such as conductivity, density and specific heat. The range of factors was defined by calculating the minimum and maximum values from a list of related materials retrieved from relevant literature (Clarke et al., 1990; Gallardo et al., 2016a; Goodhew and Griffiths, 2005; Hall and Allinson, 2009; Macdonald, 2002; Yan et al., 2005), guidelines (Butcher and Craig, 2015) and international standards (EN ISO, 2007b), as detailed in Appendix F.3. The definition of thickness of the different construction layers was based on on-site measurements. The sensibility of materials' thickness was also tested within a range of ±10% from the base value (Appendix F.2). Although infiltration and ventilation rates are dynamic and widely dependent on weather conditions, both were simulated as fixed air change per hour (ACH) to keep the model simple. The infiltration and ventilation rate distribution were set as uniform within an acceptable range for poorly airtight constructions.

c. Internal gains and occupant behaviour:

The effect of occupants' behaviour does not have a significant effect on the thermal performance of non-insulted and poorly airtight constructions (Wagner et al., 2018), as is further explained in Figure 7.5. Internal gains due to occupancy, equipment, lighting and windows/doors openings were defined based on the data collected from the archetypes' audit. Differences on metabolic rate accounted for gender and age (men = 1, women = 0.85 and children = 0.75). According to local data, energy consumption for an average dwelling in the Ecuadorian Highlands was estimated as 128.4 kWh per month (INEC, 2006). The corresponding gains were assigned to each dwelling based on the building survey observations and house appliances annotated gains.

7.3.2 Definition of hypothetical archetypes based on NEC11

In order to assess the potential repercussion in the indoor thermal performance of stringent insulation requirement incorporated in the - Ecuadorian construction standard (NEC11) (Norma Ecuatoriana de la Construcción, 2018), hypothetical archetypes' models were elaborated. These hypothetical archetypes' were modelled using the same input data, geometry and orientation as the original archetypes but changing the thermal transmittance (U-value) as established and summarised in Table 7.3.

Table 7.3: U-Factors for the thermal envelope components for free-running habitable dwellings located in Quito (Climate zone 3)

	Thermal envelope components				
Opaque elements	**Roof**	**Walls**	**Floors**	**Opaque doors**	**Windows**
U-Value [W/(m^{2}K)]	2.9	2.35	3.2	2.6	5.78

7.3.3 Sensitivity analysis (SA)

Building thermal performance results from the complex and nonlinear interaction of hundreds of factors. Sensitivity analysis identifies a few critical factors among the hundreds in each model to improve the calibration process's efficiency. As stated in the previous section, most of the model's input parameters were uncertain; thus, to identify parameters that highly contribute to the models' uncertainty, Morris's screening method for sensitivity analysis was used. This analysis allowed quantifying and ranking the factors in order of importance and identifying the elements that are largely responsible for models' accuracy within an acceptable range (Saltelli et al., 2008).

The next step consists on the sample generation from the model inputs distributions. The model input sampling used a one step-at-a-time method (OAT) that allows a low simulation cost $r*(p+1)$, where p is the number of factors and r are the trajectories ($r = 10$) (Iooss et al., 2021). The sensitivity of the factors was determined by calculating the mean (μ) and standard deviation (σ) of the factor elementary effect by the following Equations 7.1, 7.2 and 7.3:

$$d_i(j) = \frac{f(X^{ij}) - f(X^i)}{\triangle} = \frac{f(X_1, ..., X_{i-1}, X_i + \triangle, X_{i+1}, ..., X_n) - f(X_1, ..., X_n)}{\triangle} \tag{7.1}$$

$$\mu_i = \frac{1}{r} \sum_{j=1}^{r} d_i(j) \tag{7.2}$$

$$\sigma_i = \sqrt{\frac{1}{r-1} \sum_{j=1}^{r} \left[d_i(j) - \frac{1}{r-1} \sum_{j=1}^{r} d_i(j) \right]^2} \tag{7.3}$$

Where $d_i(j)$ stands for the elementary effect of the group j sample with the $i^t h$ parameter, $f(X)$ correspond to the output value when the input parameter is X, $\triangle$ stands for the disturbance variable and r is the number of repetitions.

The sensitivity μ and σ allowed determining which input factors could be considered to have effects that are a) negligible, b) linear and additive, or c) nonlinear or involved in the interaction with other factors. Both metrics should be used simultaneously to avoid cancellation due to the effects of different signs. An alternative sensitivity measure is μ^* criteria that overcome cancellation and is an effective total index substitute (Saltelli et al., 2008). μ measures the overall effect of the model performance factor; a greater μ^* value implies a more sensitive parameter. In contrast, σ calculates the effect of the factor as a whole, whether nonlinear or because of correlations with other factors. The outcome of this analysis is to identify the most influential variables (high sensitivity) in the indoor thermal environment.

7.3.4 Thermals simulation and calibration process

The calibration process for thermal performance simulation focused on tuning the most influencing variables in the archetypes model while keeping the non-influential as defined for the base model. As explained previously, for this research, the parameters considered include the physical properties of the envelope thermal insulation (conductivity, density, specif heat and thickness), ground temperature and airflow rates (ventilation and infiltration).

The archetypes were simulated in DesignBuilder, and further modifications were directly applied in EnergyPlus. The geometry, orientation, and usage profiles (occupancy, lighting and appliances) were defined as described in Section 7.3.1. Iterative simulations for the sensitivity analysis and calibration process were done in jEPlus, and the data processing and analysis using RStudio.

The initial reference value for the calibration process was defined from a base model as an initial reference. The inputs for all the base models' uncertain factors correspond to the mean value calculated from the list defined as the range of variation in Appendix F.3 and Appendix F.4. The conducted calibration process focused on matching the simulation output to measured data is known as data-driven or inverse modelling (Coakley et al., 2014). The outputs from the simulations (indoor air temperature) were compared against monitored data. An acceptable level of accuracy of archetypes simulation output was achieved when the normalised Mean Bias Error (NMBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) comply with the criteria for hourly intervals as defined in Table 7.4 (Ramos-Ruiz and Fernández-Bandera, 2017). Besides, the coefficient of determination (r^2) between simulated and monitored data was also calculated. Once obtained a calibrated model, the comfort and discomfort hours were quantified for representative archetypes' rooms.

Table 7.4: Calibration criteria for buildings performance calibration

Calibration criteria	**NMBE**	**CV (RMSE)**	r^2
Hourly criteria	$\pm$ 10%	30%	>0.75

7.3.5 Criteria for long-term thermal performance assessment

Several indices described as 'discomfort index', 'stress index', or 'heat index' have been proposed over time to describe the relationship between the indoor environment and the human thermal perception (Carlucci and Pagliano, 2012). These evaluation indices are directly connected to the thermal model used for the assessment. This research used the percentage index to report the percentage of likely discomfort hours concerning the total number of occupied hours.

Table 7.5, summarised the thermal comfort criteria used for the thermal performance assessment of the selected archetypes. The acceptability comfort limits were defined as in ASHRAE55:2017 and ISO15251:2007, as well as the high-altitude comfort equation and limits for each location. Despite different comfort equations and acceptability ranges were defined for high-altitude regions in Ecuador (Chapter 6), the comfort equation derived for the whole data set and standards' acceptability ranges were used to allow results comparison. Hence, the same ranges of acceptable temperature were defined using the high-altitude thermal comfort model. The two metrics used to evaluate the archetypes' thermal performance were the percentage of hours within a comfort category and the percentage of hours above or below comfort ranges.

Table 7.5: Adaptive thermal comfort temperature and categories for general comfort

	Comfort model	Category	Upper limit	Lower limit	Reference[4]
ASHRAE55:2017	$t_{comf} = 0.31 \cdot t_{out} + 17.8$	90%[1]	$t_{comf} + 2.5$	$t_{comf} - 2.5$	ASH ±2.5
		80%[1]	$t_{comf} + 3.5$	$t_{comf} - 3.5$	ASH ±3.5
ISO15251:2007	$t_{comf} = 0.33 \cdot t_{out} + 18.8$	Cat I[2]	$t_{comf} + 2.0$	$t_{comf} - 2.0$	EN ±2.0
		Cat II[3]	$t_{comf} + 3.0$	$t_{comf} - 3.0$	EN ±3.0
High-altitude (All)	$t_{comf} = 1.01 \cdot t_{out} + 7.09$		$t_{comf} + 2.5$	$t_{comf} - 2.5$	ALT ±2.5
			$t_{comf} + 3.5$	$t_{comf} - 3.5$	ALT ±3.5
			$t_{comf} + 2.0$	$t_{comf} - 2.0$	ALT ±2.0
			$t_{comf} + 3.0$	$t_{comf} - 3.0$	ALT ±3.0
High-altitude (A)	$t_{comf} = 0.786 \cdot t_{out} + 10.9$		$t_{comf} + 2.00$	$t_{comf} - 2.00$	Comf ± 1sd
			$t_{comf} + 4.00$	$t_{comf} - 4.00$	Comf ± 2sd
High-altitude (B)	$t_{comf} = 1.670 \cdot t_{out} - 3.3$		$t_{comf} + 1.81$	$t_{comf} - 1.81$	Comf ± 1sd
			$t_{comf} + 3.62$	$t_{comf} - 3.62$	Comf ± 2sd
High-altitude (C)	$t_{comf} = 0.738 \cdot t_{out} + 10.5$		$t_{comf} + 1.72$	$t_{comf} - 1.72$	Comf ± 1sd
			$t_{comf} + 3.44$	$t_{comf} - 3.44$	Comf ± 2sd

[1] Percentage of acceptability of indoor conditions
[2] Category I: Normal level of expectations for new buildings and renovations
[3] Category II: Acceptable and moderate level of expectation used for existing buildings
[4] Reference name used in this research

7.4 Description of studied archetypes

Three construction typologies were defined accordingly to the predominant materials used for the construction of dwelling in Ecuador. Heavy thermal mass (Typology 1) corresponds to the vernacular architecture, adobe walls and a mixed of bahareque, wood and clay tiles for the roof. Lightweight constructions (Typology 2) considered the dwellings built with hollow concrete blocks in walls and light roof construction (zinc/asbestos); these are the country's predominant construction system. Medium thermal mass (Typology 3) used the same predominant material for walls, hollow concrete block but a heavier material for the roof, reinforce cast concrete slab. The materials used for the floor (cast concrete) do not change significantly; thus, no difference was considered among the selection of archetypes.

Based on the predominant construction typologies, the dwellings selected as archetypes for monitoring represent the predominant constructions in Ecuador and the study region. A total of nine dwellings, shown in Figure 7.1, were monitored during the fieldwork study. The study archetypes will be referred from now on based on a two-digit code; the study's location (A, B and C) and the construction typology (1, 2 and 3). The selected archetypes are one-story detached dwellings accommodating single families, except for dwelling B3 (See section 7.4.1). The dwellings geometry consists of a simple rectangular floor plan, isolated from other constructions. Data was collected under the dwellings' normal operation conditions and regular users' behaviour.

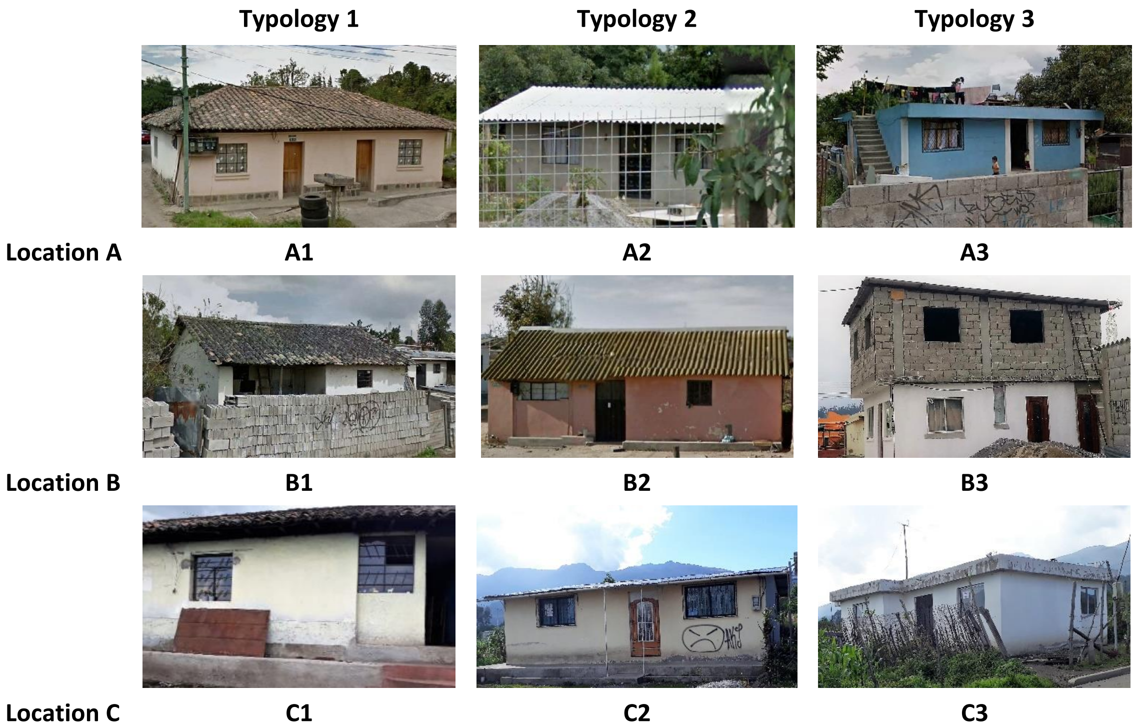


Figure 7.1: Monitored dwellings by location and construction typology

7.4.1 Monitored indoor environmental conditions

Indoor air temperature, dewpoint and relative humidity (summarised in Table 7.6) were monitored continuously over several days in nine dwellings, three different typologies at each study location. The data loggers (Tinytag) were installed in different rooms, primarily living rooms and bedrooms; in some cases, an additional logger was installed in the kitchens. Data used for the analysis presented in this chapter correspond to one of the main bedrooms to compare rooms with the same use.

The monitoring period and the data logger's location varies between dwelling according to the participant's availability and ease of access. Data was collected in five-minute intervals and transformed into hourly measurements for analysis. Due to technical issues or participants' availability, the second monitoring period was not conducted under the same conditions. For instance, participants of dwelling A3 were not available for the second monitoring period, whereas some major (Construction of additional storey) and minor renovations (Fixing ceiling) were done at B2 and C3, correspondingly. Moreover, inhabited adobe dwellings were not available in locations B and C; the monitored ones correspond to uninhabited vernacular dwellings.

Table 7.6: Monitoring period and number of data loggers per archetype

Dwell code	N loggers[1]	First monitoring period			Second monitoring period			Note
		Start	End	N days	Start	End	N days	
A1	3	26-Sep-17	16-Oct-17	21	07-Jan-18	22-Jan-18	16	
A2	2	26-Sep-17	16-Oct-17	21	07-Jan-18	22-Jan-18	16	
A3	2	26-Sep-17	16-Oct-17	21				[2]
B1	2	23-Oct-17	09-Nov-17	18	09-Jan-18	22-Jan-18	14	[4]
B2	3	30-Sep-17	25-Oct-17	26	09-Jan-18	22-Jan-18	14	[3]
B3	3	27-Oct-17	09-Nov-17	14	07-Jan-18	22-Jan-18	16	
C1	2	21-Oct-17	09-Nov-17	20	06-Jan-18	22-Jan-18	17	
C2	2	03-Oct-17	27-Oct-17	25	06-Jan-18	22-Jan-18	17	
C3	3	29-Sep-17	22-Oct-17	24	06-Jan-18	22-Jan-18	17	[3]/[4]

Note:
[1] Number of installed data loggers per house
[2] The second period not available due to technical issues or participants unavailability
[3] Major renovations change the initial conditions of the dwelling in the second period
[4] Uninhabited dwelling

The daily mean descriptive statistics (mean, maximum, minimum and daily oscillation) for air temperature and humidity of the main bedrooms in each dwelling during both monitored periods are summarised in Table 7.7. The daily mean temperature fluctuates between 15.3 °C and 21.1 °C, and the standard deviation oscillates within a narrow band between ±0.9 °C to ±2.8 °C. The broader oscillation from the daily mean was observed in dwellings C1 (±2.8 °C) and C2 (±2.3 °C). Nevertheless, the slight temperature variation between archetypes, the difference is significant between the three construction typologies regardless of the Location.

Figures 7.2 and 7.3 allow a better representation of each archetypes' daily means for indoor temperature and humidity, respectively. The indoor temperature of heavy thermal mass dwellings is generally more stable (narrower daily oscillation) than typologies 2 and 3, particularly A1 and B1. In terms of dwelling C1, the greater mean daily oscillation might be explained by the higher infiltration rates due to the construction's deterioration. It is worth remembering that dwell B1 and C1 were unoccupied; thus, the lack of internal gains might also explain the lower indoor

Table 7.7: Daily Indoor air temperature and humidity descriptive statistics - Daily mean, maximum (max), minimum (min) and daily oscillation (osc)

	Air temperature [°C]								Humidity [kg/kg]			
Dwelling	**mean**	*sd*	**max**	*sd*	**min**	*sd*	**osc**	*sd*	**mean**	**max**	**min**	**osc**
A1	18.7	0.9	19.9	1.1	17.6	1.0	2.3	1.0	0.013	0.013	0.012	0.002
A2	20.9	1.6	29.5	3.4	16.1	1.5	13.4	3.8	0.013	0.016	0.011	0.005
A3	21.1	1.4	23.0	1.4	19.3	1.6	3.7	0.8	0.014	0.017	0.012	0.004
B1	16.0	0.9	19.1	2.0	13.9	0.8	5.1	2.0	0.011	0.013	0.010	0.003
B2	19.9	1.0	23.3	1.6	17.0	1.0	6.3	1.7	0.013	0.015	0.011	0.003
B3	18.0	1.5	19.4	2.0	16.6	0.9	2.8	1.4	0.015	0.016	0.014	0.003
C1	15.3	2.8	16.8	2.7	13.6	2.7	3.2	1.1	0.011	0.013	0.010	0.002
C2	20.6	2.3	33.5	5.4	13.0	1.2	20.5	5.4	0.011	0.016	0.008	0.008
C3	17.3	1.7	19.4	2.1	15.6	1.5	3.8	1.3	0.014	0.016	0.012	0.004

temperature for both the mean daily mean and the mean daily minimum. In combination, high thermal mass and internal heat gains, as in A1, causes the narrower thermal oscillation among the study archetypes.

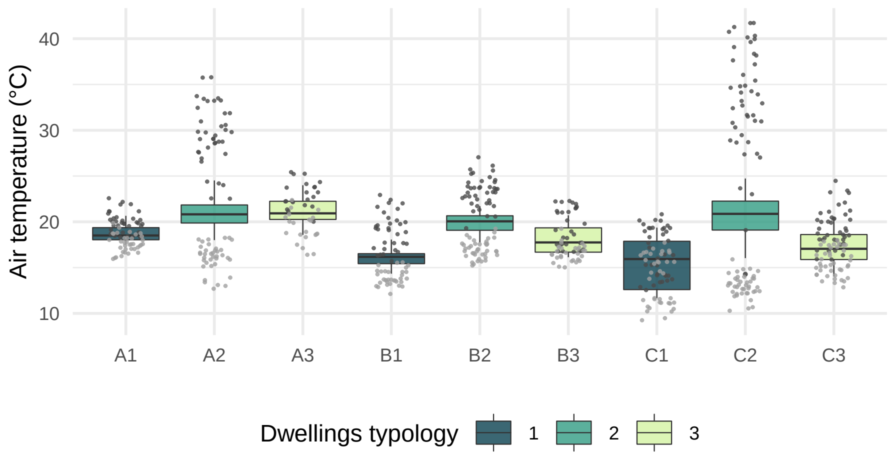


Figure 7.2: Indoor air temperature by dwelling - Daily mean (boxplot), daily maximum (dark grey points) and daily minimum (medium grey points)

The altitude effect is also evident when comparing lightweight constructions (zinc or asbestos roof) without a ceiling (A2 and C2). As expected, indoor temperatures around 30.0 °C were recorded in A2 and C2, and the daily oscillation could reach 20.0 °C (C2). Due to the lightweight construction and the time of day, higher indoor temperatures might be associated with the outdoor temperature and solar radiation (Figure 7.5). The cardboard ceiling explains the significant differences observed in B2, which is not a common construction practice in the studied locations. On average, the mean daily minimum temperature is higher in Typology 3 than the other constructions. The indoor temperature at the medium-weight constructions (Typology 3) is

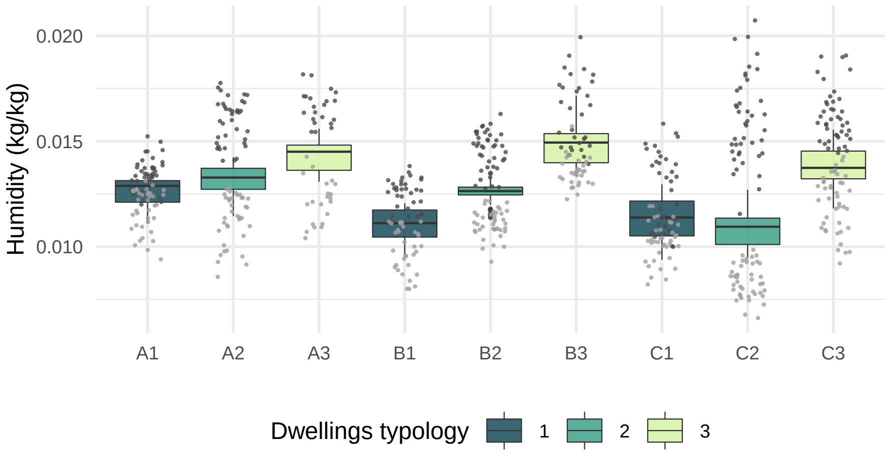


Figure 7.3: Indoor humidity by dwelling - Daily mean (boxplot), daily maximum (dark grey points) and daily minimum (medium grey points)

relatively stable; the daily temperature oscillates within a narrow range between 2.8 °C (±1.4 °C) and 3.8 °C (±1.3 °C).

A consistent but slight difference is observed in humidity between the three dwelling's typology. However, there is no evident difference across the three locations (Figure 7.3). Typology 1 have lower daily mean values, as well as a narrower oscillation. The higher daily humidity levels (mean, maximum and minimum) are observed in Typology 3, and the broader daily oscillation in Typology 2.

7.4.2 Indoor and outdoor environmental conditions

A correlation analysis between the indoor environment and the corresponding outdoor conditions was conducted to understand better the outdoor environment's effect on different construction typologies. Figure 7.4 presents the coefficients (r^2) obtained when correlating indoor and outdoor conditions. Air temperature and humidity were compared against the corresponding outdoor environmental variable; besides, the correlation between air temperature and solar radiation was also explored.

There is a significant positive correlation between outdoor temperature and solar radiation in the indoor temperature of A2 and C2, highlighting that the indoor temperature in lightweight constructions is affected by both the outdoor temperature and the solar radiation. The effect of an additional construction layer (cardboard ceiling) is evident once more in B2, where the correlation of the indoor temperature is moderate, as observed in Typology 3. Besides, the effect of solar radiation in B2 is lower. Not surprisingly, there is a weak or non-correlation between the indoor and

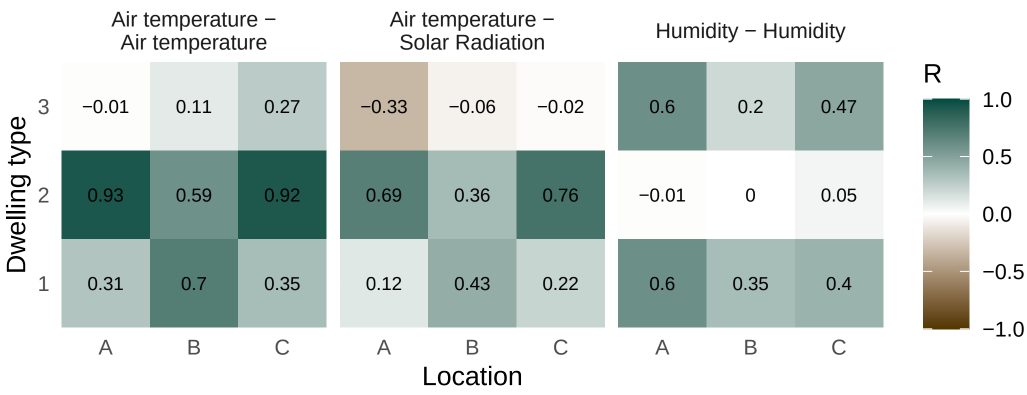


Figure 7.4: Correlation (r^2) between indoor and outdoor conditions

outdoor temperature in Typology 1 and a weak negative correlation between indoor temperature and solar radiation.

Furthermore, whenever a significant effect of outdoor temperature and solar radiation is evident in the indoor temperature, there is a minor or non-significant relationship between the outdoor and the indoor humidity. Besides, when non-correlation is observed between temperature and solar radiation, a moderate positive correlation is observed for the indoor and outdoor humidity (i.e. typologies 1 and 3).

Figure 7.5 allows a better understanding of the weak or strong relationships between indoor and outdoor temperature, as well as the relation with global horizontal solar radiation. The figure plots the daily variation of temperature (left y-axis) and global horizontal solar radiation (right y-axis) for all the dwellings' analysed rooms during the first and second monitoring periods. One could observe a strong similarity between the oscillation of indoor and outdoor temperature for Typology 3. Whereas in Typology 1, there is a narrow daily oscillation shifted (to the right) in comparison to the outdoor temperature. The displacement of curves is evident when observing the occurrence of maximum and minimum indoor temperature.

The minimum indoor temperature occurs in the morning between 6 and 8 am, and the maximum occurs within a broader range between midday until late in the afternoon (around 5 pm). Cross-correlation analysis was conducted to align the peak indoor temperature at the lag at which the indoor and outdoor temperatures are best correlated. The highest indoor temperature in Ty-

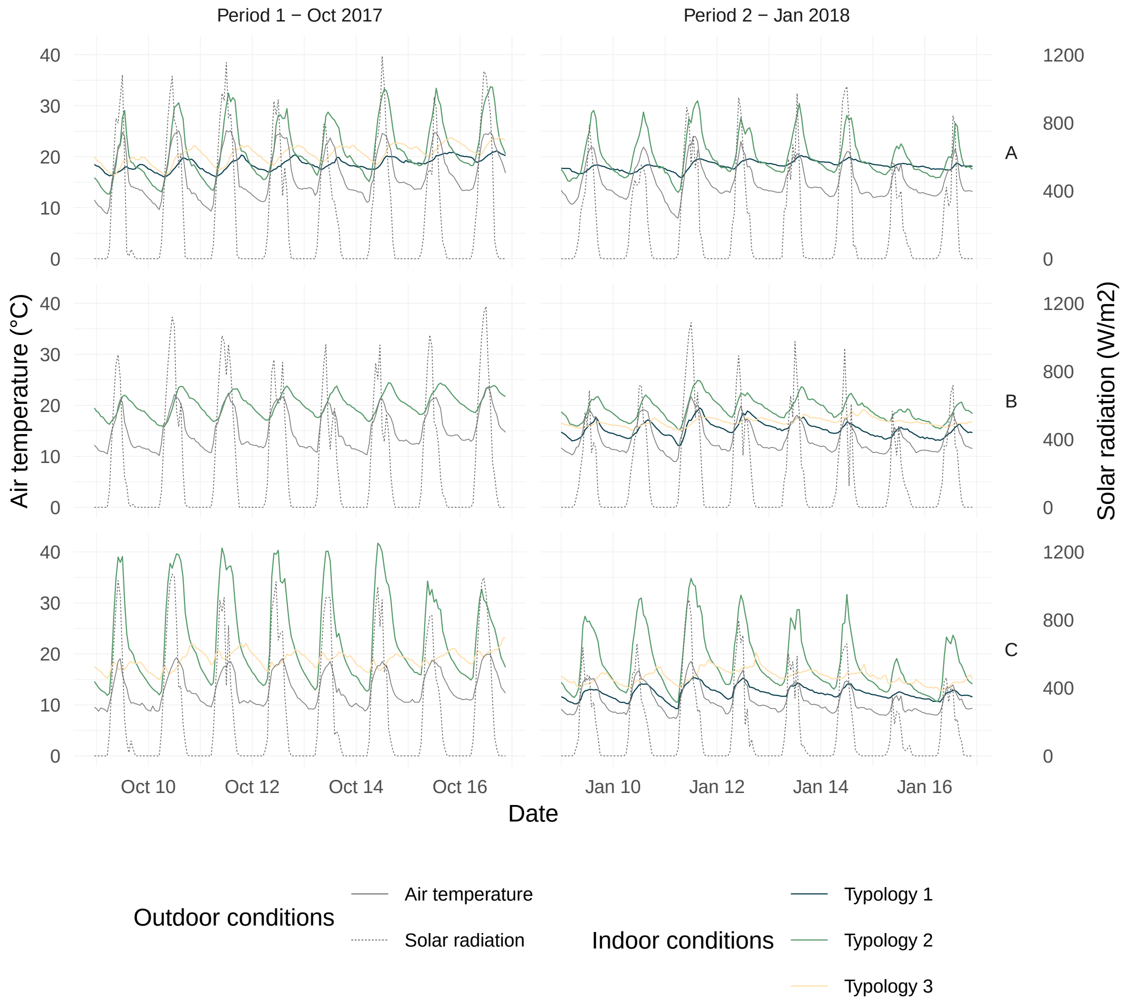


Figure 7.5: Indoor and outdoor environmental conditions of the studied archetypes

pology 1 occurs two hours after the maximum outdoor, whereas the effect is almost immediate in Typology 2 (lightweight), happening after a half to one hour. In terms of Typology 3, the calculated displacement corresponds to four or five hours. Considering the uninsulated characteristic of dwellings, a displacement of the indoor temperature of that magnitude may not only be attributed to the outdoor temperature but also additional heat sources such as internal heat gains.

7.5 Sensitivity analysis

The number of uncertainty factors was reduced to 5% for the best-case scenario and 17% for the worse situation than the number of the initially tested factors (Table 7.8). In the same way, the total simulation cost reduction was from 4440 simulations to 640 simulations.

The parameters highlighted in grey are parameters found to be influential across all the con-

Table 7.8: Summary of factors and iterations run for the sensitivity analysis and calibration process

		A1	B1	C1	A2	B2	C2	A3	B3	C3	Total
Sensitivity analysis	Tested factors	52	44	46	42	51	50	50	50	50	435
	Number of iterations	530	450	470	430	520	510	510	510	510	4440
Calibration process	Influential factors	9	6	8	2	5	4	6	7	8	55
	Number of iterations	100	70	90	30	60	50	70	80	90	640

struction typologies (Table 7.9). Overall, Typology 1 are the ones having the highest number of influential parameters. In other words, the indoor temperature highly depends on the thermal insulation of the envelope. These archetypes' influential factors are related to heat gain or loss through the floor, walls, and roof.

Regarding Typology 2, only the ground floor is a consistent influential parameter across the three locations. Besides, in B2, the layer adjacent to the ground also significantly impacts the indoor temperature. Same as in the previous typologies, the influential factors in Typology 3 correspond to the floor elements, both ground temperature and gravel (layer adjacent to the ground). Slightly smaller but still influential factors are the hollow concrete blocks in walls (B3 and C3) and light hollow concrete blocks (A3). Besides the envelope elements, infiltration and ventilation are two of the most influential parameters across all the archetypes.

Table 7.9: Influential parameters on indoor air temperature for each archetype - Based on the calibration criteria (μ^*)

Element	Factor		A1	B1	C1	A2	B2	C2	A3	B3	C3
Floor	Ground temperature		0.27	0.29	0.31	0.23	0.37	0.42	0.23	0.21	0.39
	Gravel	Conductivity	1.68	0.94	1.00	0.45	0.69	0.12	0.62	0.83	0.80
		Thickness	0.26	0.20	0.19		0.16		0.13	0.19	0.18
	Screed	Conductivity	0.16	0.15	0.13		0.12			0.12	0.11
Walls	Adobe	Conductivity	0.39	0.34	0.18						
		Thickness	0.11								
	Hollow concrete block	Conductivity									0.17
		Thickness				0.12				0.12	0.17
Roof	Light hollow concrete block	Conductivity							0.16		
		Thickness							0.11		
	Plywood	Conductivity	0.11	0.43	0.24						
		Thickness		0.15							
Air flow	Infiltration		0.88	0.49	0.48	0.43	0.75	0.54	0.74	0.92	0.87
	Ventilation		0.26	0.11	0.22	0.64	0.71	0.80	0.22	0.46	0.52

7.6 Calibration of archetypes' thermal models

The baseline models already provide some reliable values of indoor air temperature for most archetypes. For instance, the error between the observed and the simulated data in A1, A2, A3 B1, B2 and C3 is already within the acceptable uncertainty criteria limits (NMBE and CvRMSE). The r^2 values in A2, B1, B2 and C2, are above 0.75 (Table 7.10). After calibrating each dwelling's most uncertain parameter, the NMBE error for all the archetypes is almost null, and the CvRMSE is below 20%. Thus, the models' calibration not only complies with the criteria in the international standards (Table 7.4) but is way below the established threshold, as shown in Figure 7.6.

Table 7.10: Uncertainty index for each studied archetype - Baseline and best fit (Room B1)

Case	Criteria	A1	A2	A3	B1	B2	B3	C1	C2	C3
Baseline	NMBE	-0.08	-0.02	-0.03	-0.04	-0.05	-0.11	0.13	0.12	-0.09
	CvRMSE	0.11	0.15	0.08	0.07	0.10	0.13	0.16	0.21	0.11
	R^2	0.48	0.86	0.60	0.87	0.85	0.68	0.58	0.94	0.76
	Compliance	**	***	**	***	***				***
Best fit	NMBE	0.00	0.00	0.01	-0.02	0.01	-0.01	0.06	0.07	0.01
	CVRMSE	0.08	0.16	0.08	0.06	0.09	0.08	0.09	0.18	0.09
	R^2	0.60	0.86	0.55	0.89	0.84	0.63	0.62	0.94	0.58
	Compliance	**	***	**	***	***	**	**	***	**
	Case	029	020	069	014	004	079	065	033	078

*** Complies criteria for NMBE, CvRMSE and R^2
** Complies criteria for NMBE and CvRMSE

Figure 7.6: Uncertainty criteria for the baseline and calibrated models for each studied archetype (Room B1)

Figure 7.7 plots seven consecutive days of the outdoor temperature, observed indoor and simulated (Baseline and Calibrated) indoor temperatures. For instance, the input data used for A2, B1 and B2 allowed an almost perfect representation of the indoor temperature. Whereas in some dwellings, such as C2, the models need further tuning to represent the maximum indoor temperature. In Typology 3, the indoor temperature oscillation pattern of simulated temperature does not follow a similar pattern as the observed data. Particularly in C3, the indoor temperature is affected by other parameters likely to be solar radiation or internal gains rather than only the outdoor temperature as in the other archetypes.

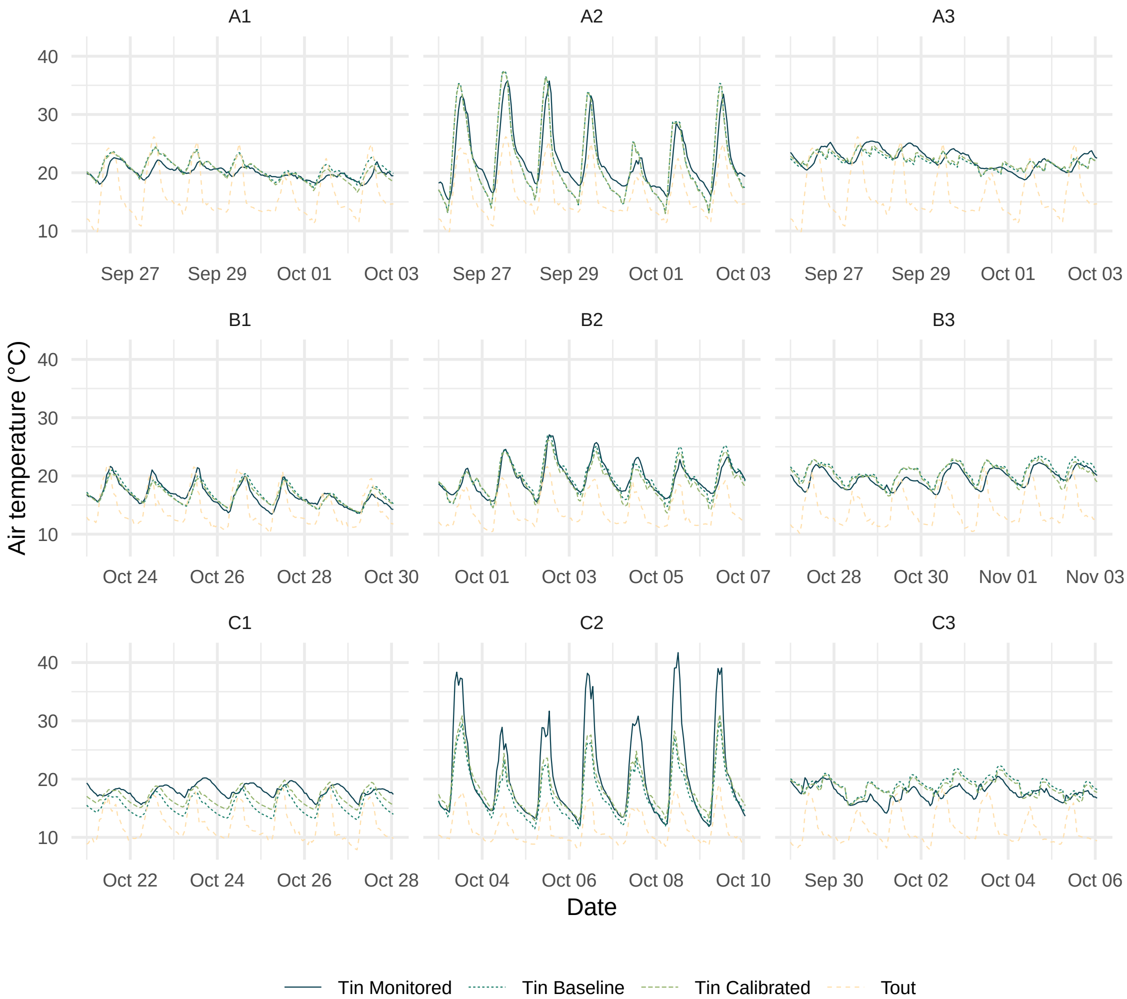


Figure 7.7: Monitored and simulated (base and best fit) indoor temperature and the corresponding outdoor conditions

7.7 Thermal performance assessment

The comfort and discomfort hours for the representative rooms were quantified after obtaining a calibrated model. The indoor air temperature obtained from the calibrated models was used to conduct an annual thermal assessment based on the criteria detailed in Table 7.5. The an-

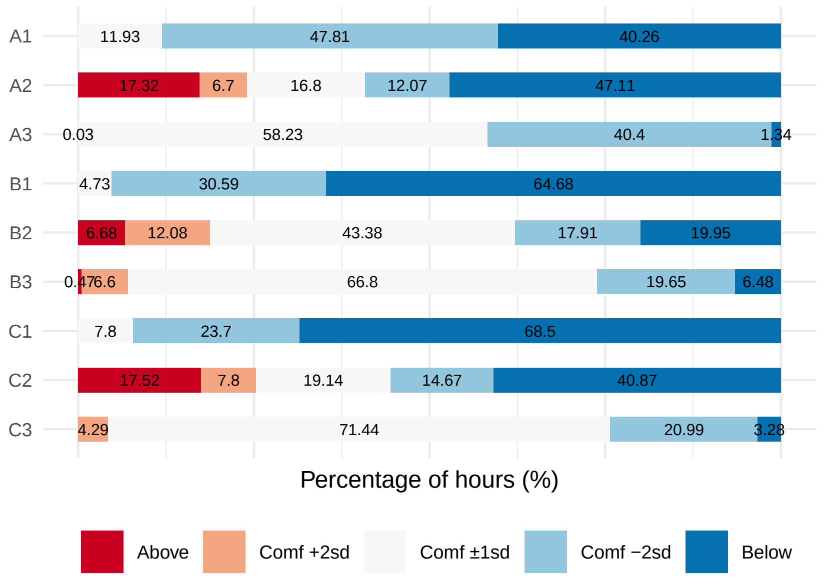


Figure 7.8: Annual percentage of hours within comfort range per archetype - Dedicated comfort equation and comfort limits by location

nual percentage of comfort and discomfort hours calculated for each dedicated comfort equation and comfort limits by location are summarised in Figure 7.8. Overall, discomfort in the studied archetypes is associated with the percentage of hours below comfort limits, except for Typology 2, where temperature above the comfort limits is a source of discomfort. It is not a surprise that Typology 2 (A2 and C2) are among the ones with suboptimal thermal performance. Lightweight constructions have a broader thermal oscillation, reflected in a higher percentage of discomfort hours than the other typologies. However, an extra layer in the roof construction (i.e. gypsum plasterboard ceiling), as in B2, significantly reduces the total hours of discomfort.

Regardless of the narrow thermal oscillation of high thermal mass dwellings, the higher percentage of discomfort hours are observed in Typology 1. However, the effect of heavier thermal mass in A1 and C1 may explain the higher percentage of discomfort hours in these dwellings than B1 (thinner adobe walls). Besides, one could attribute the slightly higher percentage of hours within the acceptability range in A1 to the internal gains than the unoccupied C1. Alternatively, that occupants exercise control over the indoor environment. Typology 3 (A3, B3 and C3) had an outstanding performance within the acceptable thermal comfort range (80% voting between -1 and +1 on the ASHRAE scale). Overall, the percentages of discomfort hours estimated in Figure 7.8 are ∼7% lower in locations A and B and ∼1.8% higher in Location C than those calculated in Figure 7.9.

Figure 7.9 and Figure 7.10 compared the percentage of comfort and discomfort hours for each archetype within the acceptability comfort ranges defined by ASHRAE55:2017 and ISO15251:2007, and the high-altitude comfort model (All). As previously mentioned, the main differences between the ASHRAE55:2017 and ISO15251:2007 rely on the comfort equation and the acceptability comfort ranges.

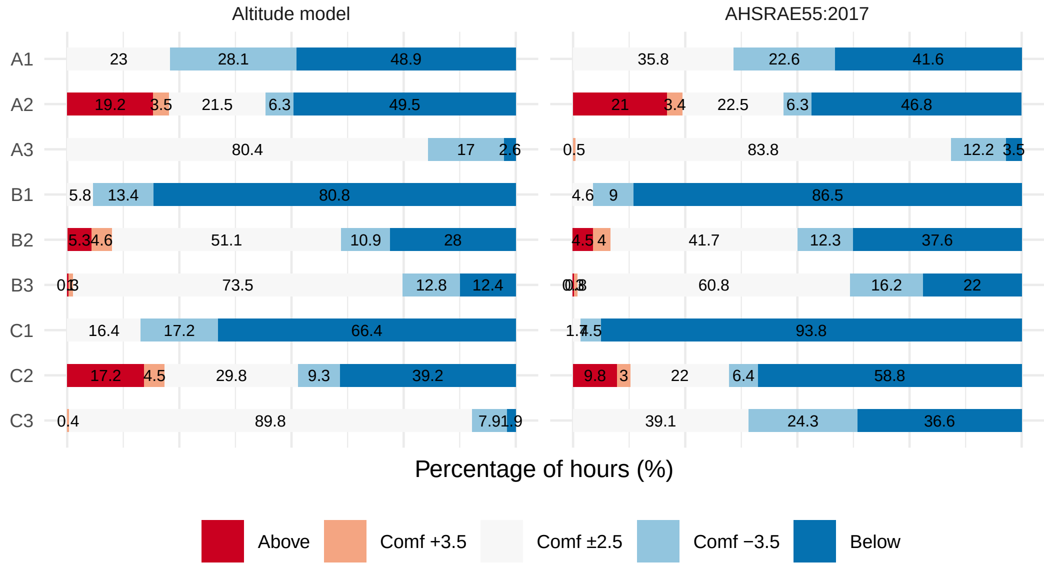


Figure 7.9: Annual percentage of hours within comfort ranges per archetype - Comparison with ASHRAE55:2017

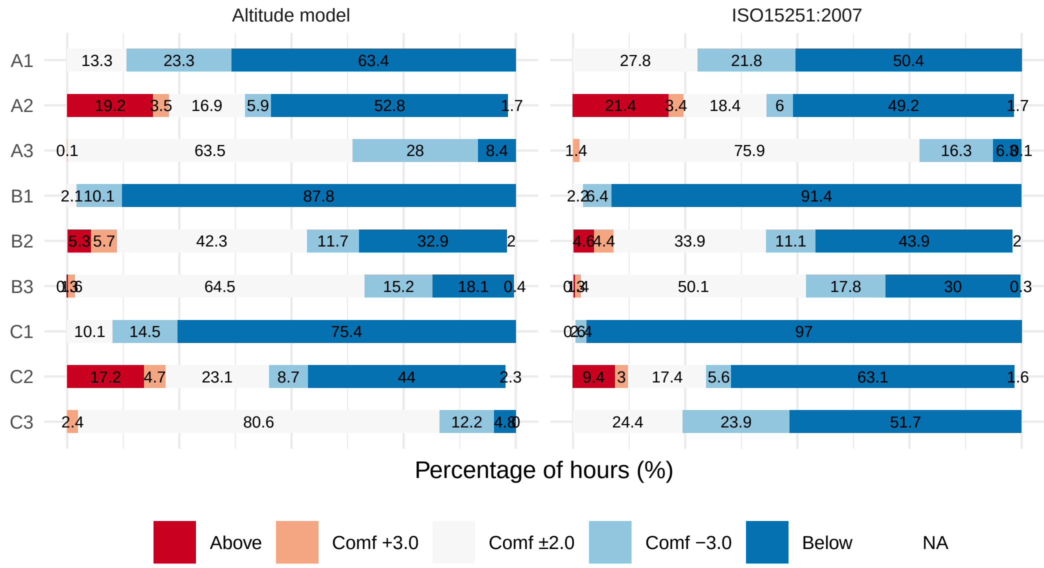


Figure 7.10: Annual percentage of hours within comfort ranges per archetype - Comparison with ISO15251:2007

Despite the different limits of comfort acceptability between international standards (ASHRAE55:2017 and ISO15251:2007), the general archetypes' thermal performance patterns yield similar results. Moreover, when looking at Figure 7.9 and Figure 7.10, the high-altitude model and the international comfort standards return similar results for archetypes in locations A (A1, A2, A3) and B (B1, B2, B3). The main difference occurs when evaluating archetypes in Location C. The percentages of comfort hours ($\pm$2.5 °C) predicted by the high-altitude model are 16.4% (C1), 29.8% (C2) and 89.8% (C3). In contrast, ASHRAE55:2017 and ISO15251:2007 predicted lower percentages than the high-altitude model. For instance, in C3, the ASHRAE55:2017 standard predicts 50.7% fewer comfort hours ($\pm$2.5 °C) than the high-altitude model, whereas 56.2% less comfort hours ($\pm$2.0 °C) were predicted ISO15251:2007. The reduced percentage of comfort hours predicted by ISO15251:2007 is attributed to the differences in the regression coefficients, as well as the narrower acceptability comfort limits.

Based on the predictions by high-altitude comfort (Figure 7.9), the minimum percentage of discomfort is 1.9% (C3) and the maximum 80.8% (B1), and the mean percentage of annual discomfort hours is $\sim$36%. Some envelope elements such as floor and roof (influential parameters in thermal performance, Table 7.9) will benefit from additional thermal mass or insulation in practical terms. Figure 7.11 compared the current and hypothetical archetypes' percentage of comfort hours based on the high-altitude comfort model and the ASHRAE55:2017. The hypothetical archetypes were modelled in compliance with the envelope thermal insulation requirements incorporated in NEC11 (Table 7.3). As expected, the total percentage of discomfort hours increases significantly for the hypothetical archetypes, except for B1. The mean percentage of discomfort based on high-altitude comfort for the hypothetical archetypes is $\sim$61%, which is $\sim$24.4% higher than the one estimated for current archetypes. The maximum percentage of discomfort will be over 86% (C2), and the minimum below 10.1% (A3). Moreover, hours of discomfort above comfort threshold are only observed in three current archetypes (A2, B2, C2), whereas this phenomenon is observed in all the hypothetical archetypes.

7.8 Summary of the chapter

The chapter evaluated the developed high-altitude comfort model's applicability to evaluate the existing housing stock's thermal comfort and new dwellings in compliance with the new - Ecuadorian construction standard (NEC11). Thus, archetypes' thermal performance representing the existing housing stock in the Ecuadorian Andes were evaluated. The methodological approach used a

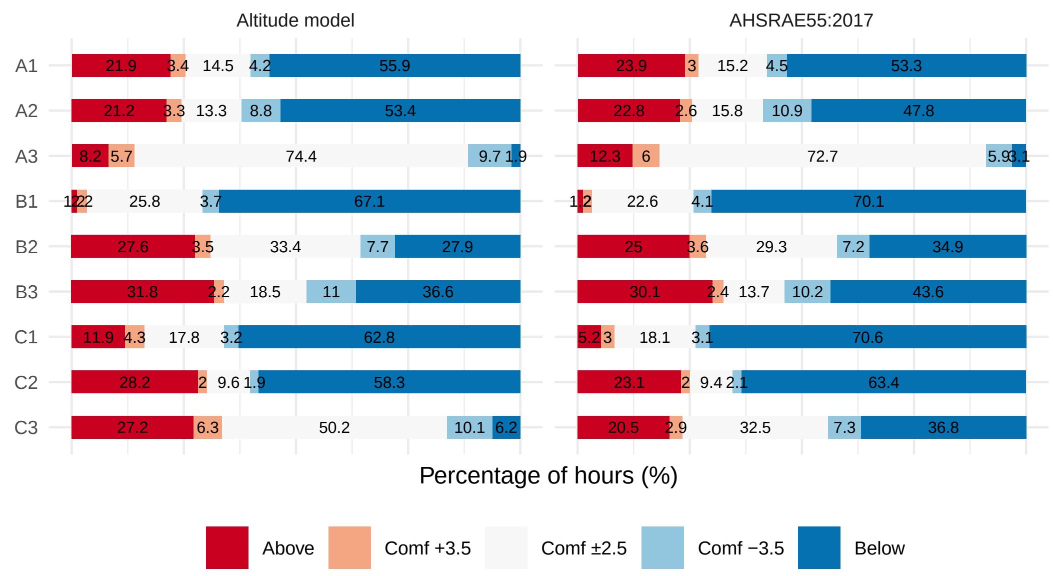


Figure 7.11: Annual percentage of hours within comfort ranges per hypothetical archetype - Comparison high-altitude model and ASHRAE55:2017

combination of monitoring and building performance simulation (BPS).

The first insight of the collected data highlights the significant impact of construction and occupancy patterns on the indoor temperature. The daily mean thermal oscillation in medium weight and vernacular dwellings (Typology 1) varies within a narrow range. Whereas in lightweight constructions (Typology 2), the incident solar radiation has a significant impact on the maximum daily temperature. The indoor air temperature of Typology 2 has a high correlation with the outdoor air temperature and solar radiation. On the contrary, medium weight constructions (Typology 3) have a moderate or little effect of solar radiation, a moderate positive effect of temperature, and a moderate humidity effect. Overall, Typology 1 has lower relative humidity levels, whereas a higher level of relative humidity was recorded at Typology 3. Humidity does not change significantly across locations but between constructions typologies.

Regarding the calibration and archetypes model simulation, common factors were found to affect indoor air temperature across the three locations and archetypes. For instance, floor elements, wall materials, infiltration and ventilation are among the most influential. For archetypes similar to those described in this research, one can conclude that thermal simulation models could be accurately calibrated by an appropriate definition of infiltration and ventilation rates (ACH) and the thermo-physical properties material of floor elements. The proposed calibration process allowed a good estimation of the indoor temperature for dwellings typologies 1 and 2. In typology

3, a good fit is also achieved; nevertheless, other input factors could be included in the calibration process to get more precise outputs for further studies.

Finally, the quantification of thermal performance was conducted for the nine current and hypothetical archetypes based on the high-altitude thermal comfort model and international comfort standards. In order to allow for the comparison, the comfort acceptability ranges were defined according to international standards. Dwellings with a uniform thermal mass in walls, roofs and floor (Typology 3) have an outstanding thermal performance in the Ecuadorian Highlands. Moreover, in lightweight construction (Typology 2), a significant improvement in the indoor thermal environment could be achieved by slightly increasing the insulation or mass of zinc or asbestos roofs. It is clear that the current housing stock requires some improvement to enhance thermal performance; however, the adoption of comfort models and envelope thermal insulation requirements for dwellings is not the optimal solution for the housing stock in the Ecuadorian Highlands. Despite the envelope thermal insulation requirements are not very stringent, thermal comfort could be seriously compromised when applying the criteria defined in NEC11. In the absence of contextualised criteria for assessing comfort and thermal performance, building standards trigger a combination of wasting resources and exacerbating discomfort.

Chapter 8

Conclusions

8.1 Overview

The research in this thesis aimed to define a thermal comfort criterion, aligned with the perception of residents in subtropical highlands, to be used for long-term thermal performance assessment in dwellings in high-altitude regions. This chapter integrates the main findings and results obtained from the thermal comfort surveys and thermal performance assessment in three high-altitude locations in the Ecuadorian Andes. Besides, the chapter details the main contributions to the body of knowledge arising from this research and recommendations for future work.

In order to address the objectives defined for this thesis, thermal comfort surveys to high-altitude residents and thermal performance assessment of dwellings archetypes were conducted. The research focused on three high-altitude locations in Quito, Ecuador, to assess the effect of low-pressure in thermal comfort, between 2400 and 3000 meters above sea level. On the one hand, 398 thermal comfort surveys were collected from permanent residents in three high-altitude locations between September 2017 and January 2018. The cross-sectional thermal comfort survey collected subjective votes of the indoor environment and data regarding subjects' acclimatisation, behavioural responses and predominant symptoms, and perceived discomfort at home. On the other hand, nine calibrated thermal models corresponding to three dwellings archetypes were developed based on the monitoring and dwellings audits.

8.2 Contextual and individual drivers of diversity

Several contextual and individual factors were identified to affect the thermal responses and comfort temperature in the studied high-altitude locations. In terms of contextual factors, the weather conditions and the dwellings construction typologies significantly impact the indoor environment, which influence occupants' perception. For instance, the weather's peculiarities in the Ecuadorian Andres are the narrow annual temperature oscillation, large diurnal temperature variation, low atmospheric pressure, and high solar radiation levels. Besides the inherent decrease in temperature as altitude above sea level increases, a significant difference in humidity ratio, wind speed, and solar radiation was confirmed. This differences in weather conditions are reflected in the dwellings' thermal performance and occupants' perception. The high levels of solar radiation have a significant impact on the indoor temperature of lightweight constructions.

The total comfort votes decrease as altitude above sea level increases; on the contrary, the preference for warmer conditions is higher at higher altitudes than the lower studied location (Location A). Humidity perception is more even across the studied locations, whereas drier spaces' preference increases consistently from Location A to Location C. Contrary to air movement preference, occupants at Location C reported a clear preference for reduced air movement and increased air movement preference at Location A. At the same range of temperature (21.0 °C - 22.0 °C), residents in Location C voted between 'neutral' or 'slightly warmer' in the ASHRAE scale, residents' in Location B towards 'neutral' and 'slightly cool', and residents' in Location A voted between 'slightly cool' and 'cool'. These results highlight that residents have a different perception of the indoor at different altitudes, even when the indoor temperature is the same. Besides, residents in high-altitude regions tend to be more sensitive to draught.

Thermal comfort diversity was explored at the individuals' level. The participants in this research correspond to male and females adults between 18 and 65 years old. The drivers of diversity explored include gender, age, body surface area (BSA), and acclimatisation. No significant differences were observed in comfort temperature across the abovementioned groups. However, the key finding was observed in the range of acceptability of comfort temperature. Non-acclimatised residents (mid and low levels in the overall adaptation index) in the three locations consistently reported a decreasing percentage of temperature, humidity and air movement sensation votes. On the contrary, a marked preference for warmer, drier and reduced air movement was observed among non-acclimatised. The same voting trend but lower percentages were observed in acclimatised subjects (high level in the overall adaptation index).

Moreover, acclimatised residents are more permissive with the indoor environment; broader comfort temperature limits were observed in this group. These broader comfort ranges suggest residents' acclimatisation or adaptation to the prevailing conditions or increased coping strategies compared to the non-acclimatised residents. The attenuated thermal perception of high-altitude residents' may be attributed to previous experiences and expectations of the indoor climate, socio-cultural background, or the repeated exposure to an environmental stressor.

Around 30% of the surveyed participants reported experiencing at least one symptom associated with poor indoor environments, while a higher percentage of complaints was observed in the lower location (Location A). Regarding the major sources of discomfort, participants reported issues related to draught and temperature daily oscillation. These results draw important conclusions in practical terms; despite the high percentage of participants voting for a neutral environmental sensation, the reported prevalence of symptoms and discomfort at home challenge whether current dwellings are of adequate quality.

One of the main outcomes of this work is some 'unpacking' of the adaptive model. Through the investigation, it was possible to identify some of the contextual and individual factors driving diversity in the subjective assessment of comfort in Ecuador's high-altitude regions. The acclimatisation to a cool and low-pressure environment in the Ecuadorian Highlands was mainly observed in the limits of acceptability of thermal comfort. Besides, as it has been widely reported in the literature, clothing is a major part of the surveyed population's adaptive behaviour not only to the prevailing conditions but to the climate in the highlands. The reported disparity in clothing was observed throughout the environmental votes and comfort temperature across the three study locations. Furthermore, the different behavioural adaptation strategies confirm that high-altitude residents are adapted to a certain extent to the outdoor conditions.

8.3 High-altitude thermal comfort model

In order to identify a thermal comfort model that better represents residents' thermal sensation in Ecuador's high-altitude regions, the data from the study locations were compared against predictions from the PMV model and adaptive comfort models from current international standards.

Thermal comfort indexes account for the effect of low-pressure when the adjusted convective heat transfer coefficient is replaced in the PMV and operative temperature calculation. When comparing observed data against comfort predictions, the key findings are that a) neither international standard accurately predicts comfort in the study sample, and b) the disparity in comfort temperature and range of comfort acceptability increases with altitude from Location A to Location C.

Specifically, people in the study sample appear to be better adapted to their conditions than the international standards predict. The inaccuracy in the predictions is not surprising since the study sample lives in a different climate to the climates in which existing comfort models were developed and tested. The current thermal comfort models result from experiments and fieldwork conducted across various climate zones, including temperate, hot-humid and cold weather. The limits of applicability for the PMV model are locations up to 3000m above sea level. In comparison, the adaptive comfort equations in the standards are recommended only when the running mean or prevailing mean temperature is above 15.0 °C (ISO15251:2007) or 10.0 °C (ASHRAE55:2017). Therefore, none of the current international standards should be used for comfort predictions in high-altitude locations, as is the case of the study Location C. Furthermore, the study people are at home, where their adaptive opportunity is greater than in workplaces. Besides, people's minimum exposure to mechanically conditioned environments might affect occupants' expectations of broader indoor temperature ranges.

The high-altitude thermal comfort algorithm derived for the Ecuadorian Highlands resulted from the regression of the comfort temperature and the 24-hour mean outdoor air temperature. Even though international standards recommend a weighted running mean outdoor temperature, a better prediction of comfort temperature was obtained using daily mean values. Multiple linear regression was performed to test if diversity drivers' inclusion would enhance the prediction of comfort in high-altitude regions. The coefficient of determination (R^2) did not improve significantly when including contextual (altitude) and/or individual (adaptation and clothing) factors in the prediction of comfort. That is not surprising, as the disparities were observed in the variance of comfort limits due to adaptation factors and clothing levels in the study sample rather than the mean comfort temperature. For instance, no significant difference was observed between acclimatised residents' mean comfort temperature (Overall adaptation = High) and non-acclimatised ones (Overall adaptation = Low-Mid); the major discrepancy is the acceptability comfort limits. A significant difference in the means was observed when comparing the mean comfort temperature across the three study locations.

The key conclusions are that the mean comfort temperature varies significantly across the study locations; as altitude increases, the comfort temperature decreases. Moreover, different comfort ranges should be considered to account for differences observed between acclimatised and non-acclimatised subjects, as well as altitude above sea level. The observed differences across locations might reflect a) the subject's exercised control over the indoor environment, b) acclimatisation to the prevailing conditions, c) more permissive thermal expectations, or d) a combination of the abovementioned factors.

The three derived thermal comfort equations, one of the main outputs of this research, allow a better prediction of comfort temperature and limits of comfort acceptability for each of the study locations. Moreover, to account for the observed difference in altitude and acclimatisation, different comfort limits are recommended. However, the definition of three thermal comfort equations for such a small geographical territory is not of practical use; thus, a single equation and comfort limits have also been derived for practical implications.

8.4 Archetypes' thermal performance

The high-altitude thermal comfort model's applicability was tested in the thermal performance evaluation of representative archetypes and hypothetical archetypes in compliance with the - Ecuadorian construction standard (NEC11). Nine archetypes' annual indoor thermal performance was evaluated through building performance simulation (BPS) and validated with the collected monitored data. The selected archetypes were single-family, detached, uninsulated and free-running dwellings corresponding to the studied region's dominant housing stock patterns.

The thermal assessment of archetypes focused on evaluating the likelihood of occupants' satisfaction with the indoor conditions based on the comfort criteria from international standards (ASHRAE55:2017 and ISO15251:2017). Overall, the discomfort in the study archetypes is associated with the percentage of hours below the comfort limits. Medium weight constructions (uniform thermal mass in walls, roofs and floor), like in Typology 3, have an outstanding thermal performance in the Ecuadorian Highlands. In contrast, the broader indoor temperature oscillation in lightweight construction (Typology 2) provoke discomfort due to temperatures above and below the limits of acceptability. International standards overestimate the percentage of hours of discomfort for all the study archetypes. For instance, the ASHRAE55:2017 standard predicts 50.7% fewer hours of comfort than the high-altitude model in archetype C3, and 56.2% lower by ISO15251:2007. The predicted percentages' differences are attributed to the regression coefficients' differences and the narrower acceptability comfort limits.

The thermal assessment of the hypothetical archetypes' thermal environments seeks to investigate the potential repercussion of modifying the envelope thermal insulation requirements in the indoor environment. Overall, the total percentage of discomfort hours increases significantly for the hypothetical archetypes. For instances, the percentage of discomfort estimated for B3 was 42.8% for the hypothetical archetypes compared to only 12.8% (A1) for the current archetype. Moreover, discomfort above the comfort limits was only observed in three current archetypes (A2, B2, C2), whereas this phenomenon is observed in all the hypothetical archetypes.

In conclusion, international standards significantly overestimate discomfort in the study archetypes. Considering the estimation of discomfort based on international standards, it is not surprising that current construction standards, such as the NEC11, incorporate more stringent requirements for the thermal insulation of dwellings in the Ecuadorian Andes. It is clear that the current housing stock requires some improvement to enhance thermal performance. However, adopting thermal insulation requirements and comfort models from international standards could trigger a combination of wasting energy, exacerbating discomfort and losing the benefit of existing ways in which people adapt to their local climate.

An important outcome of this research is some 'unpacking' of the adaptive model through a deeper understanding of why and how people adapt to high-altitude locations. This investigation provides some grounded evidence that contextualises the adaptive comfort model to the high-altitude climate's particular characteristics and the population's socio-cultural characteristics. Thermal comfort models adjusted to the occupants' perception are fundamental in assessing free-running dwellings as users rely on adaptation to restore comfort; hence, thermal comfort models become the main criteria for thermal performance evaluation.

8.5 Contribution to the knowledge

The thesis advances understanding of thermal comfort and adaptation strategies of residents in high-altitude locations in the Ecuadorian Highlands. The key theoretical, methodological, and practical contributions of this thesis are:

a. In terms of practical contribution and the primary outcome in this thesis is the development of a contextualised thermal comfort algorithm and comfort range for high-altitude regions. The thermal comfort model proposed in this research aims to enhance the prediction of comfortable indoor temperatures for dwellings in the Ecuadorian Andes. Although the model was developed with data from three locations nearby Quito, the model could be used as a reference for other high-altitude regions in Ecuador and South America due to similarities in contextual and cultural background.

b. One of the main theoretical contribution relates to the adaptive comfort theory. The results in this thesis identified one contextual (altitude above sea level) and two individual factors (Adaptation and clothing) that explain the diversity in thermal sensation and comfort temperature in the Ecuadorian Highlands. Understanding of the factors driving diversity allow a better prediction of thermal comfort and expand the mechanisms to restore comfort.

Furthermore, the research extends knowledge regarding the limits of the existing adaptive comfort model's applicability.

c. A significant methodological contribution is the development and validation of data collection instruments and modelling processes. In order to overcome the inherent requirements, limitations, and constraints in developing countries, additional efforts in reshaping and adjusting research instruments were required. The thermal comfort surveys used in this research combine sets of standardised and specific questions that are helpful for a broader research community, particularly in Latin American countries. The validated Latin America Spanish version of the questionnaire constitute an important reference for further thermal comfort studies in the region. Although the subjective judgement scales to assess the influence of the indoor environment have been translated to different languages and widely used in thermal comfort research. Very few versions have been translated and adapted to Latin American Spanish. The structure and wording of the subjective judgement scales were tested and piloted following the criteria and compliance for inclusion in the activities of the 'Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings' initiative (Schweiker et al., 2020). The subjective judgement scales' wording was discussed with seven bilingual (Native Spanish speakers and English) peers working in the building physics field. The experts provide feedback about the judgement scales wording and comments about the survey structure and content. Besides, a sociologist provided input to the document's content and appropriateness of language usage for breaching gaps and building trust with participants.

Furthermore, the original set of questions designed to collect information about general contextual differences (i.e. birthplace, length of residence) and within or intra-contextual differences (i.e. exposure to different environmental conditions) provides a background for further researching acclimatisation. In this study, this approach allowed to define a proxy to measure adaptation in high-altitude environments. However, it could be further expanded to investigate acclimatisation to different stressors.

d. Another significant contribution relates to defining a simple methodological approach for calibrating and modelling poorly detailed free-running dwellings. Most of the existing calibration methods do not account for uncertainty, oversimplify input parameters, and use energy as the most common output to validate a model's accuracy. This research proposes a comprehensive methodology for calibrating free-running dwellings using an automated process and high-resolution data. A combination of analytical techniques was used, including uncertainty quantification and global sensitivity analysis using an automated. Since the calibration goal is to achieve hourly indoor air temperature, the most important parameters for fine-tuning are the building envelope and infiltration rate. Besides, the primary calibration goal is to quantify thermal discomfort and minimise the difference between monitored and predicted indoor temperature. Therefore, the minimum and maximum indoor air temperature values must be accurately predicted to quantify discomfort in the studied dwellings opposite to mean values. Furthermore, the unique calibration methodology explains how to define an appropriate and valid range of input values when no data on the materials' thermal properties is available. Although the proposed calibration method was applied in small and relatively simple dwellings geometry, the methodological approach could be transferred and scaled up to other free-running buildings. Although the proposed calibration method was applied in small and relatively simple dwellings geometry, the methodological approach could be transferred and scaled up to other free-running buildings.

e. Furthermore, the thermal comfort algorithm constitutes a pivotal contribution to inform policymakers. The developed high-altitude model serves as a reference for defining the minimum thermal insulation requirements for free-running dwellings in the local construction codes. The followed approach allows for the contextualisation and tailoring of indices and criteria according to the climatic and socio-cultural conditions in the Ecuadorian Highlands.

8.6 Recommendations from research towards to policy

Based on the results and findings from this study recommendations towards policy related to preferred building typology and guidance on health mitigation to tackle overheating and overcooling.

8.6.1 Recommendations towards policy for buildings

Results from this study have highlighted the overheating and overcooling risk of the existing housing stock, mainly of lightweight dwellings. Poorly insulated and high infiltration constructions together with lower temperature and low pressure intensify overcooling. Meanwhile, the combination of poor insulation and high infiltration together with the incident solar radiation increases overheating. Besides, the interaction of factors such as climate change, increasing urbanisation and urban heat islands, the incessant drive to reduce construction costs, the technical ability to identify and quantify the problem can exacerbate overheating and overcooling in dwellings. In a way, high-altitude residents are culturally prepared to tackle overcooling than responding to overheating. On the one hand, the finding in this research revealed the thermal performance deficiencies and strengths of the most common construction typologies in the Ecuadorian Andes. On the other hand, results from this study have begun to identify some of the interventions that should be taken to mitigate the problem and enhance the thermal indoor environment. Findings have been combined and traduced below in recommendations for improving the thermal indoor environment of existing and new housing stock.

- The monitoring data revealed that uninsulated lightweight dwellings (Typology 2) are the most thermally inefficient construction systems. The large diurnal temperature oscillation resulted in overheated and overcooled dwellings. Despite the broad temperature difference, results from this study highlight that minimum intervention could significantly improve the indoor environment. For instance, the daily oscillation of a lightweight dwelling was 20.5∼°C (C2 in Table 7.7), reaching up to 33.5 °C during the day and a minimum temperature of 13 °C, which traduces in 58.4 % of annual hours of discomfort (Figure 7.8). Meanwhile, a simple and effective intervention in existing dwellings, such as B2, significantly improve the thermal environment. Taking advantage of the roof shape and adding a ceiling layer (cardboard, thickness 1.5cm) reduces the diurnal thermal oscillation to 6.3 °C (Table 7.7) and increases comfort conditions to 73.4% (Figure 7.8).

- The mediu mweight construction dwellings have exemplary thermal performance compared to the other two studied typologies. The effect of thermal mass in the entire envelope, as in C3 (Table 7.7), keeps the indoor temperature between 15.6 °C (minimum) to 19.4 °C (maximum) and within comfortable ranges 96.7% of hours a year. Therefore, the construction of new dwellings, in which the envelope u-values are within a range of the studied medium weight archetypes, would significantly improve dwellings' indoor environmental conditions.

Many new and emerging buildings' standards focus on climate change mitigation through energy and carbon reduction. The local construction standards (NEC11) set a minimum envelope thermal insulation to optimise the building for heat retention and improve the indoor environment. However, improving the insulation of housing stock and reducing unwanted air infiltration is a combination that would exacerbate overheating.

Before any real progress in policy is made, further research is clearly needed to get a robust definition of the minimum envelope thermal insulation requirements to be implemented in building standards to improve the thermal environment and minimise unintended consequences. Regulatory requirements might not only include the minimum thermal properties of envelope materials but a provision of adequate adaptive opportunities through ventilation and shading.

8.6.2 Recommendations towards health guidelines

Climate change, the increasing population projected to live in cities, and the growing urbanisation magnify the heat risk due to rising temperature and the heat island effect. Furthermore, the increasing housing demand proliferates the construction of uninsulated lightweight dwellings, as it is a viable approach for reducing costs and increasing construction speed. As a result, existing and new housing stock risks continuous overheating and overcooling.

Concerns about housing demand and climate change have enhanced policies attempting to improve housing stock affordability and quality. Besides, new and existing buildings must ensure resilience and an ability to adapt over time. Thermal insulation and airtightness should be combined with appropriate climate change mitigation strategies such as shading and natural ventilation. Otherwise, the risk of uncomfortable conditions may be inadvertently increased and consequently health and well-being implications. Thus, protection against cold temperature and high incidence solar radiation emerge as a priority in housing standards requirements to ensure quality is critical in determining health.

Findings from this research uncovered the high level of adaption to the prevailing conditions of residents in high altitude regions. However, it is worth remembering that adaptation is a form of coping with adverse conditions, and coping should not be confused with comfort. Coping can carry a cost, as shown in the results of reported health issues and discomfort at home. 30% of the participants reported health issues prevalent at home, and 95% of the householders reported discomfort associated with the quality of the indoor environment. Thus the importance of addressing overheating and overcooling is a genuine concern for ensuring safe and healthy homes.

Poorly built dwellings might cause a significant prevalence of Sick Building Syndrome (SBS) and thermal discomfort. Besides, places with cold winters have recorded increasing annual excess winter deaths, particularly amongst vulnerable groups. A better understating of the impacts of the physiological effect of the strain (heat or cold) exposure duration and the acclimatisation process over successive days will inform the debate around adaptive thermal comfort and limitations.

Further research requires public health bodies to closely work with building physics' researchers to quantify the extent to which the housing sector addresses current and future climate hazards. Mapping the existent risks would allow prioritising areas for public health and policy-makers and embedding climate resilience in planning, building design, and retrofit of housing stock.

8.7 Limitations and future work

The conducted research used a cross-sectional thermal comfort survey, indoor environment monitoring, and building performance simulation. These research approaches gathered different types of data that require diverse data analysis methods from descriptive to inferential statistics. Therefore, the limitations of this research range from data collection limitations to results generalisability.

The inherent limitations of field studies are related to the lack of control over study variables, difficulty replicating or recording data accurately, and ethical issues. Despite the cooperative attitude of participants, guarantee the same conditions for data collection was not always achieved. For instance, during thermal comfort surveys, participants could have changed position or activity. In the monitored archetypes, two of the dwellings suffered major renovations in between monitoring periods. Despite the limitations of this research due to the dwellings' renovations, the collected data allow for new opportunities to investigate further the effect of these interventions in the archetypes' thermal performance.

One of this research's limitations was to assure a representative sample of the study population; due to the lack of a sample frame, the sampling technique employed for the thermal comfort surveys and archetypes' audit was a convenience sample. Furthermore, the data was collected in detached dwellings at three high-altitude locations between 2400m and 3000m; further research in other locations at different altitude and different dwellings typologies would improve the high-altitude comfort model. Besides, by the nature of the locations, mainly medium and low-income families were surveyed; thus, the research should be extended to other population segments.

Measuring and analysing acclimatisation was one of the most challenging research tasks. Due to modern populations' mobility, studying the adaptation and acclimatisation of subjects to different environmental conditions becomes difficult or even impractical. Additionally, the operationalisation or definition of altitude adaptation measurement as a concept is underspecified and certainly omits essential features. However, the designed set of questions provides a reasonable proxy to address this study's research objectives to differentiate between acclimatised participants from non-acclimatised ones. The adaptation factors analysis and overall adaptation index follow a simple approach; however, the overall adaptation index definition could be further improved by employing more advanced mathematical and statistical methods such as principal component analysis.

The perceived symptoms and discomfort associated with poor indoor environmental quality in dwellings provide valuable information regarding the indoor environment's quality. Results in this thesis only described the most frequent symptoms and sources of discomfort experienced by occupants. However, further investigation of these reported symptoms frequency or a combination of symptoms and discomfort could be a more useful measure of the indoor environment's quality.

Besides identifying the different drivers of diversity affecting thermal responses, the challenge in thermal comfort studies also relies on exploring different comfort algorithms and stretching the limits to contextualise comfort criteria without creating inherently uncomfortable conditions. Adaptation is a coping mechanism; however, coping does not necessarily imply comfort, and it could carry at a cost. For instance, wearing heavier clothing ensembles might be viewed as a necessary inconvenience for occupants. Heavier clothing could either imply that subjects are generally satisfied with colder conditions or attributed to a combination of adaptation and coping mechanisms. Understanding the extent to which behavioural adjustments are a suitable response to provide comfort or become a coping mechanism is relevant not only to academic interest but also the practical implications. Therefore, future research is recommended to explore further the extent to which clothing level is energy-efficient and culturally satisfying people's behaviour or rather an inconvenient necessity of adaptation. Some additional considerations include investigating the unintended excess energy use and other resources resulting from certain acclimatisation or behavioural adjustment mechanisms (i.e. using other appliances not intended for heating the space). Besides, further research could be conducted to understand if the behaviour that leads to comfort have an adverse effect on health and well-being. Further research of particular interest for this segment of the population would be to understand if discomfort or behaviour that leads to comfort interfere with occupants' daily activities at home, affecting the socio-economic development.

Appendix A

Supplementary material literature review

A.1 Main cities in the Ecuadorian Highlands

Table A.1: Population and altitude level of the main cities in the Ecuadorian Highlands

Province	Province capital	Population[1]	Altitude(m)[2]
Pichincha	Quito	2,239,191	2850
Azuay	Cuenca	505,585	2550
Tungurahua	Ambato	329,856	2500
Chimborazo	Riobamba	225,741	2754
Loja	Loja	214,855	2060
Imbabura	Ibarra	181,175	2225
Cotopaxi	Latacunga	170,489	2800
Bolivar	Guaranda	91,877	2668
Carchi	Tulcan	86,498	2980
Canar	Azogues	70,064	2518

Note:
[1] Population of the province capital city
[2] Altitude above sea level of the geographic centroid of the city

A.2 Systematic literature review process

Few studies have been conducted to investigate the effect of low-pressure environments on thermal performance and thermal comfort. The systematic literature review aimed to identify relevant studies on thermal comfort and thermal performance, investigating the effect of low-pressure environments. Conceptual themes used for the systematic search were environmental analysis, location, and environment. The specific themes and combination of keywords used for the search are detailed in Table A.2. Besides, the search was constrained to search terms used in the publication's title, keywords, and abstracts. Regarding the specific context, two separate searches were conducted; the first one centred on getting a general overview of studies conducted in the high-

Table A.2: Themes and search terms for literature review in the high-altitude regions

Conceptual themes	Specific themes	Search terms
Environmental analysis	Thermal	”temperature sensation” OR ”preferred temperature” OR ”temperature vote” OR ”thermal sensation” OR ”thermal preference” OR ”thermal satisfaction” OR ”thermal vote” OR ”thermal comfort” OR ”thermal analysis” OR ”thermal performance” OR ”indoor thermal” OR ”thermal analysis”
Location	Altitude	highland OR highlands OR “high altitude” OR altitude OR hypoxic OR hypoxia OR hypobaric OR “low pressure” OR mountain OR mountainous
	Regional	Ecuador OR Ecuadorian OR Ecuadorean Colombia OR Colombian Peru OR Peruvian
Environment	Indoor	dwelling OR dwellings OR building OR buildings OR residential OR house

altitude regions across the world, whereas the second focused on regional publications. Lastly, a third conceptual theme, environment, was used to constrain the indoor environment’s search only.

The systematic literature review used electronic databases available up to November 2019 at Scopus. Besides, some references found in the selected publications were also included. As well as any additional relevant paper published until November 2020. A total of 138 publications results from the searching criteria. After the electronic search, all the papers’ titles, abstracts, and keywords of each publication were analysed for further analysis. The criteria applied for inclusion and exclusion of a publication is described above:

Inclusion criteria:

- The main criteria for selection was the location conceptual theme. The criteria for selection correspond only to studies conducted in areas located at elevations above 1000m.
- Habitable indoor environments only.
- Studies that reports findings of the effect of altitude in human beings.
- Publications in English and Spanish.

Exclusion criteria:

- Search terms used in a different context as intended for the literature review. Location theme refers to the place where the study was conducted and not in a different context.
- Studies reporting the same results by the same author.

All papers reporting findings on subjective response to the thermal environment were included in the review of thermal comfort studies in high-altitude regions. Other publications relevant to the thermal environment assessment for enhancing comfort were included in the review of thermal performance in high-altitude regions.

Appendix B

Data collection instruments for data collection

B.1 Data collection instruments for the thermal comfort survey

The appendix contains the templates the instruments used for the thermal comfort data collection and the corresponding English translations. The instruments used include:

- Invitation letter used to provide information to potential participants (Section B.1.1 for the Spanish and English version)
- Thermal comfort questionnaire (Section B.1.2 for the Spanish version and Section B.1.3 for the English version)
- Auxiliary cards
- Survey observations sheet (Section B.1.4 for the Spanish version and Section B.1.5 for the English version)

B.1.1 Invitation letter for the thermal comfort survey

Estimado/a residente:

Amablemente queremos invitarlos a participar como voluntario en la recolección de datos para el proyecto **"ANÁLISIS DEL CLIMA INTERIOR DE VIVIENDAS EN LOS ANDES ECUATORIANOS"**. Este estudio es parte del trabajo de titulación de estudiantes de la **Escuela Politécnica Nacional** y **University College London**. El objetivo del estudio es entender el grado de satisfacción de los usuarios con la temperatura, humedad y movimiento del aire al interior de sus viviendas. Con el único fin de contribuir al conocimiento de la calidad ambiental interior en viviendas. Los resultados del mismo serán publicados en revistas y congresos académicos.

Su participación consta en responder un cuestionario, mientras se toman simultáneamente medidas de temperatura, humedad y movimiento del aire al interior de su vivienda. La visita durará entre 15 minutos aproximadamente y se coordinará previamente de acuerdo con su disponibilidad de tiempo. Si tiene alguna duda o requiere más información por favor comuníquese por mensaje o llamada telefónica al número 0998453645 o por correo electrónico a isabel.mino.16@ucl.ac.uk.

Esperamos contar con su valiosa participación.

Atentamente,

Adriana Cuenca, Alex Toasa e Isabel Miño

Escuela Politécnica Nacional y University College London

Dear resident:

We kindly invite you to participate as a volunteer in the data collection for the project **"ANALYSIS OF THE INTERIOR CLIMATE OF HOUSING IN THE ECUADORIAN ANDES"**. This study is part of the research work of students from the National Polytechnic School and University College London. The objective of the study is to understand the degree of satisfaction of the users with the temperature, humidity and air movement inside their homes. With the sole purpose of contributing to the knowledge of indoor environmental quality in homes. The results will be published in academic journals and conferences.

Your participation consists of answering a questionnaire, while simultaneously taking measurements of temperature, humidity and air movement inside your home. The visit will last approximately 15 minutes and will be previously coordinated according to your time availability. If you have any questions or require further information, please contact us by message or phone at 0998453645 or by email at isabel.mino.16@ucl.ac.uk.

We look forward to your valuable participation.

Sincerely,

Adriana Cuenca, Alex Toasa and Isabel Miño

National Polytechnic School and University College London

B.1.2 Thermal comfort questionnaire - Spanish template

TC002_ENCUESTA DE CONFORT TÉRMICO

Número de encuesta	TC-	Código participante	P-
Hora inicio		Lugar / Fecha	

Muchas gracias por su interés en participar en esta encuesta que busca entender que tan satisfechos están los usuarios con el clima interior de sus viviendas. Este estudio es parte de un proyecto de investigación desarrollado por estudiantes de "University College London" y de la Escuela Politécnica Nacional.

La encuesta durará 15 minutos aproximadamente. En este período se medirá la temperatura, humedad del ambiente y el movimiento del aire al interior de su vivienda. Simultáneamente, se le realizaran varias preguntas relacionadas al clima interior. No hay respuestas correcta o incorrecta, así que por favor responda lo primero que venga a su mente. Responder a esta encuesta no presenta ningún riesgo y usted y puede no responder cualquiera de las preguntas. Además, usted puede dejar de participar de este estudio en cualquier momento si así lo desea sin represalia alguna.

Su participación es completamente voluntaria. Sus datos personales no serán compartidos y usted no podrá ser identificado como participante en ningún momento. Los resultados de este proyecto se compartirán en publicaciones académicas.

Si tiene dudas o requiere una copia de sus datos y documentos, no dude en ponerse en contacto con Isabel Miño (09 9845 3645 o isabel.mino.16@ucl.ac.uk) o con el supervisor de este proyecto Héctor Altamirano (h.altamirano-medina@ucl.ac.uk).

Al responder las preguntas de esta encuesta usted confirma que se encuentra saludable y es mayor de 18 años. Que ha entendido la información del proyecto y acepta participar libremente.

SECCIÓN A – INFORMACIÓN DEL PARTICIPANTE

El objetivo de este estudio es entender que tanto frío o calor siente en su hogar. Está sensación se ve afectada por su vestimenta y las actividades que realiza.

1. Por favor, seleccione su rango de edad

☐ Menos de 20 años ☐ 20 – 29 años ☐ 30 – 39 años ☐ 40 – 49 años ☐ 50 – 59 años ☐ 60 – 65 años ☐ Más de 65 años ☐ Prefiere no indicar

Podría indicarme por favor su estatura y peso

Altura [ ] cm Peso [ ] kg Genero ☐ Hombre ☐ Mujer

2. Seleccione del listado las prendas que mejor describan lo que está usando. Indique el número correspondiente a todas las prendas que esté usando en este momento.

Parte alta del cuerpo (tronco y brazos)		Pies	
Parte baja del cuerpo (piernas)		Otros (Cuello/Cabeza)	

3. Podría indicar el estado de actividad en el que se encontraba realizando los últimos 30 minutos antes de iniciar la encuesta.

☐ Recostado ☐ Sentado ☐ De pie (quieto) ☐ Actividad ligera ☐ Actividad moderada ☐ Actividad pesada

SECCIÓN B – ADAPTACIÓN

Con el fin de entender su experiencia en ambientes residenciales, esta sección recopilará datos sobre su vivienda, así como de los lugares que más frecuenta.

4. ¿En dónde nació?
Ciudad ☐ País ☐

5. ¿Hace cuánto tiempo vive en esta casa?
☐ Menos de 1 año ☐ 1- 3 años ☐ Más de 3 años

6. Si su respuesta fue menos de un año por favor responda la siguiente pregunta. De lo contrario, continúe con la pregunta 6. Por favor llene los siguientes datos de su vivienda anterior.

a. ¿Cuánto tiempo vivió en su vivienda anterior?
☐ Menos de 1 año ☐ 1- 3 años ☐ Más de 3 años

b. Ubicación
Ciudad: ☐ Parroquia y barrio: ☐

c. Materiales de construcción predominante
Cubierta / Techo: ☐ Paredes: ☐

d. Tenía sistema de calefacción, aire acondicionado o ventiladores
☐ Si ☐ No ¿Cuál? ☐

e. Si compara la temperatura de su vivienda actual, con la de su casa anterior. Durante el día, la temperatura en mi vivienda anterior era…

☐	☐	☐	☐	☐	☐	☐
Mucho más fría	Más fría	Ligeramente más fría	Ni más fría, ni más caliente	Ligeramente más caliente	Más caliente	Mucho más caliente

f. Si compara la temperatura de su vivienda actual, con la de su casa anterior. Durante la noche, la temperatura en mi vivienda anterior era…

☐	☐	☐	☐	☐	☐	☐
Mucho más fría	Más fría	Ligeramente más fría	Ni más fría, ni más caliente	Ligeramente más caliente	Más caliente	Mucho más caliente

7. En promedio, ¿cuántas horas al día pasa al interior de su vivienda? ____________________ horas

8. En una semana típica, ¿cuántos días sale regularmente de su parroquia/barrio?
☐ Ninguno ☐ 1 d ☐ 2 d ☐ 3 d ☐ 4 d ☐ 5 d ☐ 6 d ☐ 7 d

9. ¿A dónde se dirige usualmente cuando sale de su parroquia/barrio?
☐ Sur ☐ Centro ☐ Norte ☐ Valles ☐ Otro

10. ¿Cuántos días a la semana está en ambientes que tienen aire acondicionado (Incluyendo el auto)?
☐ Ninguno ☐ 1 d ☐ 2 d ☐ 3 d ☐ 4 d ☐ 5 d ☐ 6 d ☐ 7 d

11. ¿Cómo es la temperatura en su lugar de trabajo?

☐	☐	☐	☐	☐	☐	☐
Muy frío	Frío	Ligeramente frío	Ni caliente, ni frío	Ligeramente caliente	Caliente	Muy caliente

12. ¿Aproximadamente cuántas horas al día realiza actividades al aire libre? ________________ horas

SECCIÓN C – SÍNTOMAS Y MOLESTIAS EN EL HOGAR

13. Durante los últimos tres meses, ¿Ha tenido alguno de los siguientes síntomas?

				¿Cree que está asociado al clima en su vivienda?	
	Mucho	A veces	Nunca	Si	No
Fatiga o cansancio	☐	☐	☐	☐	☐

Dolor de cabeza	☐	☐	☐	☐	☐
Nauseas o mareo	☐	☐	☐	☐	☐
Irritación de los ojos	☐	☐	☐	☐	☐
Congestión nasal	☐	☐	☐	☐	☐
Garganta seca o ronca	☐	☐	☐	☐	☐
Resfrío	☐	☐	☐	☐	☐
Picazón del cuero cabelludo u orejas	☐	☐	☐	☐	☐
Piel reseca o enrojecida del rostro	☐	☐	☐	☐	☐
Manos secas, picazón o piel roja	☐	☐	☐	☐	☐
¿Algún otro?	☐	☐	☐	☐	☐

14. Durante los últimos tres meses, ¿Ha sentido alguna de las siguientes molestias en su vivienda?

	Mucho	A veces	Nunca
Corrientes de aire (chiflón)	☐	☐	☐
Temperatura del cuarto muy alta	☐	☐	☐
Cambio brusco de temperatura durante el día	☐	☐	☐
Temperatura del cuarto muy baja	☐	☐	☐
Aire denso / concentrado	☐	☐	☐
Ambiente húmedo	☐	☐	☐
Aire seco	☐	☐	☐
¿Algún otro?	☐	☐	☐

15. Que tanto le afecta la temperatura a las actividades que realiza al interior de su vivienda...

a. Al dormir

☐ Mucho ☐ Poco ☐ Nada

b. Al realizar las tareas del hogar/o actividades ligeras

☐ Mucho ☐ Poco ☐ Nada

SECCIÓN D – ESTRATEGIAS DE CONTROL

16. ¿Ha hecho algún cambio en su casa para mejorar la temperatura, es decir, para que los espacios sean más caliente o más frío?

17. En un día típicamente frío, ¿Qué hace normalmente para mantenerse caliente? Seleccione todas las acciones que aplican de la lista.

☐	Abrir puertas				
☐	Cerrar puertas	☐	Comer alimentos calientes	☐	Usar ropa más ligera
☐	Abrir ventanas	☐	Comer alimentos fríos	☐	Uso de ventilador
☐	Cerrar ventanas	☐	Tomar bebidas calientes	☐	Uso de calefactor
☐	Abrir cortinas	☐	Tomar bebidas frías	☐	Ninguna
☐	Cerrar cortinas	☐	Usar ropa más abrigada	Otra	

18. En un día típicamente caluroso, ¿Qué hace normalmente para mantenerse fresco? Seleccione todas las acciones que aplican de la lista.

☐	Abrir puertas				
☐	Cerrar puertas	☐	Comer alimentos calientes	☐	Usar ropa más ligera
☐	Abrir ventanas	☐	Comer alimentos fríos	☐	Uso de ventilador
☐	Cerrar ventanas	☐	Tomar bebidas calientes	☐	Uso de calefactor
☐	Abrir cortinas	☐	Tomar bebidas frías	☐	Ninguna
☐	Cerrar cortinas	☐	Usar ropa más abrigada	Otra	

SECCIÓN E – CLIMA INTERIOR

En la siguiente nos vamos a enfocar únicamente en lo que está sintiendo en esta habitación, aquí y ahora.

19. **En este momento, ¿Cómo siente la temperatura de está habitación?**

☐	☐	☐	☐	☐	☐	☐
Muy frío	Frío	Ligeramente frío	Ni caliente, ni frío	Ligeramente caliente	Caliente	Muy caliente

20. **A su criterio, como la encuentra…**

☐	☐	☐	☐	☐
Agradable	Ligeramente desagradable	Desagradable	Muy desagradable	Extremadamente desagradable

21. **Por favor, indique cómo preferiría que sea la temperatura en este momento. Yo preferiría que sea…**

☐	☐	☐	☐	☐	☐	☐
Mucho más frío	Más frío	Ligeramente más frío	Sin cambio	Ligeramente más caliente	Más caliente	Mucho más caliente

22. **¿Hay alguna parte de su cuerpo en la que sienta frío ahora?**

☐	☐	☐	☐	☐	☐	☐	☐	☐
Manos	Pies	Cabeza	Pecho	Espalda	Brazos	Piernas	Otro	Ninguna

23. **¿Hay alguna parte de su cuerpo en la que siente más calor ahora?**

☐	☐	☐	☐	☐	☐	☐	☐	☐
Manos	Pies	Cabeza	Pecho	Espalda	Brazos	Piernas	Otro	Ninguna

24. **En este momento, ¿Cómo siente la humedad del ambiente?**

☐	☐	☐	☐	☐	☐	☐
Muy seco	Seco	Ligeramente seco	Ni seco, ni húmedo	Ligeramente húmedo	Húmedo	Muy húmedo

25. **Por favor indique, ¿Cómo preferiría que sea la humedad ahora? Yo preferiría que sea…**

☐	☐	☐	☐	☐	☐	☐
Mucho más seco	Más seco	Ligeramente más seco	Sin cambio	Ligeramente más húmedo	Más húmedo	Mucho más húmedo

26. **En este momento, ¿Puede sentir el movimiento de aire al interior?**

☐	☐	☐	☐	☐
Sin movimiento	Muy ligero	Ligero	Intenso	Muy intenso

27. **Por favor, Indique como preferiría que sea el movimiento del aire en esta habitación ahora. Yo preferiría que haya…**

☐	☐	☐	☐	☐	☐	☐
Mucho más aire	Mas aire	Un poco más de aire	Sin (ningún) cambio	Un poco menos aire	Menos aire	Mucho menos aire

28. **Tomando en cuenta las preguntas anteriores sobre temperatura, humedad y movimiento del aire. ¿Cómo se siente con respecto al clima interior de su vivienda?**

☐ Satisfecho ☐ Insatisfecho

29. **Tiene algún comentario adicional sobre el clima interior en su vivienda**

Muchísimas gracias por su tiempo y participación en esta encuesta. Si está de acuerdo en continuar como voluntario/a en esta investigación dentro de los próximos meses y acepta ser contactado a futuro para otra encuesta, por favor indique al encuestador/a sus datos y modo de contacto preferidos.

B.1.3 Thermal comfort questionnaire - English template

UCL

THERMAL COMFORT TC002_SURVEY

Survey number	TC-	Participating code	P-
Start time		Place / Date	

Thank you very much for your interest in participating in this survey to understand how satisfied users are with their homes' interior climate. This study is part of a research project developed by students from University College London and the National Polytechnic School.

The survey will last approximately 15 minutes. In this period, the temperature, humidity and air movement will be measured. Simultaneously, you will be asked several questions related to the indoor environment. There are no right or wrong responses, so please answer the first thing that comes to your mind. Answering this survey presents no risk, and you and may not answer any of the questions. Besides, you may stop participating in this study at any time if you wish without any reprisal.

Your participation is entirely voluntary. Your personal data will not be shared, and you will not be identified as a participant at any time. The results of this project will be shared in academic publications.

If you have any doubts or require a copy of your data and documents, please do not hesitate to contact Isabel Miño (09 9845 3645 or isabel.mino.16@ucl.ac.uk) or the supervisor of this project, Héctor Altamirano (h.altamirano-medina@ucl.ac.uk).

By answering the questions in this survey, you confirm that you are healthy and over 18 years old and understand the project information and agree to participate freely.

SECTION A - PARTICIPANT INFORMATION

The goal of this study is to understand how hot or cold you feel in your home. This feeling is affected by your clothing and activities.

1. Please select your age range

☐	☐	☐	☐	☐	☐	☐	☐
Under 20 years old	20 - 29 years old	30 - 39 years old	40 - 49 years old	50 - 59 years old	60 - 65 years old	Over 65 years	Prefers not to indicate

Could you please tell me your height and weight?

Height ☐ Cm Weight ☐ Kg Gender ☐ Male ☐ Female

2. Select from the list the garments that best describe what you are wearing. Enter the number for all the garments you are currently wearing.

Upper body part (trunk and arms)		Feet	
Lower body (legs)		Other (Neck/Head)	

3. You could indicate the activity status you were doing in the last 30 minutes before starting the survey.

☐	☐	☐	☐	☐	☐
Lying	Sitting	Standing (quiet)	Light activity	Moderate activity	Heavy activity

SECTION B - ACCLIMATISATION

In order to understand your experience in residential environments, this section will collect data about your home, as well as the places you frequent most.

4. Where were you born?

City ☐ Country ☐

5. How long have you lived in this house?

☐ Less than 1 year ☐ 1- 3 years ☐ More than 3 years

6. If your answer was less than one year, please answer the following question. Otherwise, continue with question 6. Please fill out the following information about your previous home.

a. How long did you live in your former home?

☐ Less than 1 year ☐ 1- 3 years ☐ More than 3 years

b. Location

City: ☐ Parish and ward: ☐

c. Predominant building envelope materials

Roof/Ceiling: ☐ Walls: ☐

d. Does it had a heating system, air conditioning or fans?

☐ Yes ☐ No Which one? ☐

e. If you compare the temperature in your current home with that of your previous home. During the day, the temperature in my previous home was...

☐ Much cooler ☐ Cooler ☐ Slightly cooler ☐ Neither warmer nor cooler ☐ Slightly warmer ☐ Warmer ☐ Much warmer

f. If you compare the temperature in your current home with that of your previous home. During the night, the temperature in my previous home was...

☐ Much cooler ☐ Cooler ☐ Slightly cooler ☐ Neither warmer nor cooler ☐ Slightly warmer ☐ Warmer ☐ Much warmer

7. On average, how many hours a day do you spend inside your home? ________________days

8. In a typical week, how many days do you regularly leave your parish/neighbourhood?

☐ None ☐ 1 d ☐ 2 d ☐ 3 d ☐ 4 d ☐ 5 d ☐ 6 d ☐ 7 d

9. Where do you usually go when you leave your parish/neighbourhood?

☐ On ☐ Centre ☐ North ☐ Valleys ☐ Other

10. How many days a week are you in an air-conditioned environment (including the car)?

☐ None ☐ 1 d ☐ 2 d ☐ 3 d ☐ 4 d ☐ 5 d ☐ 6 d ☐ 7 d

11. What is the temperature like in your workplace?

☐ Cold ☐ Cool ☐ Slightly cool ☐ Neutral ☐ Slightly warm ☐ Warm ☐ Hot

12. Approximately how many hours a day do you spend outdoors? ____________________ hours

SECTION C – SYMPTOMS AND DISCOMFORT AT HOME

13. During the past three months, have you had any of the following symptoms?

				Do you think it is associated with the climate in your home?	
	A lot	Sometimes	Never	Yes	No
Fatigue or tiredness	☐	☐	☐	☐	☐
Headache	☐	☐	☐	☐	☐

Nausea or dizziness	☐	☐	☐	☐	☐
Eye irritation	☐	☐	☐	☐	☐
Nasal congestion	☐	☐	☐	☐	☐
Dry throat	☐	☐	☐	☐	☐
Flu	☐	☐	☐	☐	☐
Itching of the scalp or ears	☐	☐	☐	☐	☐
Dry or red skin on the face	☐	☐	☐	☐	☐
Dry hands, itching or red skin	☐	☐	☐	☐	☐
Any others?	☐	☐	☐	☐	☐

14. For the past three months, have you felt any of the following discomfort in your home?

	A lot	Sometimes	Never
Draught	☐	☐	☐
High temperature	☐	☐	☐
Diurnal temperature oscillation	☐	☐	☐
Low temperature	☐	☐	☐
Stuffy or dense air	☐	☐	☐
Humid environment	☐	☐	☐
Dry air	☐	☐	☐
Any others?	☐	☐	☐

15. How much does the temperature affect the activities you do inside your home?

a. While sleeping

☐ A lot ☐ Little ☐ Nothing

b. While performing household chores/or light activities

☐ A lot ☐ Little ☐ Nothing

SECTION D - CONTROL STRATEGIES

16. Have you made any changes in your home to improve the temperature, that is, to make the spaces warmer or colder?

17. On a typical cold day, what do you normally do to keep warm? Select all the actions that apply from the list.

☐ Open doors		
☐ Close doors	☐ Eating hot foods	☐ Wearing lighter clothing
☐ Open windows	☐ Eating cold foods	☐ Fan use
☐ Closing windows	☐ Drinking hot drinks	☐ Using a heater
☐ Drawing curtains	☐ Drinking cold drinks	☐ None
☐ Closing curtains	☐ Wearing warmer clothes	Another

18. On a typically hot day, what do you normally do to keep cool? Select all the actions that apply from the list.

☐ Open doors		
☐ Close doors	☐ Eating hot foods	☐ Wearing lighter clothing
☐ Open windows	☐ Eating cold foods	☐ Fan use
☐ Closing windows	☐ Drinking hot drinks	☐ Using a heater
☐ Drawing curtains	☐ Drinking cold drinks	☐ None
☐ Closing curtains	☐ Wearing warmer clothes	Another

SECTION E – INDOOR CLIMATE

This section will focus only on what you are feeling in this room, right here and right now.

19. Right now, how do you feel the temperature of this room?

☐ Cold ☐ Cool ☐ Slightly cool ☐ Neither warn, nor cool ☐ Slightly warm ☐ Warm ☐ Hot

20. In your opinion, how do you find it…?

☐ Comfortable ☐ Slightly uncomfortable ☐ Uncomfortable ☐ Very uncomfortable ☐ Extremely uncomfortable

21. At this moment, please state how would you prefer it to be…

☐ Much cooler ☐ Cooler ☐ Slightly cool ☐ Without change ☐ Slightly warmer ☐ Warmer ☐ Much warmer

22. Is there any part of your body where you feel cooler right now?

☐ Hands ☐ Feet ☐ Head ☐ Chest ☐ Back ☐ Arms ☐ Legs ☐ Other ☐ No

23. Is there any part of your body where you feel warmer right now?

☐ Hands ☐ Feet ☐ Head ☐ Chest ☐ Back ☐ Arms ☐ Legs ☐ Other ☐ No

24. Right now, how do you feel the humidity in the environment?

☐ Very dry ☐ Dry ☐ Slightly dry ☐ Neither humid nor dry ☐ Slightly humid ☐ Humid ☐ Very humid

25. Please indicate how would you prefer the humidity to be now? I'd rather it be…

☐ Very dry ☐ Dry ☐ A bit drier ☐ Without change ☐ A bit more humid ☐ Humid ☐ Much more humid

26. Right now, can you feel the movement of air inside?

☐ No movement ☐ Still ☐ Just right ☐ Breezy ☐ Too breezy

27. Please indicate how I'd rather have the air movement in this room now. I would prefer that there be…

☐ Much more air ☐ More air ☐ A bit more air ☐ Without change ☐ A bit less air ☐ Less air ☐ Much less air

28. Taking into account the above questions about temperature, humidity and air movement. How do you feel about the interior climate of your home?

☐ Satisfied ☐ Dissatisfied

29. You have some additional comments about the interior climate in your home

Thank you very much for your time and participation in this survey. If you agree to continue volunteering in this research within the next few months and agree to be contacted in the future for another survey, please indicate to the surveyor your preferred contact information and mode of contact.

B.1.4 Survey observations sheet - Spanish template

UCL

TC003_OBSERVACIONES DEL ENCUESTADOR

Fecha		Parroquia		Código de la encuesta	TC-
				Código participante	
Hora Inicio		Hora de voto		Hora finalización	

SECCIÓN A – VIVIENDA

Datos de la vivienda	
☐ Tipo A (Bloque y zinc)	☐ Tipo C (Ladrillo y tejas de arcilla)
☐ Tipo B (Bloque y hormigón armado)	☐ Otro

SECCIÓN B – CONTEXTO

Ubicación del participante		
En qué posición se encuentra sentado el participante		
Participante	☐ Espalada apoyada atrás	☐ Sentado al borde sin apoyar la espalda
Participante	☐ Espalada apoyada atrás	☐ Sentado al borde sin apoyar la espalda

En qué tipo de silla-sillón se encuentra sentado				
☐ Silla de malla/metal	☐ Taburete de madera	☐ Silla de oficina	☐ Sillón	Otra

Observaciones del entorno	
Fuentes de calor o frío	
Ventanas (Abiertas/cerradas)	
Puertas (Abiertas/cerradas)	
Condición especial	
Otros	

SECCIÓN C – CONDICIONES DEL AMBIENTE INTERIOR

Variable	Inicio		Voto (3M- Testo)		Final	
Temperatura del aire		°C		°C		°C
Temperatura de globo		°C		°C		°C
Humedad relativa		%		%		%
Velocidad del aire		m/s		m/s		m/s
CO2		ppm		ppm		ppm
Temperatura superficial – Pared		°C		°C		°C
Temperatura superficial – Pared		°C		°C		°C
Temperatura superficial – Pared		°C		°C		°C
Temperatura superficial – Pared		°C		°C		°C
Temperatura superficial – Techo		°C		°C		°C
Temperatura superficial - Piso		°C		°C		°C
Presión atmosférica		hPa		hPa		hPa

Comentarios

B.1.5 Survey observations sheet - English template

UCL

TC003_INTERVIEWER'S COMMENTS

Date		Parish		Survey code	TC-
				Participant code	
Start Time		Voting time		End time	

SECTION A – DWELLING

Dewlling data	
☐ Type A (Block and Zinc)	☐ Type C (Brick and Clay tiles)
☐ Type B (Block and Reinforced Concrete)	☐ Other

SECTION B - CONTEXT

Participant's position		
In which position the participant is sitting		
Participant	☐ Back resting on the chair/sofa	☐ Sitting on the edge without back support
Participant	☐ Back resting on the chair/sofa	☐ Sitting on the edge without back support

What kind of chair-chair you're sitting in				
☐ Net/metal chair	☐ Wooden stool	☐ Office chair	☐ Armchair	Another

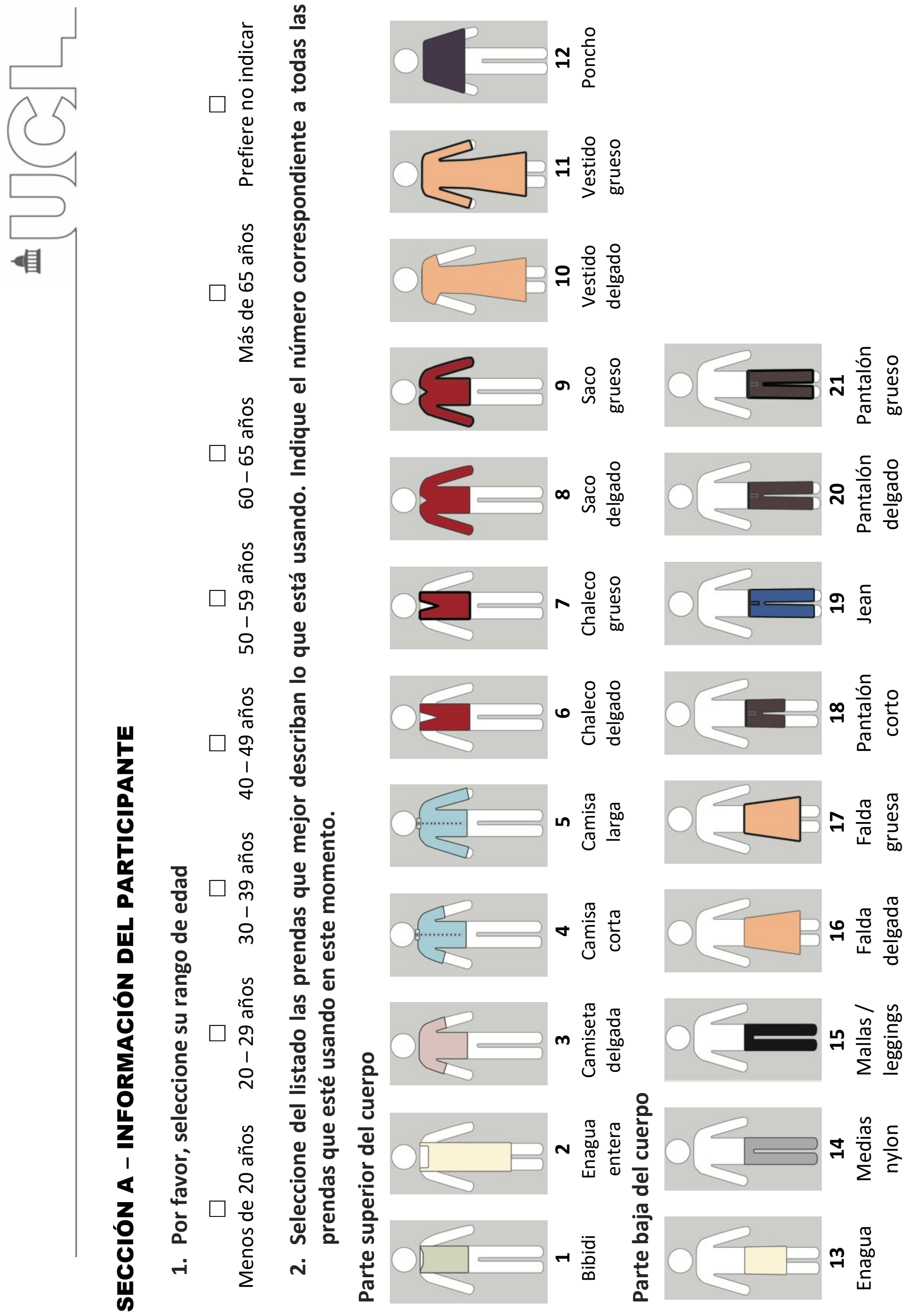
Environmental observations	
Heat or cold sources	
Windows (Open/Closed)	
Doors (Open/Closed)	
Special condition	
Other	

SECTION C – INDOOR ENVIRONEMNTAL CONDITIONS

Variable	Home		Vote (3M- Text)		Final	
Air temperature		°C		°C		°C
Globe temperature		°C		°C		°C
Relative humidity		%		%		%
Air speed		m/s		m/s		m/s
CO2		ppm		ppm		ppm
Surface temperature - Wall		°C		°C		°C
Surface temperature - Wall		°C		°C		°C
Surface temperature - Wall		°C		°C		°C
Surface temperature - Wall		°C		°C		°C
Surface temperature - Roof		°C		°C		°C
Surface temperature - Floor		°C		°C		°C
Atmospheric pressure		hPa		hPa		hPa

Observations

B.1.6 Auxiliary cards for multiple choice and scale answers



SECCIÓN A – INFORMACIÓN DEL PARTICIPANTE

1. Por favor, seleccione su rango de edad

☐ Menos de 20 años ☐ 20 – 29 años ☐ 30 – 39 años ☐ 40 – 49 años ☐ 50 – 59 años ☐ 60 – 65 años ☐ Más de 65 años ☐ Prefiere no indicar

2. Seleccione del listado las prendas que mejor describan lo que está usando. Indique el número correspondiente a todas las prendas que esté usando en este momento.

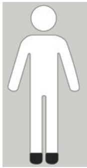
Parte superior del cuerpo

1 Bibidi
2 Enagua entera
3 Camiseta delgada
4 Camisa corta
5 Camisa larga
6 Chaleco delgado
7 Chaleco grueso
8 Saco delgado
9 Saco grueso
10 Vestido delgado
11 Vestido grueso
12 Poncho

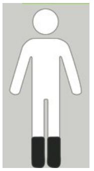
Parte baja del cuerpo

13 Enagua
14 Medias nylon
15 Mallas / leggings
16 Falda delgada
17 Falda gruesa
18 Pantalón corto
19 Jean
20 Pantalón delgado
21 Pantalón grueso

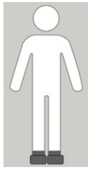
Pies



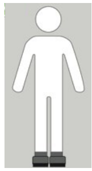
22
Medias tobilleras



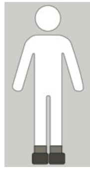
23
Medias altas



24
Zapatos de suela delgada

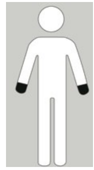


25
Zapatos de suela gruesa

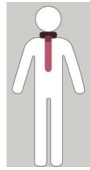


26
Botas

Otros

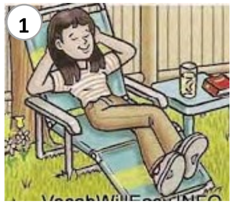


27
Guantes



28
Bufanda

3. Listado de actividades



1
Recostado

2
Sentado, relajado

3
De pie (quieto)

4
De pie – Actividad ligera
Ej. Caminar lento

5
De pie – Actividad moderada
Ej. Quehaceres del hogar, cocinar, lavar platos

6
De pie – Actividad pesada
Ej. Levantar o mover muebles, ejercicio

SECCIÓN B – ADAPTACIÓN

5. Tiempo de residencia en su vivienda

a. Menos de 1 año b. Entre 1 y 3 años c. Más de 3 años

6. La temperatura en mi vivienda anterior era…

☐	☐	☐	☐	☐	☐	☐
Mucho más fría	Más fría	Ligeramente más fría	Ni más fría, ni más caliente	Ligeramente más caliente	Más caliente	Mucho más caliente

8. ¿Cuántos días a la semana…?

☐ Ninguno ☐ 1 día ☐ 2 días ☐ 3 días ☐ 4 días ☐ 5 días ☐ 6 días ☐ 7 días

9. ¿A dónde se dirige usualmente cuando sale de su parroquia/barrio?

☐ Sur ☐ Centro ☐ Norte ☐ Valles ▭ Otro

10.¿Cuántos días a la semana está en ambientes que tienen aire acondicionado (Incluyendo el auto)?

☐ Ninguno ☐ 1 día ☐ 2 días ☐ 3 días ☐ 4 días ☐ 5 días ☐ 6 días ☐ 7 días

11.¿Cómo es la temperatura en su lugar de trabajo?

☐	☐	☐	☐	☐	☐	☐
Muy frío	Frío	Ligeramente frío	Ni frío, ni caliente	Ligeramente caliente	Caliente	Muy caliente

SECCIÓN C – SÍNTOMAS Y MOLESTIAS EN EL HOGAR

13.Durante los últimos tres meses, ¿ha tenido alguno de los siguientes síntomas?

Síntoma	Cada semana **MUCHO** ☐	Una vez al mes **A VECES** ☐	No **NUNCA** ☐	¿Cree que este síntoma se debe a la temperatura en su vivienda? Si ☐ No ☐

14.Durante los últimos tres meses, ¿Ha sentido alguna de las siguientes molestias en su vivienda?

Molestias	Cada semana **MUCHO** ☐	Una vez al mes **A VECES** ☐	No **NUNCA** ☐

15.Que tanto le afecta la temperatura al interior de su vivienda…

a. Al dormir

☐ Mucho ☐ Poco ☐ Nada

b. Al realizar las tareas del hogar/o actividades ligeras

☐ Mucho ☐ Poco ☐ Nada

SECCIÓN E – CLIMA INTERIOR

En la siguiente sección se consultará su opinión sobre el clima interior en su vivienda.

TEMPERATURA

17.En este momento, ¿Cómo siente la temperatura de está habitación?

☐	☐	☐	☐	☐	☐	☐
Muy frío	Frío	Ligeramente frío	Ni caliente, ni frío	Ligeramente caliente	Caliente	Muy caliente

18.A su criterio, como la encuentra…

☐	☐	☐	☐	☐
Agradable	Ligeramente desagradable	Desagradable	Muy desagradable	Extremadamente desagradable

19.Por favor, indique cómo preferiría que sea la temperatura en este momento. Yo preferiría que sea…

☐	☐	-1 ☐	☐	☐	☐	☐
Mucho más frío	Más frío	Ligeramente más frío	Sin cambio	Ligeramente más caliente	Más caliente	Mucho más caliente

20.¿Hay alguna parte de su cuerpo en la que sienta frío ahora? Alguna parte que la sienta más caliente.

☐	☐	☐	☐	☐	☐	☐	☐	☐
Manos	Pies	Cabeza	Pecho	Espalda	Brazos	Piernas	Otro	Ninguna

HUMEDAD

21.En este momento, ¿Cómo siente la humedad del ambiente?

☐	☐	☐	☐	☐	☐	☐
Muy húmedo	Húmedo	Ligeramente Húmedo	Ni húmedo, ni seco	Ligeramente seco	Seco	Muy seco

22.Por favor indique, ¿Cómo preferiría que sea la humedad ahora? Yo preferiría que sea…

☐	☐	☐	☐	☐	☐	☐
Mucho más seco	Más seco	Ligeramente más seco	Sin cambio	Ligeramente más húmedo	Más húmedo	Mucho más húmedo

MOVIMIENTO DEL AIRE

23.En este momento, ¿Cómo se siente el movimiento de aire al interior de esta habitación?

☐	☐	☐	☐	☐
Muy ligero	Ligero	Sin movimiento	Intenso	Muy intenso

24.Por favor, Indique como preferiría que sea el movimiento del aire en esta habitación ahora. Yo preferiría que haya…

☐	☐	☐	☐	☐	☐	☐
Mucho menos aire	Menos aire	Un poco menos aire	Sin cambio	Un poco más aire	Más aire	Mucho más aire

25.¿Cómo se siente con respecto al clima interior de su vivienda?

☐ Satisfecho ☐ Insatisfecho

B.2 Data collection instruments for archetypes' audit

The appendix contains the templates the instruments used for dwellings audit and monitoring and the corresponding English translations. The instrument used include:

- The project information sheet for the householders of audited dwellings (Section B.2.1 for the Spanish version and Section B.2.2 for the English version)
- Consent form template for dwelling audit and monitoring campaign (Section B.2.3 for the Spanish version and Section B.2.4 for the English version)
- Dwellings data collection form is the template used for the collection of data from the surveyed dwelling (Section B.2.3 for the Spanish version and Section B.2.4 for the English version)

B.2.1 Information sheet for householders - Spanish template

BS002_HOJA INFORMATIVA

ANÁLISIS DEL CLIMA INTERIOR DE VIVIENDAS EN LOS ANDES ECUATORIANOS

¿Por qué estamos haciendo esta investigación?
El clima al interior de la vivienda podría influir positiva o negativamente en la salud, bienestar y productividad de los usuarios. Este estudio es parte del trabajo de titulación de estudiantes de la Escuela Politécnica Nacional y University College London. El objetivo del estudio es entender el grado de satisfacción de los usuarios con la temperatura, humedad y movimiento del aire al interior de sus viviendas.

¿Qué implica su participación en este estudio?
Su valiosa participación en este estudio comprende en que nos permita:

Tomar medidas de su vivienda, tales como (a) dimensiones de la vivienda y (b) mediciones de temperatura, humedad y calidad del aire al interior de su vivienda. Además, Llenar un cuestionario sobre su apreciación del ambiente interior en la vivienda y el uso de la misma.

Como participante, usted recibirá una copia de los datos e información de su vivienda, tales como planos arquitectónicos, fotografías y otros.

Equipo de medición de temperatura y humedad

¿Quién está invitado a participar?
Se ha invitado a participar a los usuarios cuyas viviendas cumplen con los criterios de selección de este estudio. Uno o más personas que habitan la vivienda pueden ser parte del estudio. Los participantes tienen que adultos que gocen de buen estado de salud y se encuentren entre 18 y 65 años.

¿Alguien podrá saber sobre mi participación?
Su participación es confidencial, es decir, sus datos personales no serán compartidos. Además, ni usted, ni su vivienda podrán ser identificado en ningún momento.

¿Existe algún riesgo al participar?
No hay ningún riesgo asociado para usted como participante de este proyecto de investigación.

¿Qué pasará con los resultados de la investigación?
Los resultados de esta investigación nos permitirán concluir exitosamente nuestros estudios y se presentarán en tesis de titulación, así como en conferencias y publicaciones académicas. Finalmente, si es de interés de los participantes, se preparará una charla para presentar los resultados preliminares del trabajo una vez finalizada la recolección de los datos.

¿Tengo que participar?
Su participación es este estudio es totalmente voluntaria. Usted puede dejar de responder cualquiera de las preguntas, además, puede dejar de participar de este estudio en cualquier momento sin represalia alguna.

Si tiene alguna duda o requiere más información por favor comuníquese con Isabel Miño (0998xxxxxx / isabel.mino.16@ucl.ac.uk). Esperamos contar con su participación y que esta sea una grata experiencia.

Esperamos contar con su valiosa participación.
Adriana Cuenca, Alex Toasa e Isabel Miño
Escuela Politécnica Nacional y Universtiy College London

B.2.2 Information sheet for householders - English template

BS002_INFORMATION SHEET

ANALYSIS OF THE INTERIOR ENVIRONMENT OF DWELLINGS IN THE ECUADORIAN ANDES

Why are we doing this research?

The indoor environment could positively or negatively influence the health, well-being and productivity of users. This study is part of the graduate work of students from the National Polytechnic School and University College London. The aim of the study is to understand users' satisfaction with the temperature, humidity and air movement inside their homes.

What does your participation in this study entail?

Your valuable participation in this study understands that it allows us:

Take measurements of your home, such as (a) dimensions of the home and (b) measurements of temperature, humidity and air quality inside your home. In addition, fill out a questionnaire about your assessment of the indoor environment in the dwelling and the use of it.

As a participant, you will receive a copy of your home's data and information, such as architectural plans, photographs, and others.

Temperature and humidity monitoring equipment

Who is invited to participate?

Users whose homes meet the selection criteria of this study have been invited to participate. One or more persons who live in the dwelling may be part of the study. Participants must be adults in good health between the ages of 18 and 65.

Will anyone know about my participation?

Your participation is confidential, that is, your personal information will not be shared. In addition, neither you nor your household will be identified at any time.

Is there any risk in participating?

There is no risk associated with your participation in this research project.

What will happen to the results of the research?

The results of this research will allow us to successfully conclude our studies and will be presented in degree theses, as well as at conferences and in academic publications. Finally, if it is of interest to the participants, a talk will be prepared to present the preliminary results of the work once the data collection is completed.

Do I have to participate?

Your participation in this study is entirely voluntary. You may stop answering any of the questions, and you may stop participating in this study at any time without reprisal.

If you have any questions or require further information please contact Isabel Miño (0998xxxxxx / isabel.mino.16@ucl.ac.uk). We hope to count on your participation and that this will be a pleasant experience.

We hope to count on your valuable participation.
Adriana Cuenca, Alex Toasa and Isabel Miño
National Polytechnic School and University College London

B.2.3 Consent form for the dwellings audit - Spanish template

BS003_CONSENTIMIENTO INFORMADO

ANÁLISIS DEL CLIMA INTERIOR DE VIVIENDAS EN LOS ANDES ECUATORIANOS

Agradecemos gratamente su disposición a participar en este estudio. Antes de continuar, por favor, podría completar el siguiente formulario marcando las casillas que correspondan y firmando al final del documento.

He entendido que...

- Que mi participación en el estudio es completamente voluntaria ☐
- Que puedo omitir cualquier pregunta y dejar de participar de este estudio en cualquier momento sin represalia alguna. ☐
- Mis datos personales no serán compartidos ☐
- No podre ser identificado como participante en ninguna fase del proyecto ☐
- Los resultados de este estudio serán presentados en congresos y publicaciones científicas. ☐
- La información recibida del proyecto y las repuestas a inquietudes fueron satisfactorias. ☐

Además, confirmo que

- Acepto libremente a participar en este proyecto de investigación según se indica en la hoja informativa. ☐
- La entrevista sea grabada en audio ☐
- Se tomen fotografías de ciertos detalles de mi vivienda ☐
- Se instalen equipos de monitoreo ☐
- Se tomen mediciones de la vivienda ☐

Si está de acuerdo en continuar como voluntario en esta investigación y acepta ser contactado a futuro para otra encuesta, por favor seleccione la casilla e indique al encuestar sus dato y modo de contacto preferidos. ☐

Si tiene dudas o requiere una copia de sus datos, por favor contacte a Isabel Mino (09 xxxx xxxx o isabel.mino.16@ucl.ac.uk) a al supervisor de tesis, Héctor Altamirano (h.altamirano-medina@ucl.ac.uk).

PARTICIPANTE	ENCUESTADOR
Nombre	Nombre
Firma	Firma
	Fecha

*Una vez que complete el formulario, una copia es para el participante y otra para el encuestador.

B.2.4 Consent form for the dwellings audit - English template

BS003_ INFORMED CONSENT

ANALYSIS OF THE INTERIOR ENVIRONMENT OF DWELLINGS IN THE ECUADORIAN ANDES

We appreciate your willingness to participate in this study. Before continuing, please complete the following form by checking the appropriate boxes and signing at the end of the document.

I understand that...

- That my participation in the study is completely voluntary ☐
- That I may skip any questions and stop participating in this study at any time without reprisal. ☐
- My personal data will not be shared ☐
- I cannot be identified as a participant in any phase of the project ☐
- The results of this study will be presented at congresses and in scientific publications. ☐
- The information received from the project and the responses to concerns were satisfactory. ☐

I also confirm that

- I freely agree to participate in this research project as outlined in the fact sheet. ☐
- The interview is recorded on audio ☐
- Photographs are taken of certain details of my home ☐
- Monitoring equipment is installed ☐
- Measurements are taken of the dwelling ☐

f you agree to continue volunteering in this research and agree to be contacted in the future for another survey, please check the box and indicate your preferred contact information and mode of contact when surveying. ☐

Si tiene dudas o requiere una copia de sus datos, por favor contacte a Isabel Mino (09 xxxx xxxx o isabel.mino.16@ucl.ac.uk) a al supervisor de tesis, Héctor Altamirano (h.altamirano-medina@ucl.ac.uk).

PARTICIPANT	INTERVIEWER
Name	Name
Signature	signature
	Date

*Once the form is completed, one copy is for the participant and one for the interviewer.

B.2.5 Dwellings data collection form - Spanish template

UCL

BS004_ENCUESTA DE VIVIENDAS

Fecha		Parroquia		Código de la encuesta	BS-
Hora Inicio		Barrio		Tipo de vivienda	
Hora final		Altitud			

SECCION A - PLANOS DE LA EDIFICACION

- ☐ Orientación
- ☐ Elementos de sombra
- ☐ Contexto (Anexo 1)
- ☐ Planos arquitectónicos (Anexo 2)

SECCIÓN B – MATERIALES DE LA ENVOLVENTE

	Materiales	Espesor
Pared norte		
Pared sur		
Pared este		
Pared oeste		
Piso		
Techo		
Ventanas		
Puerta(s) exterior		

SECCIÓN C – PERFILES DE USO

En la siguiente sección se recolectará datos sobre las principales fuentes de ganancia de calor al interior de las viviendas, es decir, personas, equipos e iluminación, y sus horarios de ocupación y uso.

USUARIOS				Semana				Fin de semana			
	Niño/Adulto	Género	Espacio favorito	Despierta	Sale	Regresa	Duerme	Se despierta	Sale	Regresa	Se duerme
1											
2											
3											
4											
5											
6											

EQUIPOS	Potencia	Semana				Fin de semana			
		Encendido	Apagado	Encendido	Apagado	Encendido	Apagado	Encendido	Apagado

ILUMINACIÓN			COCINA	Semana		Fin de semana	
Operación		Potencia		Inicio	Duración	Inicio	Duración
Encendido			Desayuno				
Apagado			Almuerzo				
Encendido			Cena				
Apagado			Otros				

RENOVACIONES DE AIRE	Tipo	Semana				Fin de semana			
		Abierto	Cerrado	Abierto	Cerrado	Abierto	Cerrado	Abierto	Cerrado
Ventanas									
Puertas									

SECCIÓN D – MONITOREO DEL AMBIENTE INTERIOR

La temperatura del aire y la humedad relativa serán monitoreadas al interior de la vivienda en dos lugares que se definirán con los usuarios.

Código del sensor	Ubicación	Intervalo	Inicio		Control inicio	Finalización		Control descarga
			Fecha	Hora		Fecha	Hora	

COMENTARIOS

Agradecemos gratamente su disposición a participar en este estudio. Antes de continuar, por favor, podría completar el siguiente formulario marcando las casillas que correspondan y firmando al final del documento.

B.2.6 Dwellings data collection form - English template

UCL

BS004_DWELLING SURVEY

Date		Parish		Survey code	BS-
Start Time		Neighbourhood		Housing type	
Final time		Altitude			

SECTION A - BUILDING PLANS

- ☐ Orientation
- ☐ Shading elements
- ☐ Context (Annex 1)
- ☐ Architectural drawings (Annex 2)

SECTION B - MATERIALS OF THE ENVELOPE

	Materials	Thickness
North Wall		
South Wall		
East Wall		
West Wall		
Floor		
Ceiling		
Windows		
Exterior door(s)		

SECTION C - USE PROFILES

The following section will collect data on the main sources of indoor heat gain, i.e. people, equipment and lighting, and their occupancy and use patterns.

Users				Week (Hour)				Weekend (Hour)			
	Child/Adult	Gender	Favourite space	Wake up	Going out	Come back	Sleeping	Wake up	Going out	Come back	Sleeping
1											
2											
3											
4											
5											
6											

Equipment	Power	Week				Weekend			
		On	Off	On	Off	On	Off	On	Off

Lighting			Kitchen	Week		Weekend	
Operation		Power		Start	Duration	Start	Duration
On			Breakfast				
Off			Lunch				
On			Dinner				
Off			Other				

AIR CHANGE	Type	Week				Weekend			
		Open	Closed	Open	Closed	Open	Closed	Open	Closed
Windows									
Doors									

SECTION D – MONITORING THE INTERIOR ENVIRONMENT

Air temperature and relative humidity will be monitored inside the house in two places that will be defined with users.

Sensor code	Location	Range	Home		Start control	Completion		Control download
			Date	Time		Date	Time	

COMMENTS

We appreciate your willingness to participate in this study. Before continuing, please complete the following form by checking the appropriate boxes and signing at the end of the document.

Appendix C

Evaluating the effect of participants' simultaneous response

Thermal comfort field studies were conducted in three locations nearby Quito at different altitudes above sea level. A total of 398 surveys were collected in 287 dwellings; 180 participants were interviewed individually (Independent group) and 218 simultaneously with another respondent (Non-independent group), as shown in Table C.1. Before conducting any analysis, data from simultaneous participants were checked for similarities between responses.

Table C.1: Independent and Non-independent groups size by location

Location	Independent	Non-independent	Total by location
A	68	66	134
B	68	64	132
C	46	86	132
Total by groups	182	216	398

Non-independent responses were tested between groups (independent vs non-independent) and for the whole sample. The main issues that might arise from simultaneous responses are similarity on subjective responses, over-representation of dwellings sample and false-positive significance results. Moreover, the responses between simultaneous participants might be biased based on the response from the first respondent. Participants were recalled about the importance of replying based on their own opinion and perception; however, the second response could affect the independent sample's condition. Laslty, the dwelling sample could be over-represented as the paired responses represent the same indoor environment and probably shared comfort strategies. Thus, the sample size is inflated (398 respondents and only 289 independent measurements of each variable); hence, statistical tests might report an inflated probability or a false-positive result.

In order to evaluate the effect of non-independent responses (simultaneous respondents) on the overall sample group, three analyses were conducted:

- Testing the similarity between non-independent subjective responses.
- Evaluating the distribution of subjective votes between groups (independent vs non-independent).
- Investigating the output of the correlation of subjective and objective data between groups and the whole sample.

The first analysis focused on testing the level of similarity between non-independent subjective responses. The second step centred on evaluating the distribution of subjective votes of independent and non-independent groups. Moreover, the last one seeks to evaluate difference on correlations between subjective and objective environmental variables. The following sections describe the approach followed to evaluate each of the analysis conducted to evaluate potential bias due to simultaneous response.

C.1 Testing similarity of simultaneous subjective responses

The non-independent group comprises 216 surveys; the first participant of a paired survey in the same dwelling is identified as participant *a* (n=108) and the second participant as participant *b* (n=108). The subjective votes from participants *a* and *b* were correlated. Results from the correlation analyses, correlation coefficients (r) and p, are summarised in Table C.2.

Table C.2: Spearman's rank correlation between non-independent groups of participants (*a* and *b*)

Subjective votes	p	r
TSV (Thermal sensation vote)	3.10E-07	0.48
TPV (Thermal preference vote)	8.77E-09	0.53
HSV (Humidity sensation vote)	2.25E-11	0.60
HPV (Humidity perception vote)	1.06E-16	0.70
ASV (Air movement sensation vote)	7.54E-14	0.65
APV (Air movement preference vote)	1.02E-09	0.55
TCV (Thermal comfort vote)	3.32E-10	0.57
Overall	4.12E-07	0.47

The correlation between subjective votes from participants *a* and *b* denote a moderate significant correlation. However, the similarity in subjects' responses might be attributed to an existing influence due to simultaneous responses from participant *a* and *b*, or an actual similarity in sensation and perception of the indoor environment. Therefore, the resulting moderate correlation of subjective responses is not decisive to conclude the effect of simultaneous responses in this study.

C.2 Evaluating the distribution of subjective votes between groups (independent vs non-independent)

In order to compare the distribution of subjective votes of the independent group and non-independent groups (*a* and *b*), the sample size of the three groups must be the same. Hence, random sampling was used to select n=108 responses from the independent group to match the sample number of non-independent groups. The distributions of subjective votes for each group were compared both graphically (Figure C.1) and statistically (Table C.3).

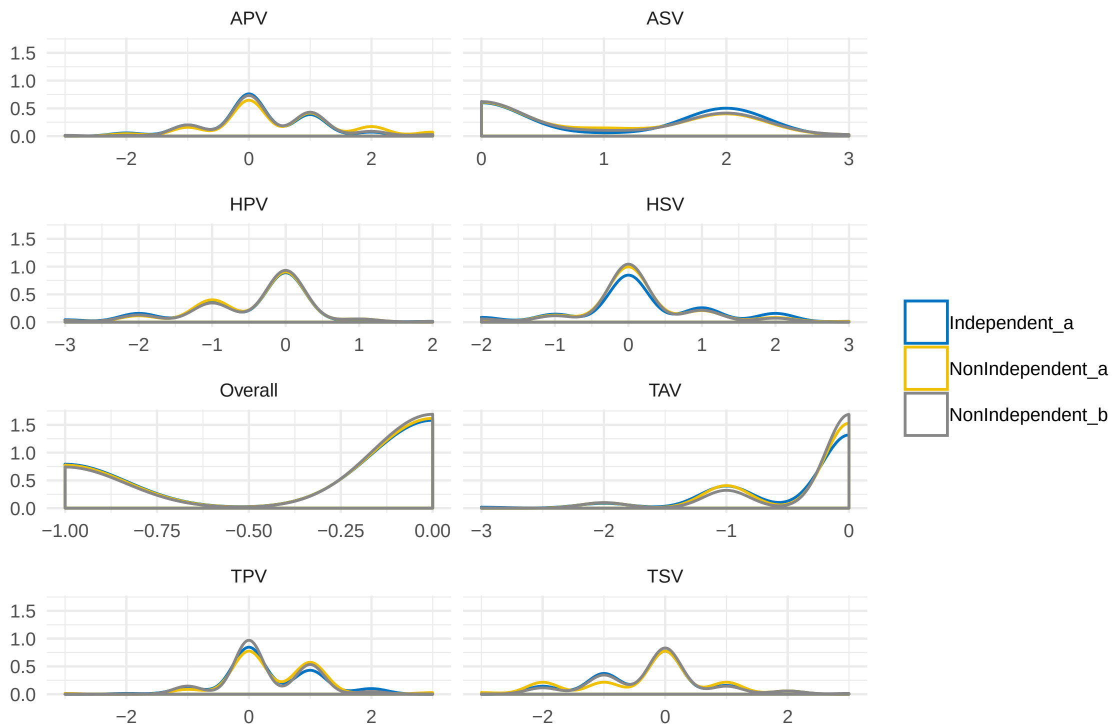


Figure C.1: Distribution of subjective votes between independent and non-independent groups

Figure C.1 shows a similar distribution of votes between the three groups. Furthermore, to test whether the three groups (independent and non-independent) originated from the same distribution, a Kruskal-Wallis test was carried out. The null hypothesis that each group's votes come from identical populations is accepted for the three groups of participants for all the subjective votes at a significant $p<0.001$ (Table C.3). From the observed results, one can conclude that subjective groups' distribution is not significantly different between independent and non-independent groups of participants.

Table C.3: Kruskal-Wallis rank-sum test between independent and non-independent participants' groups a and b

Subjective votes	Statistic	*p*	parameter
TSV	0.271	0.873	2
TPV	1.430	0.490	2
HSV	0.819	0.664	2
HPV	0.494	0.781	2
ASV	0.219	0.896	2
APV	3.980	0.137	2
TCV	1.610	0.446	2
Overall	0.203	0.903	2

C.3 Correlation of subjective and objective data between groups

A correlation analysis was carried out to evaluate any significant difference between subjective and objective environmental variables. The three groups defined for the analyses consist of the whole data set (n=398) and the two 'independent' sample groups (n=287). Group *A* clustered all independent surveys (n=182) with the first participants from the simultaneous surveys (Non-Independent participant A = 108). Group *B* also included all independent surveys (n=182) with the second respondent from the simultaneous surveys (Non-Independent B = 108).

Figure C.2 shows that the distribution of votes for the whole sample, and groups A and B are not significantly different between the three groups. The Kruskal-Wallis test results (p >0.05) confirmed that the three groups' votes (independent and non-independent) originated from the same distribution (Table C.4).

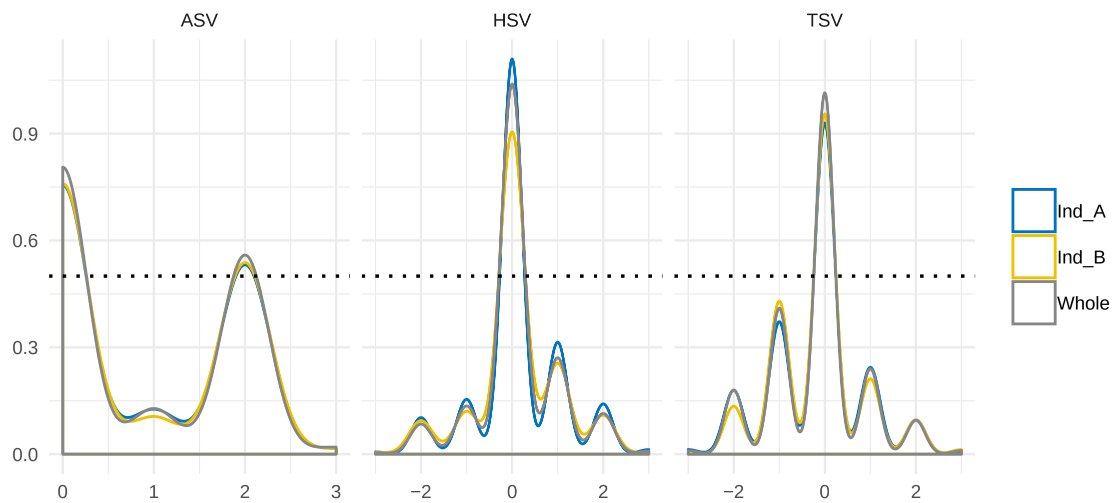


Figure C.2: Cumulative distribution between whole sample and independent samples *A* and *B*

Table C.4: Kruskal-Wallis rank sum test between entire group and independent samples

Subjective votes	Statistic	*p*	Parameter
TSV	0.0116	0.994	2
HSV	1.3	0.523	2
ASV	0.0495	0.976	2

Furthermore, the subjective votes were correlated with the corresponding environmental variable for each sampling group. That is, thermal sensation vote (TSV) was correlated against indoor temperature, humidity sensation vote (HSV) to humidity ratio and air movement sensation vote (ASV) to airspeed. The correlation coefficients and significant values are summarised in Table C.5.

Table C.5: Spearman's rank correlation between the whole sample and independent samples *A* and *B*

Subjective votes	Sample	Size	*p*	Correlation
TSV	Independent A	287	0.000	0.46
	Independent B	287	0.000	0.43
	Whole	398	0.000	0.45
HSV	Independent A	287	0.167	0.08
	Independent B	287	0.249	0.07
	Whole	398	**0.053**	0.10
ASV	Independent A	287	0.257	0.07
	Independent B	287	0.289	0.06
	Whole	398	0.108	0.08

There is no significant difference between the correlation coefficients of the two independent groups and the whole dataset. Besides, the significance of results denotes strong evidence against the null hypothesis either for a reduced sample as for the whole dataset. In other words, the correlation between subjective and objective responses is not being affected due to simultaneous responses. A slightly lower correlation was observed for humidity between groups; thus, attention should be paid when including this variable for further analysis.

C.4 Conclusions

In conclusion, when testing the similarity between non-independent subjective responses, a moderate significant correlation was observed between the non-independent and the independent subjective responses. However, the results are not decisive as moderate correlation could be attributed to responses bias due to simultaneous responses or an actual similarity in sensation and perception of the indoor environment. Results from the evaluation of subjective votes distribution showed no significant difference in votes' distributions between the groups. No significant difference was observed from the correlation between subjective and objective data across independent and non-independent groups. The strong correlation significance confirmed that results in correlation analysis of subjective and objective data would be the same regardless of the groups.

Therefore, the study would use the whole sample (n=398) when reporting results where individuals are the analysis unit. Moreover, to avoid over-representation in the dwelling sample due to duplicated responses from the same environment, the dwellings unit (n=287) would be used to analyse control strategies at the house level.

Appendix D

Ethics application, risk assessment and data protection

The appendix contains the forms and corresponding approvals for ethics, risk assessment and data protection.

D.1 Low risk ethics application

UCL Research Ethics Committee
Before completing this form, first check that your research is low risk using Step 4 checklist. Please also attach your answers to Step 4 Checklist to this low risk application form. This will help UCL monitor the numbers of different categories of low risk research.

Step 5 – Low Risk Application Form
Note to Applicants: It is important for you to include all relevant information about your research in this application form as your ethical approval will be based on this form. Therefore, anything not included will not be part of any ethical approval. If the application does not address one or more issues adequately and requires re-submission, the revised application will only be considered a *minimum* of two weeks after the applicant was advised to re-submit. To avoid this, applicants are advised to pay particular attention to Section G on Data Protection and Q30a on Consent. Data collection cannot start until the project has research ethics approval.

You are advised to read the Guidance for Applicants when completing this form.

Application for Ethical Review: Low Risk	
Which committee are you applying to? BSEER	
Are you applying for an urgent accelerated review? Yes ☐ No ☒ If yes, please state your reasons below. Note: Accelerated reviews are for exceptional circumstances only.	
Is this application for a continuation of a research project that already has ethical approval? *For example, has a preliminary/pilot study been completed and this is an application for a follow-up project?*	Yes ☐ No ☒
If yes, provide brief details (see guidelines) including the title and ethics reference number for the previous study:	

Section A: Application details		
1	**Title of Project**	INDOOR ENVIRONMENT ASSESSMENT OF DWELLINGS IN THE ECUADORIAN HIGHLANDS
2	**Proposed start date**	August 2017
3	**Proposed end date**	April 2019
4	**Principal Investigator**	Isabel Mino Rodríguez
5	**Position held** (Staff/Student)	Research Student
6	**Faculty/Department**	BSEER
7	**Course Title** *(if student)*	BS of Environment, Energy and Resources
8	**Contact Details** Email: Telephone:	
9	**Provide details of other Co-Investigators/Partners/Collaborators who will work on the project.** ***Note:*** *This includes those with access to the data such as transcribers.*	
	Name: Freddy Ordonez Position held: Collaborators Faculty/Department: Faculty of mechanical Engineering Location (UCL/overseas/other UK institution): National Polytechnic School Email:	Name: Position held: Collaborators (2) Faculty/Department: Faculty of mechanical Engineering Location (UCL/overseas/other UK institution): National Polytechnic School Email:
	If you **do not know** the names of all collaborators, please write their roles in the research.	
10	**If the project is funded *(this includes non-monetary awards such as laboratory facilities)***	
	Name of Funder	
	Is the funding confirmed?	
12	**Name of Sponsor**	

The Sponsor is the organisation taking responsibility for the project, which will usually be UCL. If the Sponsor is *not* UCL, please state the name of the sponsor. SENESCYT - The National Secretariat for Higher Education, Sciences, Technology & Innovation of Ecuador	
13 If this is a student project	
Supervisor Name	Hector Altamirano
Position held	Lecturer
Faculty/Department	Institute for Environmental Design and Engineering
Contact details	

Section B: Project details

The following questions relate to the objectives, methods, methodology and location of the study. Please ensure that you answer each question in lay terms.

14 Provide a *brief* (300 words max) background to the project, including its intended aims.

In Ecuador, 1.2 million households live in substandard dwellings mainly associated with poor-quality building materials. Dwellings in the Ecuadorian Highland are unconditioned and thus operate under free-running conditions throughout the year. The local common dwellings are uninsulated lightweight construction, hollow concrete block in walls and zinc roofs. In contrast with the vernacular architecture, a medium-exposed thermal mass dwelling, adobe walls and clay tiles roofs. The indoor environment is a result of the building materials and the local weather conditions. The Andes Region is characterised by narrow annual temperature oscillation, diurnal temperature variation and high levels of solar radiation due to its latitude and elevation. The main cities in the Ecuadorian Andes are located between 2000m and 3000m. Due to the singular climate and non-energy consumption related to building conditioning, the adoption of assessment parameters from energy-targeted standards may not be appropriate for the local conditions. Hence, the aim of this research is to define acceptable thermal comfort criteria for the assessment of unconditioned housing located in - high altitude regions. The research objectives are:
To evaluate the indoor environment of the existing archetype low-cost dwelling in the Ecuadorian Highland.
To assess the subjective responses of the local inhabitants to the indoor environment in dwellings located at high altitude in the Andes.
To determine indoor environment criteria for assessing the performance of unconditioned dwellings located in the highlands.

15 Methodology & Methods (tick all that apply)

☐ Interviews*	☒ Collection/use of sensor or locational data
☐ Focus groups*	☐ Controlled trial
☒ Questionnaires (including oral questions) *	☐ Intervention study (including changing environments)
☐ Action Research	☐ Systematic review – ***(See Section D)***
☐ Observation	☐ Secondary data analysis – ***(See Section E)***
☐ Use of personal records	☐ Advisory/consultation
☒ Audio/visual recordings (including photographs)	☐ Other, give details:
**Attach copies to application (see below).*	

16a **Provide an overview of the project; focusing on your methodology** and including information on what data/samples will be taken (including a description of the topics/questions to be asked), how data collection will occur and what (if relevant) participants will be asked to do. This should include a justification for the methods chosen.
Please do not attach or copy and paste a research proposal or case for support.

The research methodology is divide into two instances according to the research objectives: building survey and thermal comfort survey.

Building survey

The indoor environmental performance of three archetype dwellings will be evaluated through a dynamic thermal simulation (annual assessment). In order to produce an accurate simulation model, a data-drive approach will be followed to validate the base models and a forward approach to conducting the annual evaluation. To fulfil the first objective three research stages have been defined: data collection, thermal model development and calibration, and assessment of indoor environment conditions.
The required data for developing and calibrating the dwellings thermal model will be included in the building survey. 18 dwellings will be surveyed during the fieldwork. Among the data to be collected building

	specifications, usage profiles and indoor environment data are the topics included in the questionnaire. The building survey will include the collection of the following variables: **Building details** Architectural building drawings including floor plans, sections and facades. **Envelope materials** Due to the characteristic of being informal construction, most of the dwellings would not have this information available. Therefore, all the necessary measurements to develop the drawings and define the dwelling construction specifications will be collected on during the building survey. **Usage profiles** Internal loads profiles and schedule of occupancy, ON/OFF equipment, cooking, lighting and ventilation will be collected through a questionnaire. **Indoor environment monitoring** Small data-logger (Tynitag) will be installed in two rooms at each dwelling for measuring air temperature and relative humidity. A minimum of 15 consecutive days of monitoring at each period are intended. However, if participants agreed, a long-term monitoring of 6 months will be conducted. The data will be collected in a minimum of two visits. At the first meeting, participants will be asked to complete the building survey and the data logger will be installed in one or two different rooms of the dwellings. At the second visit, the building survey will be completed again and the data loggers will be removed from the dwellings. **Thermal comfort survey** The subjective data to assess the dwellings indoor environment will be collected through thermal comfort surveys conducted in the same parishes as the building surveys. A representative number of surveys is expected (384 completed questionnaires), however, a random selection of participants is not possible. Thus, a quota sampling approach based on altitude range and gender will be follow. Occupants from the monitored dwellings would also be considered for the thermal comfort interviews, however, this survey is also open to other inhabitants of the selected parishes. The questionnaires would collect the required information to compare the actual thermal comfort votes with the standard models. The sections in the thermal comfort questionnaire are: **Participant and dwelling data** Name and punctual identifiers are not included as part as the survey. Personal data, such as age will be collected as ranges. If participants agreed height and weight data will also be included. These parameters have been included as corrections on the metabolic rate can be done according to the average height and weight of the population. The parish and city where the dwelling is located will be included as well as the altitude range. **Acclimatisation to high-altitude** Data regarding participants indoor and outdoor environments experiences will be collected as parish and city location. Frequent commuting information will be collected as a high variation of altitude can be expected within short distances. **Thermal questionnaire** Perception, satisfaction and preference scales of air temperature, humidity and draught are included in this section. **Environmental control strategies** This section is intended to identify the control strategies commonly used by occupants to keep warm or cold. **Indoor environment observations** Spot measurement or air temperature, globe temperature, relative humidity, air velocity, CO2 levels, atmospheric pressure and radiant temperature. In addition, if participants agree, thermographic images of the hands and forehead will be taken. All the readings will be taken by the surveyor during the interview. **Outdoor meteorological observations** Readings from local weather stations will be included, this data would be filled after the thermal comfort survey. However, for further practical analysis, the space is given in the survey to have all the required data in the same document. Participants of the thermal comfort survey will be asked to reply the questionnaire once or several times according to their willing. The researcher will facilitate the completion of the questionnaire and will collect the reading of the different environmental variables. The thermal comfort survey will be conducted at the

	participants' dwellings; the visit will be arranging previously with all the participants that show interested on taking part of this research.
16b	**Attachments** *Please attach a copy of any interview questions / questionnaires / workshop topic guides / test (e.g. psychometric), etc and state whether they are in final or draft form.* *Please also attach your answers to Step 4 Checklist to this low risk application form. This will help UCL monitor the numbers of different categories of low risk research.*

~~**17**~~	~~**Please state which code of ethics (see Guidelines) will be adhered to for this research (for example, BERA, BPS, etc).**~~

18	**Please indicate where this research is taking place.** ☐ UK only (Skip to 'location of fieldwork') ☒ Overseas only ☐ UK & overseas
19	**If the research includes work outside the UK, is ethical approval in the host country (local ethical approval) required*?** Yes ☐ No ☒ **If no,** please explain why local ethical approval is not necessary/possible. **If yes,** provide details below including whether the ethical approval has been received. **Note:** Full UCL ethical approval will not be granted until local ethical approval (if required) has been evidenced. *To check which local ethics committee you may need to apply to, the International Compendium of Human Research Standards contains information on over 100 countries, including key organisations such as local ethics committees. http://www.hhs.gov/ohrp/international/compilation-human-research-standards/index.html An ethical approval is only required when human participants are involved for medical research. The ethical principles established by law have been consider for this research[1]. Respect for life dignity and biodiversity Participants inform consent Previous and free informed consent of people and nationalities Respect and protection of participants' rights Confidentiality of personal identifiers, as well as other data listed at the National Code of Ethics, obtained in the research process and, Respect to animals involved in research
20	**If you (or any members of your research team) are travelling overseas in person are there any concerns based on governmental travel advice (*www.fco.gov.uk)* for the region of travel?** Yes ☐ No ☒ **Note:** *Check www.fco.gov.uk and submit a travel insurance form to UCL Finance (see application guidelines for more details). This can be accessed here:* https://www.ucl.ac.uk/finance/secure/fin_acc/insurance.htm (You will need your UCL login details.).

21	**State the location(s) where the research will be conducted and data collected. For example public spaces, schools, private company, using online methods, postal mail or telephone communications.** Private dwellings
22	**Does the research location require any additional permissions (e.g. obtaining access to schools, hospitals, private property, non-disclosure agreements, access to biodiversity permits (CBD), etc.)?** Yes ☒ No ☐ **If yes, please state the permissions required.** Permissions from a senior family member will be obtained before approaching any prospective participant and thus, prior data collection.
23	**Have the above approvals been obtained?** Yes ☐ No ☒ **If yes,** please attach a copy of the approval correspondence.

[1] Asamblea Nacional. República de Ecuador, Código Orgánico de la Economía Social de los Conocimientos, Creatividad e Innovación, no. 899. 2016, p. 116.

	If not, confirm they will be obtained prior to data collection. Yes ☒ No ☐

Access to data & Dissemination of results	
24	If you are using data or information held by third party, please explain how you will obtain this. You should confirm that the information has been obtained in accordance with the UK Data Protection Act 1998. Public meteorological data will be used to create weather files for the dynamic thermal simulation. This sets of data are published at the institutions websites and can be freely downloaded; the data belongs to the National Institute of Meteorology and the City Council.
25	How will the results be disseminated (including communication of results with participants)? The results of this research will be presented at academic conferences and journals. A talk among the communities involved will be organised to present the preliminary results of the work once the data collection is completed.

Section C: Details of Participants

In this form 'participants' means human participants and their data (including sensor/locational data, observational notes/images, tissue and blood samples, as well as DNA).

26	**Does the project involve the recruitment of participants?**
Yes ☒	Complete all parts of this Section.
No ☐	Move to Section D.

27	**I confirm that I have read the high-risk checklist and this study will not include participants or data from participants that fall under sections 1-3.**
Yes ☒	Complete all parts of this Section.
No ☐	Complete the high-risk checklist and apply to the UCL Research Ethics Committee.

Participant Details	
28	Approximate Number of participants required: Approximate Upper age limit: 18 Lower age limit: 65 Justification for the age range and sample size: The age range have been stablished due to technical and ethical considerations. The research seeks into the response of adult participants. The thermal sensibility and perception of elderly and children may be affected by physical and health conditions. Moreover, including younger and elderly participants involved vulnerable population and further ethics requirements.
Recruitment/Sampling	
29	Describe how potential participants will be recruited into the study. **NOTE:** This should include reference to how you will identify and approach participants. For example, will participants self-identify themselves by responding to an advert for the study or will you approach them directly (such as in person or via email)? Recruitment documents must be written in clear language appropriate to the target audience – see the accompanying guidance on writing information sheets. **Building survey – participants' recruitment** Invitation letters and information sheets will be distributed door to door to the dwellings that comply with the selection criteria. A total of 18 dwelling, a minimum of three per parish are expected for the building survey and long-term measurement. At the first visit, participants will be asked to sign a consent form before beginning with the data collection. **Thermal comfort survey – participants' recruitment** Potential participants for the thermal comfort survey will be invited at community activities (meetings, dominical mass, etc.). Door to door invitations will be distributed in case of low participation rate is obtained at communal invitations. Project information data and active consent has been included in the first page of the thermal comfort questionnaire. Whenever is possible the local community leader or current participants would be asked to introduce the researcher furthers potential participants.
Consent	
30a	Describe the process you will use when seeking to obtain consent. **Note:** This should include reference to what participants are being asked to consent to, such as whether their contribution will be identifiable/anonymous, limits to confidentiality and whether their data can be withdrawn at a later date. For guidance on preparing information sheets and obtaining and recording consent see:

	accompanying guidance on writing information sheets in clear language appropriate to the target audience https://ethics.grad.ucl.ac.uk http://www.ucl.ac.uk/srs/research-ethics-committee/pages/ioe http://www.data-archive.ac.uk/create-manage/consent-ethics/consent **Building survey – signed consent form** A separate signed consent form has been designed for participants of building survey. This approach has been considered as the participant collaboration is required for a longer period of time and monitoring equipment will be installed in their dwellings. As far as possible, building survey will be conducted only to the head of each family. **Thermal comfort survey – active consent form** An active consent has been included in the questionnaire. This approach of consent was considered as it's more appropriate for this type of survey where participants are used to sign legal documents and the involvement of respondents is lower. In addition, as at family level, the hierarchy roles in the family is to be considered. For both surveys – building and thermal comfort - the agreement of a senior family member will always be obtained prior any prospective participant is approached.
30b	**Attachments, please list them below:** *Ensure that a copy of all recruitment documentation (recruitment emails/posters, information sheet/s, consent form/s) have been attached to the application.*
30c	If you are ***not*** intending to seek consent from participants, clarify why below:

Section D: Secondary data analysis

31	**Does your study involve the use of previously collected data?** **Yes** ☐ Complete all parts of this Section. **No** ☒ Move to Section F.		
32	**Name of dataset/s:**		
	Owner of dataset/s (if applicable):		
33	**Are the data in the public domain?** **If no,** do you have the owner's permission/license?	Yes ☐ Yes ☐	No ☐ No* ☐
34	**Are the data anonymised?** **If no:** Do you plan to anonymise the data? Do you plan to use individual level data? Will you be linking data to individuals?	Yes ☐ Yes ☒ Yes* ☐ Yes* ☐	No ☐ No* ☐ No ☐ No ☐
35	Are the data sensitive (DPA 1998 definition)?	Yes* ☐	No ☐
36	Will you be conducting analysis within the remit it was originally collected for?	Yes ☐	No* ☐
37	If no, was consent gained from participants for subsequent/future analysis?	Yes ☐	No* ☐

If you ticked any boxes with an asterisk (*), please ensure that you give further details in Section F: Ethical Issues.

Section E: Ethical Issues

Ethical Issues

38	Please address clearly any ethical issues that may arise in the course of this research, including those highlighted earlier in the form, and how they will be addressed. Possible harms include physical, psychological, emotional, economic, reputational, and legal. The potential severity, duration and probability of harm vary from minimal to high. Further information and advice can be found in the guidelines. **Note:** All ethical issues should be addressed - *do not leave this section blank*. If you think there are no ethical issues, you need to provide an explanation as to why. The ethical issues that arise in the course of this research are: **Inform consent** All prospective participants will be provided with information about the research before any consent to participate. The information sheets and consent forms have been designed to assist participants to make an informed choice. **Do not harm** There is no identified potential risk for the participants associated to this study. There is a small risk of walls property damage if there is a need to install the monitoring equipment (Tynitags) on the walls. The risk will be minimized by the usage of adhesives or fasteners that will not damage the walls finishing or painting. **Non-exploitation** The participants' benefits will be clearly explained. Special responsibility would be considered in explaining that the research may not benefit them as individuals so that they do not participate in the false expectation. **Anonymity** Personal data will be collected during the fieldwork in Ecuador. The surveys will be anonymised once the data collection period is finished and prior returning to the UK. This data will be treated according the principles of the UK Data Protection Act 1998. **Confidentiality** Raw data collected from participants will be only shared with the research team (supervisors) and collaborators for the collection of data in Ecuador (Lecturer and two undergraduate students). Any personal data will be included in the diffusion of results. **Relations of power** It would be emphasised during the data collection process that the participation is voluntary, the option of non-replying questions and withdrawal at any moment. **Socio-cultural differences** Special attention was considered in order to proceed accordingly the local context from the participant recruitment to the wording used in all the documents to be shared with the community. The documents are written in plain, clear and polite Spanish according to the Ecuadorian context. A formal signed consent will be culturally inappropriate for the survey, as potential participants experience in singing forms is related with important tax, legal or governmental forms [1]. However, due the long-term monitoring of the building survey and the installation of small equipment in dwellings, a signed formed will be used for this purpose.

Risks & Benefits	
39	Please state any *benefits* to participants in taking part in the study (this includes feedback, access to services or incentives), Gaining knowledge about their knowledge and indoor environment, through a presentation of preliminary results to the community Participants of the Building survey may also be able to have the architectural drawings for their future use.
40	Do you intend to offer incentives or compensation, including access to free services? Yes ☐ No ☒ **If yes,** specify the amount to be paid and/or service to be offered **as well as a justification for this**. A payment reward as compensation for the research respondent´s time is not being considered. This kind of incentive can be seen as coercive, so the consent is not truly freely given particularly in from financially disadvantaged groups as in this research [2]. However, potential participants will receive a small non-monetary gift at the end of the survey. This alternative was considered for this context, as is not coercive but also recognize participation.
41	Please state any *risks* to participants and how these risks will be managed. There is no identified potential risk for the participants associated to this study. There is a small risk of walls property damage if there is a need to install the monitoring equipment (Tynitags) on the walls. The risk will be minimized by the usage of adhesives or fasteners that will not damage the walls finishing or painting.

Section G: Confidentiality, Data Storage & Security

Please ensure that you answer each question and include all hard and electronic data.

42	**Will the research involve the collection and/or use of personal data (this includes when individual participants are only identifiable by the researcher)?** Yes ☒ No ☐ ***Personal data*** *is data which relates to a living individual who can be identified from that data OR from the data and other information that is either currently held, or will be held by the data controller (the researcher).* *This includes:* *any expression of opinion about the individual and any intentions of the data controller or any other person toward the individual.* *sensor, location or visual data which may reveal information that enables the identification of a face, address, etc (some postcodes cover only one property).* *combinations of data which may reveal identifiable data, such as names, email/postal addresses, date of birth, ethnicity, descriptions of health diagnosis or conditions, computer IP address (if relating to a device with a single user).* **All research projects using personal data must be registered with UCL Legal Services (http://www.ucl.ac.uk/legal-services/research) before the data is collected.** *This process will help researchers, supervisors and investigators meet their legal obligations under the UK Data Protection Act 1998 (the UK legislation implementing the EU Data Protection Directive 1995).* *To complete this process, you will need to think about how the data is being protected, e.g. whether personal data will be stored separately from the research data and linked using a link code, and whether personal data will be shared outside the research team. The following may be helpful:* *. UCL Data Protection Policy Section 5 Security of Personal Data & Section 9 Research using personal data:* *https://www.ucl.ac.uk/informationsecurity/policy/public-policy/DataProtectionPolicy1016.pdf* *. A practical note for researchers on the limited exemptions from the UK Data Protection Act is here:* *http://www.adls.ac.uk/publications-and-documents/* **Please provide your UCL Data Protection registration number:** UCL Data Protection Registration, reference No Z6364106/2017/07/84 social research If you do not have a registration number from Legal Services, please clarify why not:
43	**Is the research collecting or using?** sensitive personal data as defined by the UK Data Protection Act (racial or ethnic origin / political opinions / religious beliefs / trade union membership / physical or mental health / sexual life / commission of offences or alleged offences), and/or data which might be considered sensitive in some countries, cultures or contexts. **If yes,** state whether explicit consent will be sought for its use and what data management measures are in place to adequate manage and protect the data.

During the project *(including the write up and dissemination period)*	
44	**State what data will be generated from this project (i.e. transcripts, videos, photos, audio tapes, field notes, etc).** Transcripts Architectural drawings Weather files Dynamic thermal models – Annual thermal performance Thermal comfort votes data base
45	**How will data be stored, including where and for how long? This includes all hard copy and electronic data on laptops, share drives, usb/mobile devices.** All the collected data including personal data, photographs and dwellings measurements, survey responses and audiotapes will be stored in a secure cloud (UCL drive) accessed through a remote connection to UCL. Personal data will be kept according the Data Protection Act 1998 (DPA) and will be kept in a separate digital document only in a secure cloud. The surveys, both the thermal comfort survey and building survey, will contain personal identifiers. Data such as names, telephone number and address will be kept in a separate encrypted file. Once the fieldwork activities are finished, personal data will be securely destroyed following the

	guidance of the computer security team (http://www.ucl.ac.uk/isd/common/cst/good_practice/secure_disposal_guidelines). Due to the difficulty in guaranteeing that audio recordings would not contain personal identifiable data; the recordings will be treated as personal data. Any identifies will be removed from the transcripts and the audio tapes will be securely destroyed. Personal data will not be disclosed to any third party. Special attention will be paid so that photographs won´t contain participants, personal or dwellings identifiers. The pictures will be kept for the data analysis and might be used for the presentation of results. Hard copies of the buildings surveys and thermal comfort survey will be kept lock in a secure place and will be appropriately disposed once the data is processed.
46	**Who will have access to the data, including advisory groups and during transcription?** Supervisors Collaborators from EPN (National Polytechnic School) a lecturer, PhD Freddy Ordoñez and two undergraduate students that will assist on the data collection and processing. Personal data will not be share with any member of the research team including the collaborators.
47	**Do you confirm that all personal data will be stored and processed in compliance with the Data Protection Act 1998 (DPA 1998).** Yes ☒ No ☐ **If no,** please clarify why.
48	**Will personal data be processed or be sent outside of the European Economic Area (EEA)?*** Yes ☐ No ☒ **If yes,** please confirm that there are adequate levels of protection in compliance with the DPA 1998 and state what arrangements are below. ***Please note** that if you store your research data containing identifiable data on UCL systems or equipment (including by using your UCL email account to transfer data), or otherwise carry out work on your research in the UK, the processing will take place within the EEA and will be captured by Data Protection legislation.

After the project	
49	What data will be stored and how will you keep it secure? Data that will be kept is the data base from thermal comfort survey and the processed data required for the developing the dynamic thermal models. All data will be digital data bases. Where will the data be stored and who will have access? The data will be always kept in a secure cloud (UCL drive). Only supervision team and I will have access. Will the data be securely deleted? Yes ☐ No ☒ **If yes,** please state when will this occur: Will the data be archived for use by other researchers? Yes ☐ No ☒ **If yes,** please provide further details including whether researchers outside the European Economic Area will be given access.

Applicant Declaration: I confirm that the information in this form is accurate to the best of my knowledge.
Supervisor's Declaration: I confirm that I have checked this completed form and that the information in it is accurate to the best of my knowledge.

Signature	
Date	
If student Supervisor Name:	Héctor Altamirano
Supervisor Signature:	
Date:	

This signed form and the ethics approval should be included as an appendix in the Masters Dissertation or PhD Upgrade Documents, whichever applies.

D.2 Low risk ethics evaluation

UCL

THE BARTLETT SCHOOL OF ENVIRONMENT, ENERGY AND RESOURCES

BSEER Research Ethics – Low Risk Application – Evaluation (v1.7)

Title of Study: INDOOR ENVIRONMENT ASSESSMENT OF DWELLINGS IN THE ECUADORIAN HIGHLANDS

Date of Application: 25 August 2017 (3rd attempt at a complicated albeit low risk study – after Skype call discussing 2nd attempt)

	Unsatisfactory	Satisfactory	N/A
STUDY DETAILS			
Sufficient study details provided to evaluate ethical implications		X	
Study does not seem to include sensitive topics (see High Risk checklist)		X	
Sufficient sampling details provided to evaluate ethical implications		X	
Sample does not seem to include vulnerable individuals (see High Risk checklist)		X	
CONSENT			
Information for participants covers necessary issues adequately (Researcher & says if student, Institution, funder, study title & purpose, how participant selected, what happens to participant, how long it will take, benefits, potential risks/harms, anonymity/confidentiality, voluntariness, right to withdraw, contact details)		X	
Information for participants is sufficiently concise		X	
Information for participants is written in an appropriate style (Study title and content appropriately phrased for participants, level of detail appropriate for participants)		X	
(Where participants known to researcher) appropriate procedures to ensure participants feel free to not participate & withdraw from the study			X
EVALUATION & MITIGATION OF HARM			
Risk of harm to participants seems to be minimal (see High Risk checklist)		X	
Recognises & addresses potential risks/harms to participants		X	
(Where risks to researcher beyond those experienced in daily life) has appropriate risk assessment been completed?		X	
DATA PROTECTION & PRIVACY			
Correctly identifies whether/not personal data are being collected / used / processed (Definition of personal data is embedded in the low risk form Q42…check whole application to ensure applicant answered this Q correctly)		X	
Correctly identifies whether/not *sensitive* personal data are being collected / used / processed (Definition of sensitive personal data embedded in the low risk form Q43…check whole application to ensure applicant answered this Q correctly)		X	
(If personal data are being collected / used / processed) has registered study with UCL Data Protection Officer		X	
(Where participants are known to researcher) appropriate procedures to protect participants' privacy (EG data collected &/or collection method)			X

Study is:

X Approved

☐ Approved – Subject to you obtaining a UCL Data Protection number from UCL Legal BEFORE starting data collection – You ARE collecting personal data

☐ Approved – Subject to meeting the following conditions BEFORE starting data collection:

☐ Not Approved – Submit revised application to BSEER Research Ethics Team – data collection/processing cannot start until the research is approved

☐ Not Approved – Submit new application to UCL Research Ethics Committee – data collection/processing cannot start until the research is approved

Name(s) of BSEER evaluator(s): Michelle Shipworth

Date: 7 September 2017

D.3 Fieldwork risk assessment

UCL **Risk Assessment - Summary**

Reference **Sign-off Status:** Authorised

Date Created:	17/07/2017	**Confidential?**	No
Assessment Title:	INDOOR ENVIRONMENT ASSESSMENT OF DWELLINGS IN THE ECUADORIAN HIGHLANDS		
Assessment Outline:	A risk assessment review for fieldwork to be conducted for data collection, buildings surveys and thermal comfort surveys will be conducted in Ecuador.		
Area Responsible (for management of risks)		**Location of Risks**	Off-Site
Division, School, Faculty, Institute:	Faculty of the Built Environment	**Building:**	
Department:	Bartlett School Env, Energy & Resources	**Area:**	
Group/Unit:	All Groups/Units	**Sub Area:**	
Further Location Information:	Quito - Ecuador		
Assessment Start Date:	24/07/2017	**Review or End Date:**	30/01/2018

Relevant Attachments:

Description of attachments:
A complete risk assessment form is attached.

Location of non-electronic documents:

PEOPLE AT RISK (from the Activities covered by this Risk Assessment)

CATEGORY
Post-Graduates

08/08/2017 17:02 - Page 1 of 5
Uncontrolled Paper Copy. It is the user’s responsibility to ascertain currency of issue prior to use.

-

Reference: RA013498/1 **Sign-off Status:** Authorised

1. Field work - environmental assessment

Description of Activity:	Applies to all field work / academic study at sites external to UCL

Hazard 1. Disruption of habitats

Disruption of habitats or communities may cause long term problems in development, including cessation of breeding and decline of populations of local species	**Existing Control Measures** Disruption is minimised and time at site is kept to minimum to complete required activity All parties are appropriately trained and aware of their duties and responsibilities

Hazard 2. Injury/ill-health

any injury or ill health that could pose a risk if the person is alone and needs help	**Existing Control Measures** Contact numbers for emergency services are know to all participants Participants have means of contacting emergency services An international health insurance

Hazard 3. Lone working

Difficult to summon help	**Existing Control Measures** Lone working will be avoid.

Hazard 4. Violence (external to organisation)

Attack by another person	**Existing Control Measures**

Hazard 5. Equipment

Inappropriate, failure, insufficient training to use or repair, injury.	**Existing Control Measures** All equipment have been inspected before use all users have been advised of correct use The department written arrangement for equipment if followed Participants have been provided with necessary equipment appropriate for field work

Hazard 6. Environment	
Risk of adverse weather, assault, getting lost	**Existing Control Measures** Work abroad incorporates Foreign Office advice Participants will wear appropriate clothing and footwear for the specified environment In domestic properties, Unpleasant areas will be avoid Seek information about the area before setting out, details of local authorities, transport links, local maps Walk with purpose and confidence Do not carry more money /valuables than required
Hazard 7. Emergencies	
Loss of property	**Existing Control Measures** Contact numbers for emergency services are known to all participants Participants have means of contacting emergency services A plan in case of domestic problems have been formulated. Keep calm, attempt to placate the situation or leave. Contact the police if necessary Be familiar with the area, escape routes, public transport links and authorities contact details.
Hazard 8. Transport	
Accidents arising from lack of maintenance, suitability or training	**Existing Control Measures** Transport must be properly maintained in compliance with relevant national regulations Drivers have been trained and hold the appropriate licence
Hazard 9. Dealing with the public	
Personal attack, causing offence, being misinterpreted	**Existing Control Measures** All participants are trained in interviewing techniques Advice and support from local groups has been sought Participants do not wear clothes that might cause offence or attract unwanted attention

Risk Level

With Existing Controls:

Risk Level	**A - Very Low / Trivial**

D.4 Data protection

Dear Isabel Miño

Thank you for the application for Data Protection Registration.

Apologies for the delayed response. This was due to the large volume of submissions we have receive and annual leave of colleagues.

Your form indicates that you intend to collect data from prospective participants located within Ecuador, and returned to the UK. As with any research, it is important to note that any consent you receive clearly entails giving sufficient information about the research, so that prospective participants can make an informed and free decision about their involvement with your study. In practice, this means they should be afforded the same level of protection and security as within the United Kingdom. In terms of any transfer of identifiable research data you will need to ensure that it is encrypted if it is to be shared electronically. Data can be transferred with the explicit consent of the individual participants of the research project. This means they must be informed to which country their data will be transferred, to which organisation, and what that organisation intends to do with the information. With this in mind, I am pleased to confirm that this project is covered by the UCL Data Protection Registration, reference No Z6364106/2017/07/84 social research.

It is rarely necessary to store electronic personal data on portable devices such as laptops, USB flash drives, portable hard drives, CDs, DVDs, or any computer not owned by UCL. Similarly, manual personal data should not be regularly removed from UCL premises. In the case of electronic data, to minimise the risk of loss or disclosure, a secure remote connection to UCL should be used wherever possible.

Downloading personal data on to portable devices or taking manual personal data off-site must be authorised in writing by the Data Owner, who must explain and justify the operational need in relation to the volume and sensitivity of the data. The data must be strongly encrypted. Users should only store the data necessary for their immediate needs and should remove the data as soon as possible. To avoid loss of encrypted data, or in case of failure of the encryption software, an unencrypted copy of the data must be held in a secure environment. The Information Security Group guidance on encryption should be followed:

Manual personal data and portable electronic devices should be stored in locked units, and they should not be left on desks overnight or in view of third parties.

In order to comply with the fifth data protection principle personal data should be securely destroyed when no longer required, with consideration for the format of the data. The Information Security Group guidance should be followed.

Personal data must not be disclosed unlawfully to any third party. Transfers of personal data to third parties must be authorised in writing by the data owner and protected by adequate contractual provisions or data processor agreements, agree with UCL's notification and must use safe transport mechanisms.

There are cases where anonymised data needs to be treated as confidential, so please ensure that you comply with any further restrictions contained within contracts or agreements relating to the data.

If not already done so, please provide copies of any information sheets and consent forms that you are using.

When all essential documents are ready to archive, contact the UCL Records Office b to arrange ongoing secure storage of your research records unless you have made specific alternative arrangements with your department, or funder.

UCL

Dear team,

Please find attached the form and relevant documents for the registration of my research project for Data Protection.

List of attachments:

- Research registration form
- Invitation letter
- Information sheet
- Building survey with separate signed consent form
- Thermal comfort survey including active consent form

English and Spanish version of all the documentation are included.

The Ethical Approval is in process at BSEER Comitte, as soon as the approval is gain I will provide the required evidence.

Please let me know if additional documentation is required.

Appendix E

Summary of statistical tests

Table E.1: Summary of statistical tests for the comparison of central tendency

Var	Groups	n	Levels	Dist[5]		df	Var[6]		Central tendency				Pairwise			
				p	Dis		p	Var	Mean	sd	Test	p	Test	G1	G2	p
DB	Typology	63	Light	0.320	N	1	0.701	E	23.4	2.60	t.test	0.000				
		167	Medium	0.338	N				21.4	2.20						
	Exposure-	122	Exp	0.103	N	1	0.000	U	22.6	2.78	Wt.test	0.000				
	level	108	NoExp	0.854	N				21.3	1.82						
t_{o-mean}	Gender	165	F	0.123	N	1	0.613	E	22.1	2.54	t.test	0.613				
		159	M	0.415	N				22.0	2.41						
t_{o-mean}	Age	25	>20	0.401	N	6	0.013	U	21.5	2.44	ANOVA[7]	0.160				
		67	20-29	0.572	N				22.6	2.34						
		81	30-39	0.344	N				21.9	2.25						
		62	40-49	0.295	N				21.5	2.82						
		46	50-59	0.691	N				22.2	2.19						
		34	60-65	0.775	N				22.2	2.35						
		9	<65	0.162	N				22.6	4.03						
t_{o-mean}	BSA	111	Above	0.635	N	1	0.465	E	22.3	2.43	t.test	0.228				
		213	Below	0.061	N				21.9	2.49						
t_{o-mean}	a) Birth	92	Low	0.092	N	2	0.121	E	21.8	2.18	ANOVA	0.001	tH	Low	High	0.05
	place	202	Mid	0.557	N				22.4	2.55				Mid	High	0.05
		29	High	0.154	N				20.7	2.35						
t_{o-mean}	b) Acclima	17	Low	0.008	Nn	2	0.128	E	22.4	2.29	$k-w$	0.064				
	tisation	26	Mid	0.032	Nn				22.9	1.88						
		280	High	0.248	N				21.9	2.52						
t_{o-mean}	c) Weather	148	Low	0.671	N	2	0.064	E	22.5	2.50	ANOVA	0.002	tH	Low	Mid	0.05
	exposure	88	Mid	0.434	N				21.4	2.60				Mid	High	0.05
		88	High	0.520	N				21.9	2.13						
t_{o-mean}	d) HVAC	301	Low	0.121	N	2	0.009	U	22.0	2.52	ANOVA[7]	0.052				

Table E.1 continued from previous page

Var	Groups	n	Levels	Dist[5] p	Dis	df	Var[6] p	Var	Mean	sd	Central tendency Test	p	Test	Pairwise G1	G2	p
	exposure	10	Mid	0.263	N				23.1	1.86						
		13	High	0.335	N				22.6	1.29						
t_{o-mean}	e) Overall	3	Low	0.320	N	2	0.017	U	21.7	1.02	ANOVA[7]	0.088				
		226	Mid	0.284	N				21.9	2.34						
		93	High	0.523	N				22.4	2.79						
clo	Gender	212	F	0.003	Nn	1	0.132	E	0.67	0.15	w	0.354				
		186	M	0.000					0.68	0.14						
clo	Location	134	A	0.014	Nn	2	0.006	U	0.62	0.12	$k-w$	0.000	$w-t$	A	B	0.013
		132	B	0.000	Nn				0.66	0.13				B	C	0.000
		132	C	0.937	N				0.74	0.16				A	C	0.000
clo	Gender	68	A_F	0.195	N	5	0.016	U	0.59	0.10	$k-w$	0.000	$w-t$	A_F	B_F	0.003
	+	66	A_M	0.159	N				0.65	0.12				B_F	C_F	0.003
	Location	70	B_F	0.004	Nn				0.65	0.12				A_F	C_F	0.000
		62	B_M	0.003	Nn				0.66	0.13				A_M	B_M	0.804
		74	C_F	0.567	N				0.75	0.16				B_F	C_M	0.008
		58	C_M	0.229	N				0.74	0.17				A_M	C_M	0.003
TSV	Location	134	A	0.000	Nn	2	0.169	E	0.08	0.87	$k-w$	0.000	$w-t$	A	B	0.107
		132	B	0.000	Nn				-0.13	1.05				B	C	0.010
		132	C	0.000	Nn				-0.50	0.93				A	C	0.000
TPV	Location	134	A	0.000	Nn	2	0.156	E	-0.01	0.77	$k-w$	0.000	$w-t$	A	B	0.059
		132	B	0.000	Nn				0.20	0.74				B	C	0.000
		132	C	0.000	Nn				0.61	0.73				A	C	0.000
HSV	Location	134	A	0.000	Nn	2	0.033	U	-0.01	0.97	$k-w$	0.085	$w-t$	A	B	1.000
		132	B	0.000	Nn				0.10	0.74				A	C	0.125
		132	C	0.000	Nn				0.30	0.89				B	C	0.255
HPV	Location	134	A	0.000	Nn	2	0.002	U	-0.27	0.81	$k-w$	0.000	$w-t$	A	B	1.000
		132	B	0.000	Nn				-0.34	0.78				B	C	0.001
		132	C	0.000	Nn				-0.69	0.85				A	C	0.000
ASV	Location	134	A	0.000	Nn	2	0.526	E	0.80	0.96	$k-w$	0.352	$w-t$	A	B	1.000
		132	B	0.000	Nn				0.83	0.98				B	C	0.844
		132	C	0.000	Nn				0.95	0.96				A	C	0.512
APV	Location	134	A	0.000	Nn	2	0.063	E	0.55	0.90	$k-w$	0.000	$w-t$	A	B	1.000
		132	B	0.000	Nn				0.55	1.00				B	C	0.000
		132	C	0.000	Nn				-0.07	0.93				A	C	0.000
Overall	Location	134	A	0.000	Nn	2	0.001	U	-0.23	0.42	$k-w$	0.001	$w-t$	A	B	1.000
		132	B	0.000	Nn				-0.26	0.44				B	C	0.009
		132	C	0.000	Nn				-0.43	0.50				A	C	0.002
TSV	Gender	212	F	0.000	Nn	1	0.095	E	-0.20	1.07		0.683				

Table E.1 continued from previous page

Var	Groups	n	Levels	Dist[5] p	Dis	df	Var[6] p	Var	Mean	sd	Central tendency Test	p	Pairwise Test	G1	G2	p
		186	M	0.000	Nn				-0.16	0.87						
TPV	Gender	212	F	0.000	Nn	1	0.230	E	0.33	0.82	w	0.094				
		186	M	0.000	Nn				0.19	0.75						
HSV	Gender	212	F	0.000	Nn	1	0.275	E	0.19	0.93	w	0.121				
		186	M	0.000	Nn				0.05	0.82						
HPV	Gender	212	F	0.000	Nn	1	0.036	U	-0.50	0.88	w	0.102				
		186	M	0.000	Nn				-0.36	0.77						
ASV	Gender	212	F	0.000	Nn	1	0.335	E	0.91	0.98	w	0.353				
		186	M	0.000	Nn				0.81	0.95						
APV	Gender	212	F	0.000	Nn	1	0.040	U	0.35	1.08	w	0.803				
		186	M	0.000	Nn				0.34	0.86						
Overall	Gender	212	F	0.000	Nn	1	0.825	E	-0.31	0.46	w	0.826				
		186	M	0.000	Nn				-0.30	0.46						
TSV	e) Overall	5	Low	0.201	N	2	0.123	E	0.60	1.34	$k-w$	0.014	$w-t$	TSV	Low	Mid
	e) Overall	284	Mid	0.000	Nn				-0.28	0.99				TSV	Mid	High
	e) Overall	106	High	0.000	Nn				0.02	0.87				TSV	Low	High
TPV	e) Overall	5	Low	0.000	Nn	2	0.477	E	-0.60	1.34	$k-w$	0.045	$w-t$	TPV	Low	Mid
	e) Overall	284	Mid	0.000	Nn				0.32	0.76				TPV	Mid	High
	e) Overall	106	High	0.000	Nn				0.16	0.79				TPV	Low	High
HSV	e) Overall	5	Low	0.046	Nn	2	0.831	E	0.60	0.89	$k-w$	0.261		HSV	Low	Mid
	e) Overall	284	Mid	0.000	Nn				0.17	0.86				HSV	Mid	High
	e) Overall	106	High	0.000	Nn				0.01	0.92				HSV	Low	High
HPV	e) Overall	5	Low	0.325	N	2	0.598	E	0.00	0.71	$k-w$	0.458		HPV	Low	Mid
	e) Overall	284	Mid	0.000	Nn				-0.47	0.88				HPV	Mid	High
	e) Overall	106	High	0.000	Nn				-0.36	0.68				HPV	Low	High
ASV	e) Overall	5	Low	0.000	Nn	2	0.569	E	0.40	0.89	$k-w$	0.546		ASV	Low	Mid
	e) Overall	284	Mid	0.000	Nn				0.86	0.96				ASV	Mid	High
	e) Overall	106	High	0.000	Nn				0.85	0.99				ASV	Low	High
APV	e) Overall	5	Low	0.006	Nn	2	0.720	E	0.80	1.10	$k-w$	0.591		APV	Low	Mid
	e) Overall	284	Mid	0.000	Nn				0.35	1.00				APV	Mid	High
	e) Overall	106	High	0.000	Nn				0.33	0.96				APV	Low	High

1 N - Normal
2 Nn - Not normal
3 E - Equal
4 U - Unequal
5 Shapiro

Table E.1 continued from previous page

Var	Groups	n	Levels	Dist[5]	df	Var[6]		Central tendency					Pairwise		
				p	Dis	p	Var	Mean	sd	Test	p	Test	G1	G2	p

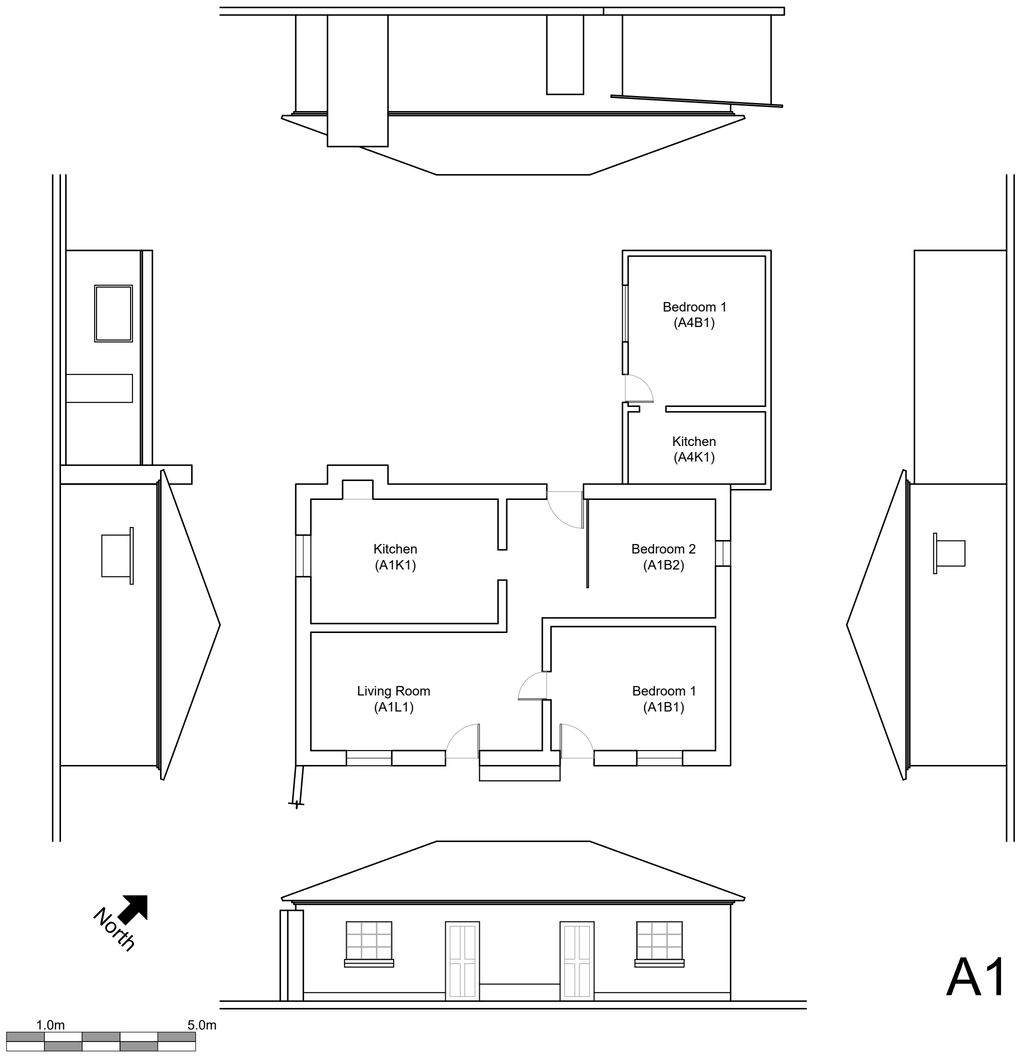
6 Levene
7 ANOVA test with no assumption of equal variances
8 $(k-w)$ Kruskal-Wallis rank sum test
9 (w) One-sample Wilcoxon rank test
10 (tH) Tukey HSD
11 $(w-t)$ Pairwise Wilcox test

Appendix F

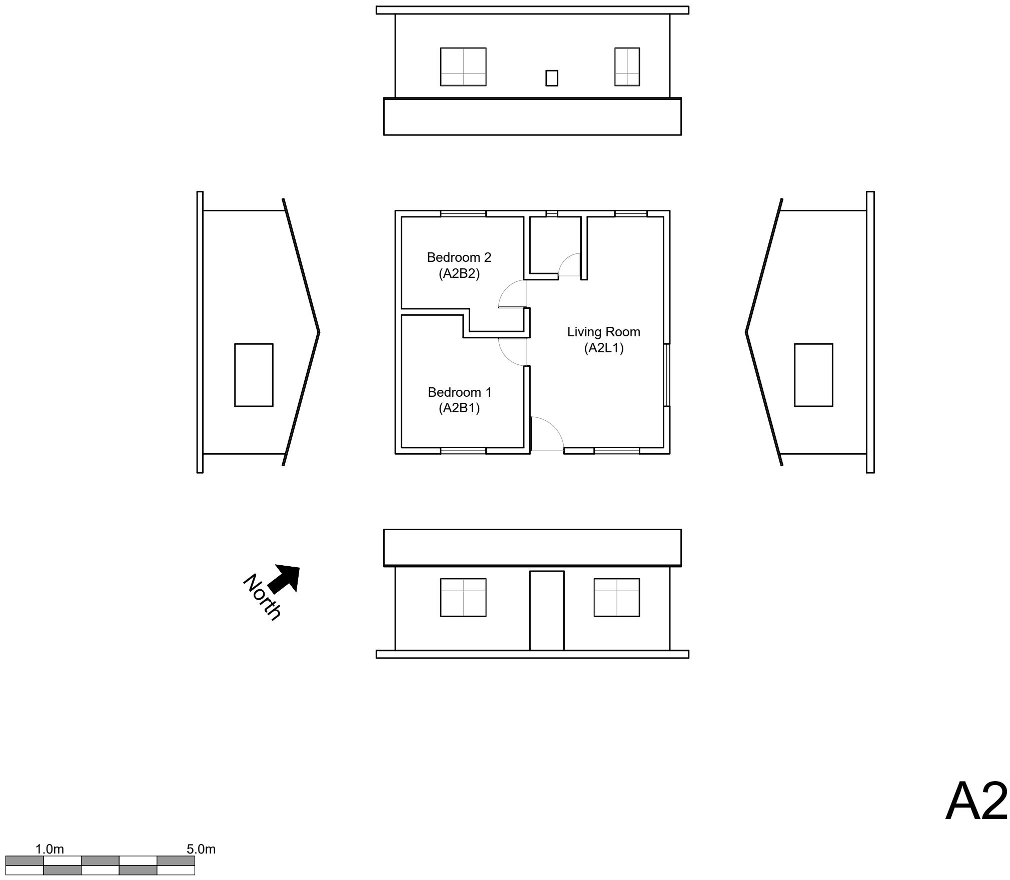
Monitoring and calibration data

F.1 Architectural drawings of the archetypes

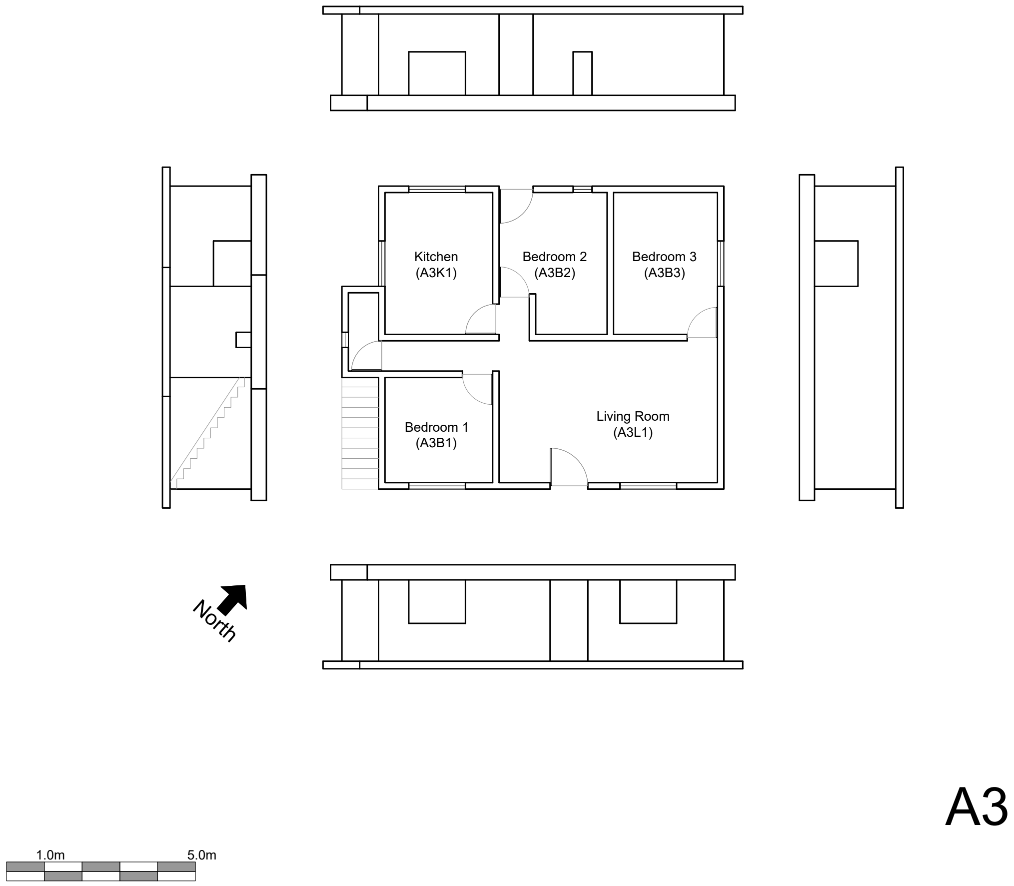
F.1.1 Dwelling A1



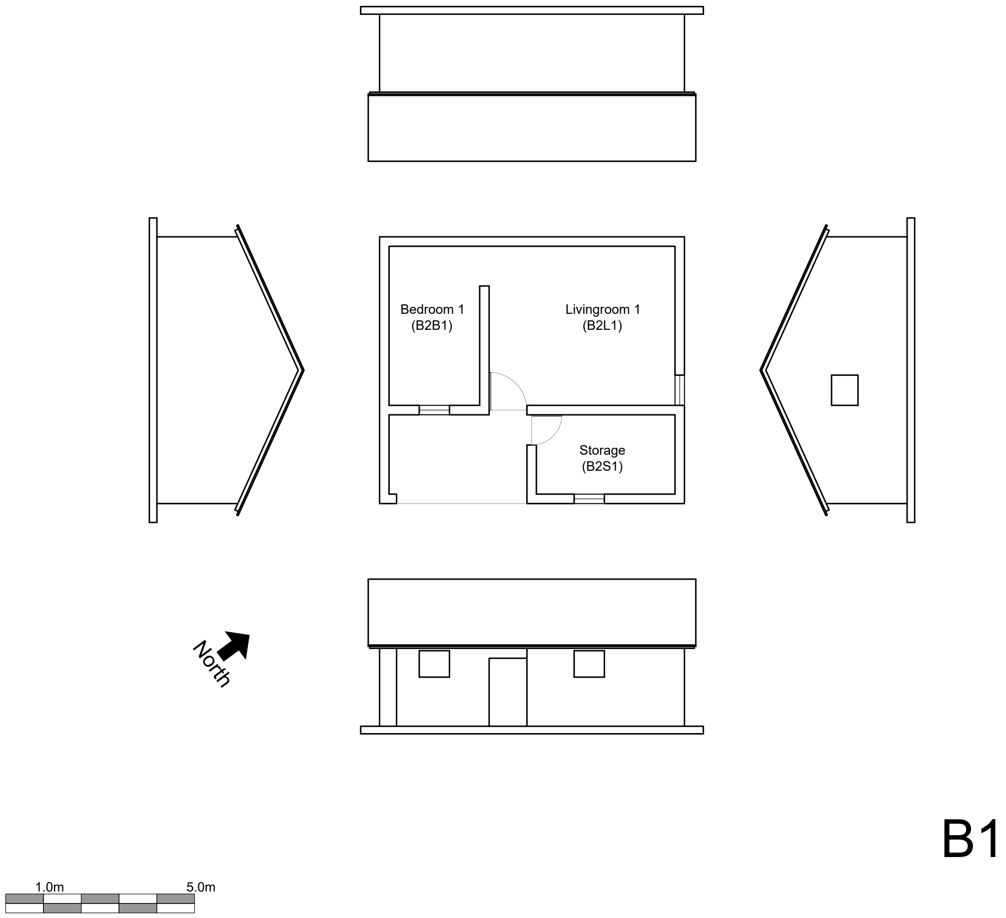
F.1.2 Dwelling A2



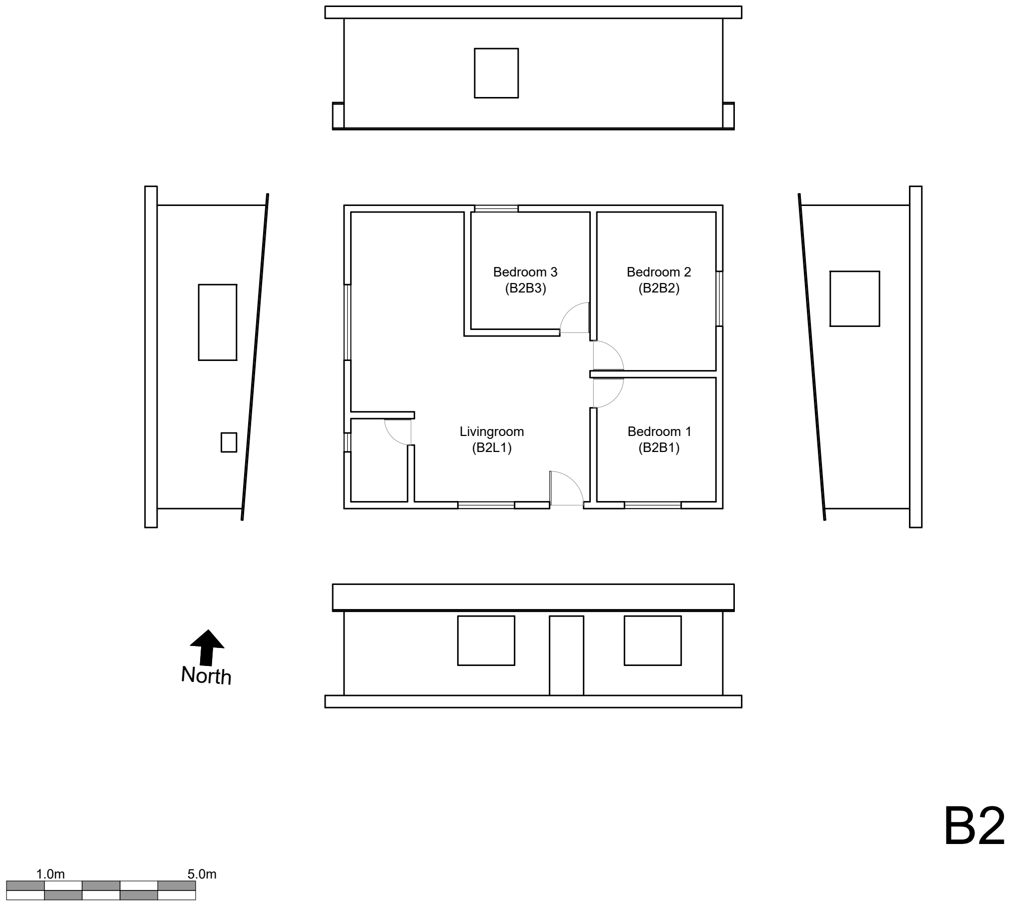
F.1.3 Dwelling A3



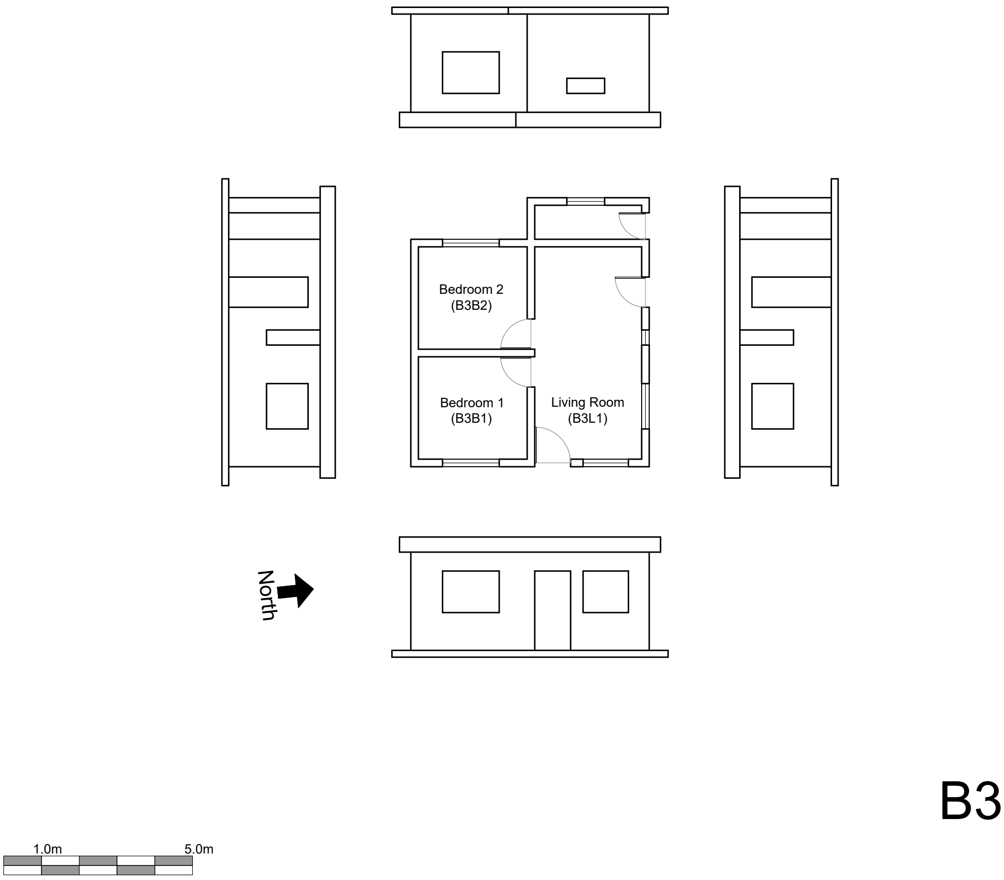
F.1.4 Dwelling B1



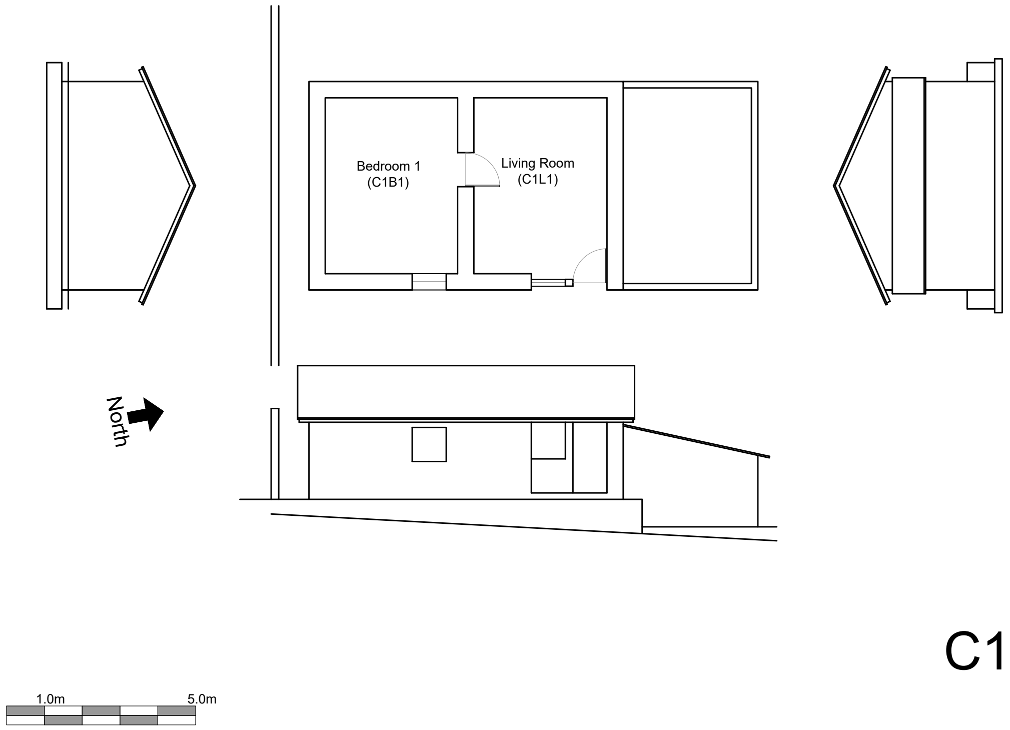
F.1.5 Dwelling B2



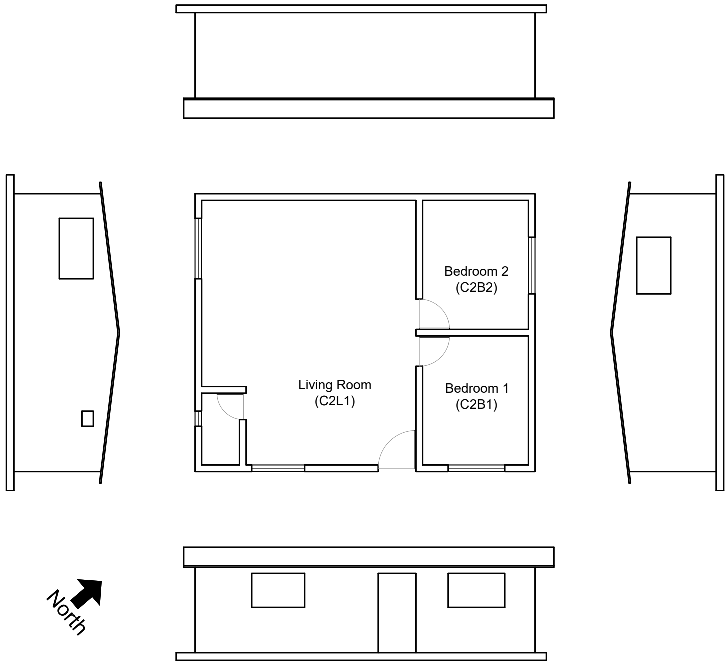
F.1.6 Dwelling B3



F.1.7 Dwelling C1

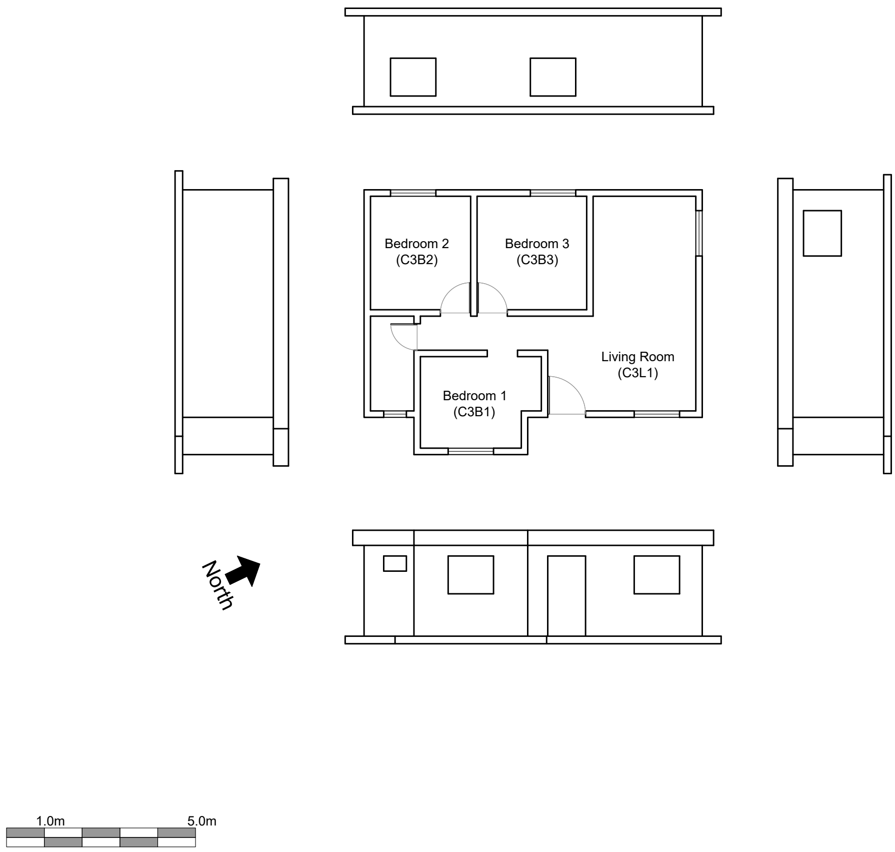


F.1.8 Dwelling C2



C2

F.1.9 Dwelling C3



C3

F.2 Description of dwellings construction and materials

Table F.1: Dwellings construction and materials

Dwell	Element	Position	Material code	Material description
A1	Ceiling	Layer 1 (outside)	Mud	Mud
	Ceiling	Layer 2	Guadua	Guadua
	Ceiling	Layer 3	Mud	Mud
	External door	Layer 1 (outside)	Wood	Wood
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Partitions	Layer 1 (outside)	Adobe	Adobe
	Roof	Layer 1 (outside)	ClayT	Clay tiles
	Roof	Layer 2	Plywood	Plywood
	Walls	Layer 1 (outside)	Adobe	Adobe
	Windows	Layer 1 (outside)	Glazing	Single glazing
A2	External door	Layer 1 (outside)	Metal	Metal
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Partitions	Layer 1 (outside)	Plaster	Cement plaster
	Partitions	Layer 2	Block	Hollow concrete block
	Partitions	Layer 3	Plaster	Cement plaster
	Roof	Layer 1 (outside)	Zinc	Zinc sheet
	Walls	Layer 1 (outside)	Plaster	Cement plaster
	Walls	Layer 2	Block	Hollow concrete block
	Walls	Layer 3	Plaster	Cement plaster
	Windows	Layer 1 (outside)	Glazing	Single glazing
A3	External door	Layer 1 (outside)	Metal	Metal
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Floor	Layer 4	Tiles	Ceramic Clay tiles
	Internal door	Layer 1 (outside)	Wood	Wood
	Partitions	Layer 1 (outside)	Plaster	Cement plaster
	Partitions	Layer 2	Block	Hollow concrete block
	Partitions	Layer 3	Plaster	Cement plaster
	Roof	Layer 1 (outside)	Screed	Cement Screed
	Roof	Layer 2	Concrete	Concrete reinforced (2% steel)
	Roof	Layer 3	LightBlock	Hollow concrete block - light
	Roof	Layer 4	Screed	Cement Screed
	Walls	Layer 1 (outside)	Plaster	Cement plaster
	Walls	Layer 2	Block	Hollow concrete block
	Walls	Layer 3	Plaster	Cement plaster

Table F.1 continued from previous page

Dwell	Element	Position	Material code	Material description
	Windows	Layer 1 (outside)	Glazing	Single glazing
B1	Ceiling	Layer 1 (outside)	Plywood	Plywood
	External door	Layer 1 (outside)	Wood	Wood
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Partitions	Layer 1 (outside)	Adobe	Adobe
	Roof	Layer 1 (outside)	ClayT	Clay tiles
	Walls	Layer 1 (outside)	Adobe	Adobe
	Windows	Layer 1 (outside)	Glazing	Single glazing
B2	Ceiling	Layer 1 (outside)	Gypsum	Gypsum board
	External door	Layer 1 (outside)	Wood	Wood
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Floor	Layer 4	LaminatedW	Laminated wood Floor
	Partitions	Layer 1 (outside)	Plaster	Cement plaster
	Partitions	Layer 2	Block	Hollow concrete block
	Partitions	Layer 3	Plaster	Cement plaster
	Roof	Layer 1 (outside)	Asbestos	Asbestos cement sheet
	Walls	Layer 1 (outside)	Plaster	Cement plaster
	Walls	Layer 2	Block	Hollow concrete block
	Walls	Layer 3	Plaster	Cement plaster
	Windows	Layer 1 (outside)	Glazing	Single glazing
B3	External door	Layer 1 (outside)	Metal	Metal
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Floor	Layer 4	Tiles	Ceramic Clay tiles
	Internal door	Layer 1 (outside)	Wood	Wood
	Partitions	Layer 1 (outside)	Plaster	Cement plaster
	Partitions	Layer 2	Block	Hollow concrete block
	Partitions	Layer 3	Plaster	Cement plaster
	Roof	Layer 1 (outside)	Screed	Cement Screed
	Roof	Layer 3	LightBlock	Hollow concrete block - light
	Walls	Layer 1 (outside)	Plaster	Cement plaster
	Walls	Layer 2	Block	Hollow concrete block
	Walls	Layer 3	Plaster	Cement plaster
	Windows	Layer 1 (outside)	Glazing	Single glazing
C1	Ceiling	Layer 1 (outside)	Plywood	Plywood
	External door	Layer 1 (outside)	Metal	Metal

Table F.1 continued from previous page

Dwell	Element	Position	Material code	Material description
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Internal door	Layer 1 (outside)	Wood	Wood
	Partitions	Layer 1 (outside)	Adobe	Adobe
	Roof	Layer 1 (outside)	ClayT	Clay tiles
	Walls	Layer 1 (outside)	Adobe	Adobe
	Windows	Layer 1 (outside)	Glazing	Single glazing
	External door	Layer 1 (outside)	Metal	Metal
	Floor	Layer 1 (outside)	Gravel	Gravel
C2	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 3	Screed	Cement Screed
	Floor	Layer 4	Tiles	Ceramic Clay tiles
	Internal door	Layer 1 (outside)	Wood	Wood
	Partitions	Layer 1 (outside)	Plaster	Cement plaster
	Partitions	Layer 2	Block	Hollow concrete block
	Partitions	Layer 3	Plaster	Cement plaster
	Roof	Layer 1 (outside)	Zinc	Zinc sheet
	Walls	Layer 1 (outside)	Plaster	Cement plaster
	Walls	Layer 2	Block	Hollow concrete block
	Walls	Layer 3	Plaster	Cement plaster
	Windows	Layer 1 (outside)	Glazing	Single glazing
C3	External door	Layer 1 (outside)	Metal	Metal
	Floor	Layer 1 (outside)	Gravel	Gravel
	Floor	Layer 2	Concrete	Concrete reinforced (2% steel)
	Floor	Layer 4	Tiles	Ceramic Clay tiles
	Internal door	Layer 1 (outside)	Wood	Wood
	Partitions	Layer 1 (outside)	Plaster	Cement plaster
	Partitions	Layer 2	Block	Hollow concrete block
	Partitions	Layer 3	Plaster	Cement plaster
	Roof	Layer 1 (outside)	Screed	Cement Screed
	Roof	Layer 3	LightBlock	Hollow concrete block - light
	Walls	Layer 1 (outside)	Plaster	Cement plaster
	Walls	Layer 2	Block	Hollow concrete block
	Walls	Layer 3	Plaster	Cement plaster
	Windows	Layer 1 (outside)	Glazing	Single glazing

F.3 Reference values for the materials thermal properties

Table F.2: Reference values for the materials thermal properties

Material	Description	Cond (W/mK)	Den (kg/m^3)	Sp Heat (J/K)	Reference
Adobe	Adobe	0.58	1280	850	(Gallardo et al., 2016a)
Adobe	Blocks of compacted earth	1.05	1700		(Clarke et al., 1990)
Adobe	Blocks of compacted earth	1.05	1900		(Clarke et al., 1990)
Adobe	Rammed earth	1.01	2120	827.36	(Hall and Allinson, 2009)
Adobe	Rammed earth	0.83	2020	855.45	(Hall and Allinson, 2009)
Adobe	Rammed earth	0.87	1980	868.18	(Hall and Allinson, 2009)
Adobe	Clay brick	0.24	800	750	(Goodhew and Griffiths, 2005)
Adobe	Rammed earth	0.68	1760	897	(Yan et al., 2005)
Adobe	Rammed earth	0.72	1824	900	(Yan et al., 2005)
Adobe	Rammed earth	0.74	1835	902	(Yan et al., 2005)
Adobe	Rammed earth	1.25	1540	1260	(Soebarto, 2009)
Asbestos	Asbestos cement decking	0.36	1500		(CIBSE Guide A, 2015)
Asbestos	Asbestos cement sheet	0.37	1520		(Clarke et al., 1990)
Asbestos	Asbestos cement sheet	0.25	1360		(Clarke et al., 1990)
Asbestos	Asbestos cement sheet	0.4	1600		(Clarke et al., 1990)
Asbestos	Asbestos cement sheet	0.55	2000		(Clarke et al., 1990)
Block	Block, hollow, mediumweight	0.62	1040	840	(CIBSE Guide A, 2015)
Block	Block, hollow, mediumweight	0.86	930	840	(CIBSE Guide A, 2015)
Block	Concrete block hollow[1]	0.86	928	837	(Clarke et al., 1990)
Block	Concrete block hollow[1]	0.62	1040	837	(Clarke et al., 1990)
Block	Concrete block hollow[1]	0.67	848	837	(Clarke et al., 1990)
Block	Concrete block hollow[1]	0.52	1216	837	(Clarke et al., 1990)
LightBlock	Lightweight hollow concrete block	0.48	880	840	(CIBSE Guide A, 2015)
LightBlock	Lightweight hollow concrete block	0.76	780	840	(CIBSE Guide A, 2015)
LightBlock	Concrete block hollow[2]	0.58	720	837	(Clarke et al., 1990)
LightBlock	Concrete block hollow[2]	0.48	880	837	(Clarke et al., 1990)
LightBlock	Concrete block hollow[2]	0.38	1040	837	(Clarke et al., 1990)
LightBlock	Concrete block hollow[2]	0.76	784	837	(Clarke et al., 1990)
ClayT	Tiles Clay (Roofing)	1	2000	800	(EN ISO, 2007b)
ClayT	Ceramic / Porcelain Tiles (Roofing)	1.3	2300	840	(EN ISO, 2007b)
ClayT	Roof tile (Roofing materials)	0.84	1900	800	(CIBSE Guide A, 2015)
ClayT	Tile, terracotta (Roofing material)	0.81	1700	840	CIBSE Guide A (2015)
ClayT	Tiles, clay	0.85	1900	837	(Clarke et al., 1990)
ClayT	Terracotta roof tiles		1600		(Clarke et al., 1990)
ClayT	Terracotta tiles	0.81	1700	840	(Clarke et al., 1990)
ClayT	Roof tile	0.84	1900	800	(Clarke et al., 1990)
ClayT	Roof tile		1900	850	(Clarke et al., 1990)
ClayT	Roof tile		1900	1010	(Clarke et al., 1990)
Concrete	Concrete reinforced (1% steel)	2.3	2300	1000	(EN ISO, 2007b)
Concrete	Concrete reinforced (2% steel)	2.5	2400	1000	(EN ISO, 2007b)

Table F.2 continued from previous page

Material	Description	Cond (W/mK)	Den (kg/m^3)	Sp Heat (J/K)	Reference
Concrete	Dense, reinforced (Concrete cast)	1.9	2300	840	(CIBSE Guide A, 2015)
Concrete	Concrete cast dense[3]	1.9	2500	840	(Clarke et al., 1990)
Concrete	Concrete cast dense[3]	2.3	2500	840	(Clarke et al., 1990)
Concrete	Concrete cast dense[4]	1.4	2300	840	(Clarke et al., 1990)
Concrete	Concrete cast dense[4]	1.9	2300	840	(Clarke et al., 1990)
Glazing	Single clear 3mm	1.05			(Clarke et al., 1990)
Glazing	Single clear 6mm	0.7			(Clarke et al., 1990)
Gravel	Sand, gravel and stone aggregated[5]	1.8	2240	840	(CIBSE Guide A, 2015)
Gravel	Aggregate (sand, gravel or stone)	1.3	2240	920	(CIBSE Guide A, 2015)
Gravel	Gravel	0.36	1840	840	(Clarke et al., 1990)
Gravel	Sand, gravel and stone aggregated[5]	1.73	2240	840	(Clarke et al., 1990)
Gravel	Sand, gravel and stone aggregated[6]	1.3	2240	921.14	(Clarke et al., 1990)
Guadua	Guadua (Bamboo)	0.3	714	1750	(Gallardo et al., 2016a)
Guadua	Hardwood	0.23	800	1880	(CIBSE Guide A, 2015)
Guadua	Hardwood	0.17	800	1880	(Clarke et al., 1990)
Gypsum	Gypsum	0.18	600	1000	(EN ISO, 2007b)
Gypsum	Gypsum	0.3	900	1000	(EN ISO, 2007b)
Gypsum	Gypsum	0.43	1200	1000	(EN ISO, 2007b)
Gypsum	Gypsum	0.56	1500	1000	(EN ISO, 2007b)
Gypsum	Gypsum	0.42	1200	840	(CIBSE Guide A, 2015)
LaminatedW	Laminated wood Floor	0.15	800	2093	(CIBSE Guide A, 2015)
LaminatedW	Laminated wood Floor	0.14	650	1200	(CIBSE Guide A, 2015)
Metal	Steel	50			(EN ISO, 2007b)
Metal	Steel	45			(CIBSE Guide A, 2015)
Mud	Clay - straw mixture	0.18	440	900	(Goodhew and Griffiths, 2005)
Mud	Mud	0.24	800	650	(Goodhew and Griffiths, 2005)
Plaster	Cement, sand (Plaster and renders)	1	1800	1000	(EN ISO, 2007b)
Plaster	Cement plaster	0.72	1760	840	(CIBSE Guide A, 2015)
Plaster	Cement plaster	1.5	1900	840	(CIBSE Guide A, 2015)
Plaster	Cement plaster, sand aggregate	0.72	1860	840	(CIBSE Guide A, 2015)
Plaster	Cement plaster	0.72	1762	840	(Clarke et al., 1990)
Plaster	Cement plaster	0.93	1900	840	(Clarke et al., 1990)
Plaster	Cement plaster	1.5	1900	840	(Clarke et al., 1990)
Plywood	Plywood	0.09	300	1600	(EN ISO, 2007b)
Plywood	Plywood	0.13	500	1600	(EN ISO, 2007b)
Plywood	Plywood	0.17	700	1600	(EN ISO, 2007b)
Plywood	Plywood	0.24	1000	1600	(EN ISO, 2007b)
Plywood	Plywood	0.12	540	1210	(CIBSE Guide A, 2015)
Plywood	Plywood	0.15	700	1420	(CIBSE Guide A, 2015)
Plywood	Plywood	0.12	544	1214.23	(Clarke et al., 1990)
Plywood	Plywood	0.12	544	1214.17	(Clarke et al., 1990)
Plywood	Plywood	0.15	560	2500	(Clarke et al., 1990)

Table F.2 continued from previous page

Material	Description	Cond (W/mK)	Den (kg/m^3)	Sp Heat (J/K)	Reference
Plywood	Plywood	0.15	700	1420	(Clarke et al., 1990)
Plywood	Plywood	0.15	800		(Clarke et al., 1990)
Plywood	Plywood	0.17	640	1760	(Clarke et al., 1990)
Plywood	Plywood	0.1	545		(Clarke et al., 1990)
Plywood	Plywood	0.14	600	1880	(Clarke et al., 1990)
Plywood	Plywood	0.15	600		(Clarke et al., 1990)
Plywood	Plywood	0.17	700	1880	(Clarke et al., 1990)
Plywood	Plywood	0.23	700	1880	(Clarke et al., 1990)
Screed	Cement screed	1.4	2100	650	(CIBSE Guide A, 2015)
Screed	Screed	1.4	2100	650	(Clarke et al., 1990)
Screed	Screed	0.41	840	1200	(Clarke et al., 1990)
Screed	Screed for roofs	0.41	1200	840	(Clarke et al., 1990)
Tiles	Ceramic / Porcelain	1.3	2300	840	(EN ISO, 2007b)
Tiles	Ceramic floor tiles Dry	0.8	1700	850	(CIBSE Guide A, 2015)
Tiles	Ceramic floor tiles Dry	0.9	1900	840	(CIBSE Guide A, 2015)
Tiles	Ceramic tiles Dry	1.2	2000	850	(CIBSE Guide A, 2015)
Wood	Wood (oak)	0.19	700	2390	(CIBSE Guide A, 2015)
Wood	Plywood Heavy	0.15	700	1420	(CIBSE Guide A, 2015)
Wood	Plywood Light	0.15	560	2500	(CIBSE Guide A, 2015)
Zinc	Zinc	110	7200	380	(EN ISO, 2007b)
Zinc	Zinc	113	7000	390	(CIBSE Guide A, 2015)
Zinc	Zinc	110	7200	390	(Clarke et al., 1990)
Zinc	Zinc	110	7200		(Clarke et al., 1990)
Zinc	Zinc	112	7130		(Clarke et al., 1990)
Zinc	Zinc	110	7130	390	(Clarke et al., 1990)
Zinc	Zinc	113	7000		(Clarke et al., 1990)
Zinc	Zinc	113	7000	390	(Clarke et al., 1990)

[1] Concrete block hollow (Medium weight)

[2] Concrete block hollow (Lightweight)

[3] Concrete cast dense compacted reinforced

[4] Concrete cast dense not compacted reinforced

[5] Sand, gravel and stone aggregated, not dried

[6] Sand, gravel and stone aggregated, oven dried

F.4 Archetypes baseline constructions and materials properties

Table F.3: Archetypes baseline constructions and materials properties

Code	Material	Description	Thick (m)	Cond (W/mK)	Den (kg/m3)	Sp Heat (J/K)	Reference
A1	Adobe	Adobe	0.43	0.58	1280	850	(Gallardo et al., 2016a)
	ClayT	Clay tiles	0.03	1	2000	800	(EN ISO, 2007b)
	Con	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			(Clarke et al., 1990)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Gua	Guadua	0.03	0.3	714	1750	(Gallardo et al., 2016a)
	Mud	Mud	0.03	0.18	440	900	(Goodhew and Griffiths, 2005)
	Ply	Plywood	0.02	0.15	560	2500	(EN ISO, 2007b)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Woo	Wood	0.03	0.19	700	2390	(CIBSE Guide A, 2015)
A2	Block	Hollow concrete block	0.12	0.62	1040	840	(CIBSE Guide A, 2015)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			(U.S. Department of Energy, 2017)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Metal	Metal	0.002	50			(EN ISO, 2007b)
	Plaster	Cement plaster	0.02	0.72	1760	840	(CIBSE Guide A, 2015)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Zinc	Zinc sheet	0.001	110	7200	380	(EN ISO, 2007b)
A3	Block	Hollow concrete block	0.14	0.62	1040	840	(CIBSE Guide A, 2015)
	LightBlock	Hollow concrete block[1]	0.1	0.48	880	840	(CIBSE Guide A, 2015)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			(U.S. Department of Energy, 2017)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Metal	Metal	0.002	50			(EN ISO, 2007b)
	Plaster	Cement plaster	0.02	0.72	1760	840	(CIBSE Guide A, 2015)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Tiles	Ceramic Clay tiles	0.01	0.9	1900	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)
B1	Adobe	Adobe	0.25	0.58	1280	850	(Gallardo et al., 2016a)
	ClayT	Clay tiles	0.03	1	2000	800	(EN ISO, 2007b)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			EnergyPlus)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Plywood	Plywood	0.02	0.15	560	2500	(EN ISO, 2007b)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)
B2	Asbestos	Asbestos cement sheet	0.01	0.36	1500		(CIBSE Guide A, 2015)
	Block	Hollow concrete block	0.15	0.62	1040	840	(CIBSE Guide A, 2015)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)

Table F.3 continued from previous page

Code	Material	Description	Thick (m)	Cond (W/mK)	Den (kg/m3)	Sp Heat (J/K)	Reference
	Glazing	Single glazing	0.003	1.05			EnergyPlus)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Gypsum	Gypsum board	0.01	0.18	600	1000	(EN ISO, 2007b)
	LaminatedW	Laminated wood Floor	0.01	0.14	650	1200	(CIBSE Guide A, 2015)
	Plaster	Cement plaster	0.02	0.72	1760	840	(CIBSE Guide A, 2015)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)
B3	Block	Hollow concrete block	0.14	0.62	1040	840	(CIBSE Guide A, 2015)
	LightBlock	Hollow concrete block*	0.1	0.48	880	840	(CIBSE Guide A, 2015)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			EnergyPlus)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Metal	Metal	0.002	50			(EN ISO, 2007b)
	Plaster	Cement plaster	0.02	0.72	1760	840	(CIBSE Guide A, 2015)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Tiles	Ceramic Clay tiles	0.01	0.9	1900	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)
C1	Adobe	Adobe	0.43	0.58	1280	850	(Gallardo et al., 2016a)
	ClayT	Clay tiles	0.03	1	2000	800	(EN ISO, 2007b)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			EnergyPlus)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Metal	Metal	0.002	50			(EN ISO, 2007b)
	Plywood	Plywood	0.02	0.15	560	2500	(EN ISO, 2007b)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)
C2	Block	Hollow concrete block	0.15	0.62	1040	840	(CIBSE Guide A, 2015)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			EnergyPlus)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)
	Metal	Metal	0.002	50			(EN ISO, 2007b)
	Plaster	Cement plaster	0.02	0.72	1760	840	(CIBSE Guide A, 2015)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Tiles	Ceramic Clay tiles	0.01	0.9	1900	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)
	Zinc	Zinc sheet	0.001	110	7200	380	(EN ISO, 2007b)
C3	Block	Hollow concrete block	0.14	0.62	1040	840	(CIBSE Guide A, 2015)
	LightBlock	Hollow concrete block*	0.1	0.48	880	840	(CIBSE Guide A, 2015)
	Concrete	Concrete reinforced	0.1	2.5	2400	1000	(EN ISO, 2007b)
	Glazing	Single glazing	0.003	1.05			EnergyPlus)
	Gravel	Gravel	0.15	1.8	2240	840	(CIBSE Guide A, 2015)

Table F.3 continued from previous page

Code	Material	Description	Thick (m)	Cond (W/mK)	Den (kg/m3)	Sp Heat (J/K)	Reference
	Metal	Metal	0.002	50			(EN ISO, 2007b)
	Plaster	Cement plaster	0.02	0.72	1760	840	(CIBSE Guide A, 2015)
	Scr	Cement Screed	0.03	0.41	1200	840	(CIBSE Guide A, 2015)
	Tiles	Ceramic Clay tiles	0.01	0.9	1900	840	(CIBSE Guide A, 2015)
	Wood	Wood	0.03	0.19	700	2390	(Tindale, 2005)

[1] Hollow concrete block - Light

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