The Development of Data-Collection Methods for Thermal Comfort Assessment in Tropical Countries

Article *in* IOP Conference Series Materials Science and Engineering · September 2019

DOI: 10.1088/1757-899X/603/5/052001

4 authors:

Carolina -Stevenson- Rodriguez
Universidad Piloto de Colombia

Juan Manuel Medina
Los Andes University (Colombia)

Maria Camila Coronado
Universidad Piloto de Colombia

Marta D'Alessandro

IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

The Development of Data-Collection Methods for Thermal Comfort Assessment in Tropical Countries

IOP Conf. Series: Materials Science and Engineering **603** (2019) 052001 doi:10.1088/1757-899X/603/5/052001

The Development of Data-Collection Methods for Thermal Comfort Assessment in Tropical Countries

Carolina M Rodriguez [1], Juan M Medina [2], Maria Camila Coronado [1], Marta D´Alessandro [3]

[1] University Piloto de Colombia, Bogotá, Colombia, Bogotá, Colombia

[2] Architecture Department, University of Los Andes, Bogota, Colombia, Colombia

[3] Architecture, Built Environment and Construction Engineering Department (ABC), Polytechnic University of Milan, Milan, Italy

carolina-rodriguez1@unipiloto.edu.co

Abstract. Thermal comfort in the built environment is one of the most defining parameters influencing energy use, environmental quality, and occupant satisfaction; therefore, it is currently receiving a great deal of academic attention. Unfortunately, there is still a pronounced lack of research in this area within developing countries in tropical regions, which are becoming increasingly urbanised and where mechanical air conditioning demands are rising dramatically. Many of these countries are adopting thermal comfort standards such as the ASHRAE Standard 55, the EN 15251, and the ISO 7730 to regulate the use of air-conditioning; even when these standards have been widely criticised for their inadequacy to suit other geographical regions and contexts, different to the ones that they were designed for. There is growing evidence to suggest the need to confirm these models through further post-occupancy studies and fieldwork in real buildings. Deficiencies in data collection and methodologies are thought to require particular attention, in order to develop algorithms that can predict thermal comfort levels with more accuracy. More comprehensive strategies considering relevant interrelated psychological, physiological and social factors are needed. This manuscript highlights gaps of research regarding thermal comfort in the built environment, through the analysis of Colombia as a case study. It is stressed here that new academic advancements in this area have had little effect on related policy. The work emphasises the importance of standardised fieldwork data and gives examples of alternative data collection and methodology systems. This aims to contribute to the current efforts of improving the understanding of occupant´s adaptive behaviours and their potential impact on the mitigation of climate change.

1. Introduction

This article highlights and justifies the need to produce more efficient, comprehensive and standardised methods to collect data from buildings and their occupants, aiming to support the development of thermal comfort assessment models in tropical countries. The above statement suggests two different but associated types of needs that require academic attention: the need for data collection methods and the need for specific models to assess thermal comfort in countries located within the tropics. The first one comprises the analysis of current methodologies used to gather information regarding thermal comfort in buildings. The second one involves the discussion on the suitability and applicability of current procedures used to predict and evaluate thermal comfort in the built environment. These presumptions are supported here with relevant literature and secondary research from different sources.

Additionally, results from primary research by the authors and collaborators is used to illustrate and stress the arguments. This research was carried out over the past five years in the context of Colombia.

1.1 Why is thermal comfort in the tropics important?

Traditionally, indoor thermal comfort had been achieved using passive architectural solutions, progressively refined over time according to the conditions of each climate and cultural context. In recent decades, however, this scenario has changed drastically worldwide due to the introduction of HVAC systems. These are now more common, affordable, desirable and, in many cases, even unavoidable. Unfortunately, this growth has contributed to the increase in energy consumption, carbon emissions and related pollution [1–4]. Paradoxically, many of the countries where use of air conditioning is rising are also geographically located in areas of high vulnerability to climate change (Figure 1).

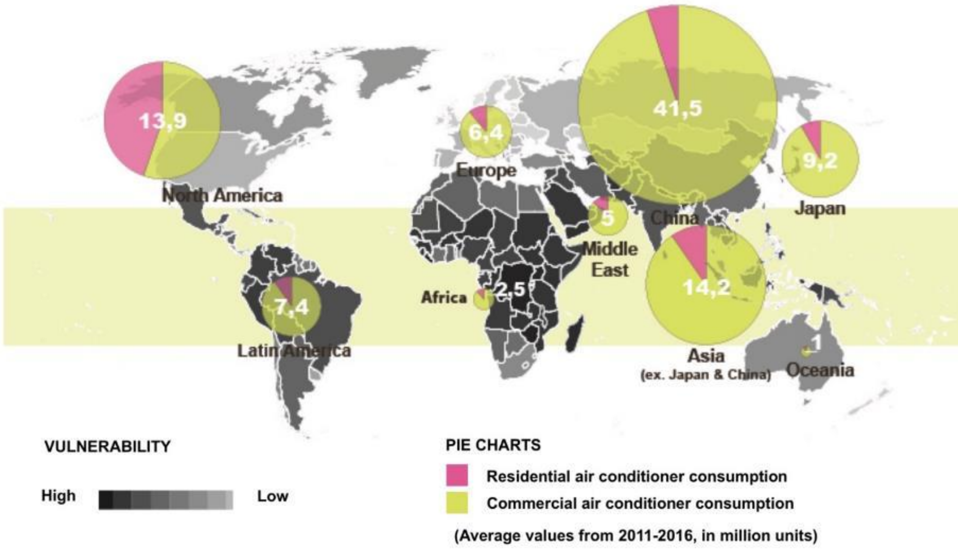


Figure 1. Air conditioning consumption in million units between 2011-2016, based on [5]. Vulnerability to climate change, based on [6].

The use of mechanical air conditioning has been linked to health problems related to poor indoor air quality, such as the Sick Building Syndrome (SBS) [7]. Certain occupants are more prone to these types of illness, for example, children whose organs are smaller, more vulnerable and in the process of development [8,9]. Furthermore, studies show that occupants who spend a lot of time in air-conditioned environments tend to acclimatise and adapt fairly quickly to lower temperatures [10], but over time become more intolerant to higher outside temperatures [11] and extreme thermal conditions, opting for "thermal indulgence" [12]. This dependency on mechanical air conditioning is very often forced into occupants, who do not have the choice of natural ventilation. Air-conditioned spaces are normally designed to be enclosed and airtight volumes, in order to make the mechanical system more efficient. On the contrary, spaces with natural ventilation require a greater volume (which usually translates into greater height) and the adequate design of openings to promote air movement. This dichotomy is a concern because these architectural features are very difficult to change once the building is built, especially in multi-storey constructions. Therefore, if the building was designed with HVAC systems in mind it is very likely that it will be limited to its use throughout its life cycle. Likewise, spaces originally used for passive conditioning in existing buildings − such as balconies and other transitional spaces − tend to lose their primal function when occupants use them to locate mechanical conditioning equipment instead (Figure 2).

The above issues related to mechanical air conditioning make *thermal comfort* one of the most studied subjects in building engineering during the last decade. Most research projects and academic publications in this area have been carried out after the year 2000 (Figure 3(C)). Generally, efforts have concentrated on studying and developing standards for countries in North America and Europe (Figure 3). Even when it is very likely that before 2050 half of the world's population will reside in tropical regions [13]. Top populated countries such as India, Indonesia, Brazil, Nigeria, and Mexico have a great parentage of their territory located with the tropics, but little research on thermal comfort. The tropics comprise a section of the world geographically located between the Tropic of Cancer (23.4°N) and Tropic of Capricorn (23.4°S), which gets most of sun exposure. This creates a preconception of tropics as being a hot and humid region, when in fact it is a region of vast environmental and climatic diversity.

Figure 2. Example of balconies and other spaces used to house air conditioning equipment.

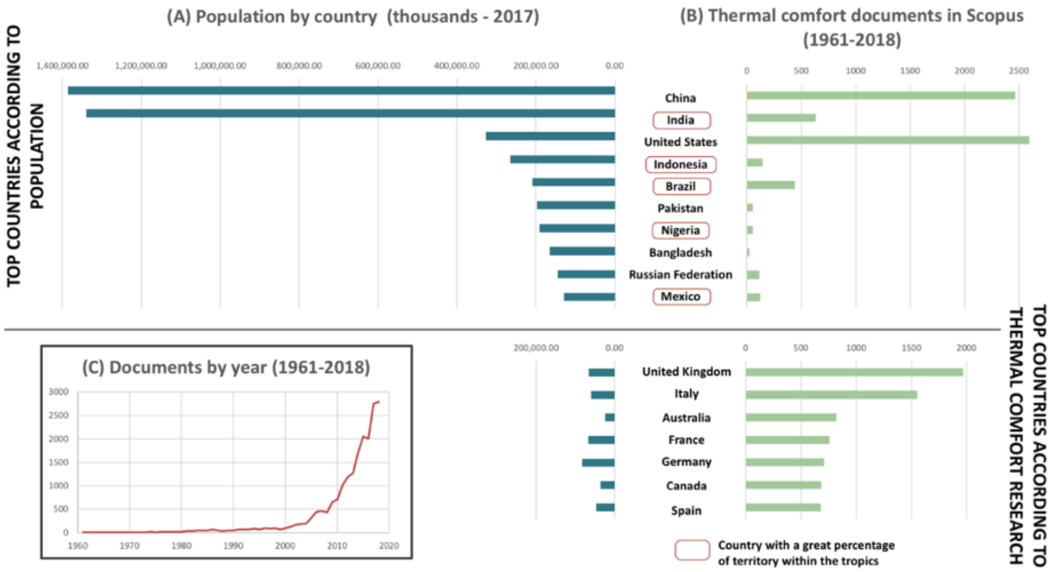


Figure 3. (A-B) Thermal comfort research according to the country and in relation to population figures. (C) Published documents on thermal comfort by year. Figure by the authors with data from the World Bank Group and SCOPUS searches on the 18 March 2019.

1.2 Why is there a need for thermal comfort models specific for the tropics

Mainstream thermal comfort standards such as the ASHRAE Standard 55, the ISO 7730 standard or the CSN EN 15251 standard, were originally developed in and for the United States and Europe [14]. However, these have been translated and implemented literally in many tropical countries, without taking into account their economic, political and geographic conditions or their cultural traditions and practices regarding climate adaptation. It is argued that these standards may be promoting the use of HVAC systems since they have been financed and endorsed by associations such as ASHRAE (American Society of Heating Engineers, Refrigeration and Air Conditioning). It is therefore likely that its content and wording suggests the superiority of mechanical conditioning over other alternatives [15]. Two main methods or models for assessing thermal comfort in buildings are normally included in the standards. These are known as the *static model*, developed by Fanger [16] and the *adaptive model* lead by de Dear et al. [17]. The static model focuses on the study of physiological variables related to the heat exchange between the human body and the environment and it is usually advised for spaces with mechanical ventilation. The adaptive model includes other dynamic variables related to the external climate and occupants' actions and it is generally advised for spaces with natural ventilation.

The adaptive model was developed and recently updated using information from two databases: the ASHRAE RP-884 database published in 1998 comprising 23 field research projects [18] and the ASHRAE Global Thermal Comfort Database II published in 2018 comprising 42 field research projects [19]. A closer look at these databases evidences their limited amount of information from tropical regions and climates of Africa, South America, Central America, and the Caribbean. Only 23% of the studies in these databases looked at climates in tropical regions. Most of the buildings were offices, including a very small percentage of buildings with natural ventilation, especially in the first sample (Figure 4).

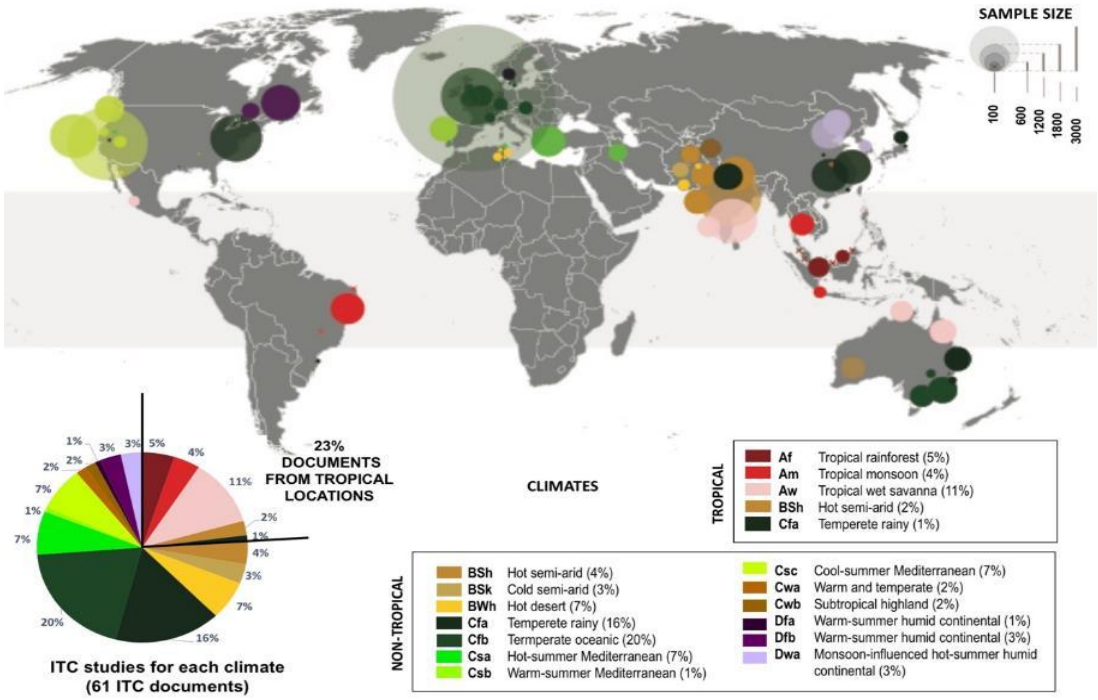


Figure 4. Location and climate of the studies used to develop the adaptive model included in the ASHRAE 55 standard. Figure by the author with data from [18–20].

1.3 Why are data-collection methods relevant?

Despite the limitations mentioned above, one of the main contributions of the ASHRAE databases is the systematisation of raw data from various thermal comfort field studies around the world. Information about environmental conditions taken from existing buildings and subjective evaluations from their occupants was categorised for these databases using multiple criteria, such as building typology, occupancy type, occupants' demographics, thermal comfort perceptions, indoor instrumental measurements, outdoor meteorological information, and calculated comfort indices. This is a considerable achievement given the complexity of comparing studies from different authors in distinct contexts and using diverse methodologies to acquire and analyse data. Deficiencies in data collection and fieldwork methodologies are one of the biggest challenges faced in thermal comfort research since the accuracy of the theoretical models relies greatly on the quality of the recorded data from real buildings. Another important limitation is geographical coverage, as there is still a general lack of research in tropical contexts and climates, compared to other regions in the world. In recent years, tropical countries such as Brazil, India, Malaysia, and Singapore have greatly increased their research efforts in this area, particularly through fieldwork. However, studies are still disjointed from the rest of the tropics and data-collection methods and evaluation techniques are varied. It is argued here that some level of standardisation is needed to facilitate comparative and statistical analysis that could influence the development of more accurate policies based on the existing data.

IOP Conf. Series: Materials Science and Engineering **603** (2019) 052001 doi:10.1088/1757-899X/603/5/052001

Although there is still no consensus on the feasibility or applicability − within different contexts − of any of the proposed models, many authors agree that assessing thermal comfort is a complex task that requires further investigation, especially in the interrelation between different physiological, psychological and social factors [21–26]. In this context, the importance of undertaking more post-occupation studies that include on-site fieldwork is highlighted [27–29]. Likewise, it is essential to achieve the coordination of the entities generating policies on thermal comfort to provide greater clarity in the minimum expected requirements, the implementation processes and the evaluation methods.

2. Case study: Thermal comfort research in Colombia

2.1. Background

Colombia is used in this manuscript as a representative example to illustrate in more detail the challenges faced by thermal comfort research in a developing country located within the topics. There are comparable characteristics and challenges that impact the study and evaluation of thermal comfort, which are present here as well as in other parts of the world. These include: **a.** steady population growth, **b.** a pronounced increase in energy consumption and HVAC demand, **c.** Great diversity of climates, **d.** a generalised lack of investment in academic research

Colombia is the third most populated country in Latin America, with approximately 45.5 million people. Decades of internal armed conflict have pushed millions of people out of the countryside and into the cities, becoming one of the most urbanised countries in the region. The intensification of displacement combined with steady population growth has had a direct impact on energy consumption and CO_2 emissions (Figure 5). Part of this is attributed to the rising demand for air conditioning, which increased by 66% between 2011 and 2016 (Japan Refrigeration and Air Conditioning Industry Association (JRAIA), 2017). This positions the country in fifth place in consumption in Latin America, with approximately 200-250 thousand units sold per year. This tendency is likely to continue in the near future, as construction grows to address current housing deficits.

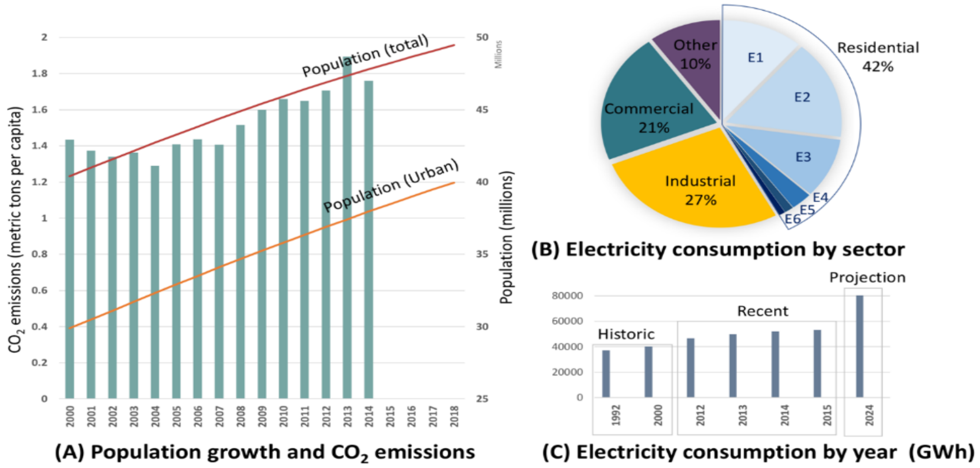
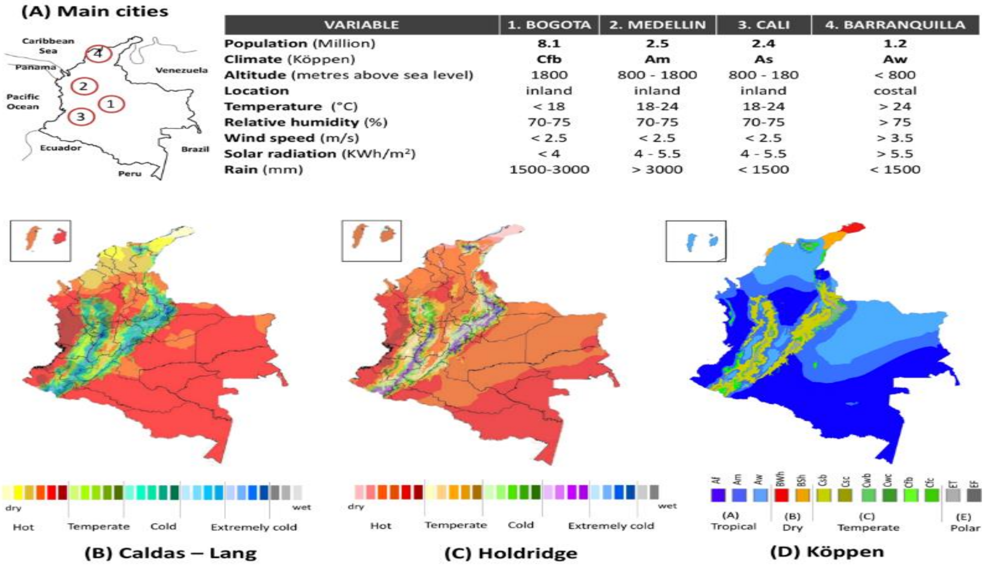


Figure 5. (A) Population growth and CO2 emissions. (B) Consumption of electricity by sector [30]. (B) Historical increase and projection of electricity consumption in Colombia[31]. Figure by the authors with data from the World Bank Group and UPME.

Colombia is also a country with a great diversity of geographies and meteorological conditions. Most of its main cities are located in very different physical contexts and climates (Figure 6). For example, Bogotá (Colombian capital) is considered to be a cold climate, located at 2,547m above sea level, with an average temperature of 14°C and 73% relative humidity. Medellín is considered a tropical monsoon climate, located at 1,490m, with an average temperature of 22°C and 68% relative humidity. Cali is considered a tropical warm-dry climate, located at 961m, with an average temperature of 23°C and 73% relative humidity. Whereas Barranquilla is considered a wet-dry tropical climate, located in a coastal zone at 52m, with an average temperature of 28°C and 80% relative humidity [32].

There are various characterisations used to describe the different climates in the country, including the Caldas-Lang, Holdridge and Köppen classifications amongst many others (Figure 6). Some of these have been described in past literature as unsuitable for the study of thermal comfort because they are based on vegetation and rainfall observations rather than on human-related aspects or variables [22]. There are also classifications that are too general and may misrepresent the actual climatic conditions of a place. For example, Bogotá is considered climate Cfb (temperate oceanic) according to the Köppen classification. This grades it in the same group as Paris, London, Berlin, Vancouver, and Melbourne. However, the climatic variables that affect thermal comfort are very different in those cities. For example, Bogotá has a relatively homogeneous climate throughout the year with no marked seasons, but its location within the Andes highlands contributes towards significant temperature changes throughout the day. It is known that altitude and changes in atmospheric pressure also affect oxygen concentration in the body and the function of the vascular system, resulting in changes in metabolic rates [33,34]. So, the perception of thermal comfort in Bogotá is expected to be unlike other cities in the same category.



VARIABLE	1. BOGOTA	2. MEDELLIN	3. CALI	4. BARRANQUILLA
Population (Million)	**8.1**	**2.5**	**2.4**	**1.2**
Climate (Köppen)	**Cfb**	**Am**	**As**	**Aw**
Altitude (metres above sea level)	1800	800 - 1800	800 - 180	< 800
Location	inland	inland	inland	costal
Temperature (°C)	< 18	18-24	18-24	> 24
Relative humidity (%)	70-75	70-75	70-75	> 75
Wind speed (m/s)	< 2.5	< 2.5	< 2.5	> 3.5
Solar radiation (KWh/m²)	< 4	4 - 5.5	4 - 5.5	> 5.5
Rain (mm)	1500-3000	> 3000	< 1500	< 1500

Figure 6. (A) Location and climatic characteristic of the main cities in Colombia. (B-D) Examples of different climatic classifications. Figure by the authors with data from IDEAM (Colombian Institute of Hydrology, Meteorology and Environmental Studies).

Despite this great diversity, there are studies that show that for most climates in Colombia, thermal comfort can be achieved with passive strategies and without the need for mechanical conditioning systems [35,36]. There is compelling evidence that the increase of air movement through natural ventilation is essential to improve indoor thermal comfort and the best way to achieve this is through appropriate design strategies and mandatory regulations in each region. This means that standards must be more specific, precise and measurable. Unfortunately, this is not the case in the context of the current legislation in Colombia, where policies regarding constructions are still very ambiguous, contradictory or lack common objectives. None of the existing policies define acceptable comfort ranges according to the different climates, nor do they include clear or mandatory requirements for new buildings, nor recommendations for the adaptation of existing buildings. Therefore, it is very difficult to measure whether a project meets minimum comfort requirements or not, especially at the design stage. Furthermore, Colombia is the country with the lowest percentage of GDP destined for research, science, and technology in Latin America. According to data from the Colombian Observatory of Science and Technology, in 2014 Colombia only invested US $14.97 per inhabitant per year in research and development. The average in Latin America was US $74.93, the global average was US $194.47, whilst in the countries that are members of the Organization for Economic Cooperation and Development it was US $933.91 (Gómez-Mejía, 2015). As a result, research production in the country is very low, especially in disciplines such as architecture and the built environment.

3. Fieldwork

This manuscript describes four projects by the authors that involved fieldwork, carried out between 2015 and 2018. Two of them were in apartment buildings and two in school buildings all located in Bogotá

(Table 1). The projects differed from each other in terms of building features, use and occupancy characteristics. Quantitative and qualitative information was collected for all of these projects using varied methods, tools, and procedures. The static and adaptive models, from the ANSI/ASHRAE standard 55 [37], were both used to analyse the collected data, plus an alternative theory of environmental satisfaction.

Table 1. General information from the fieldwork projects.

		APARTMENT BUILDINGS		SCHOOL BUILDINGS	
		PROJECT ONE	**PROJECT TWO**	**PROJECT THREE**	**PROJECT FOUR**
ST	**Year of study**	2015-2016	2017	2018	2018
	Studied sample (units)	44	28	12	8
	Studied occupants	44	28	166	168
BUILDING	**Year of construction**	2014	1987	1940s	1960s
	Nº storeys	6	7	4	1
	Ceiling height (m)	2.3	2.3	3.7	3
	Total Nº of units (apartments or classrooms)	456	227	37	29
	Total occupants (approx.)	1368	681	1172	669
	Occupants per unit (avg.)	3	3	32	51
	Average unit size (m^2)	70	63	62.5	72
	Building type	Block	Courtyard	Courtyard	Block
CONSTRUCTI	**Wall construction**	Concrete wall structure with a single-leaf brick wall facade, with no thermal insulation	Concrete and masonry wall structure with a single-leaf brick wall facade, with no thermal insulation	Concrete and masonry wall structure with a single-leaf brick wall facade with a stone finish or a double-leaf brick wall facade, both without thermal insulation	Concrete and masonry wall structure with a single-leaf brick wall facade, with no thermal insulation
	Wall thickness (m)	0.13	0.25	0.35-0.5	0.25
	Windows	single-glassed aluminium-frame, featuring fixed top grills for ventilation. 4mm glass.	single-glassed aluminium-frame. 4-6mm glass.	single-glassed iron-frame, operable windows. 4mm glass.	single-glassed aluminium-frame, featuring top small operable panes for ventilation. 5mm glass.

3.1. Project one

This was a new housing complex representative of the majority of social housing projects built in Bogotá in the past decade. It featured 456 apartments in 19 six-storey towers with 4 apartments per level. A sample of 44 apartments distributed on different floors and towers was evaluated during fieldwork. The apartments were classified into 4 groups according to their orientation and position within the building. Information was collected from the building and the occupants between November 2015 and April 2016.

3.2. Project two

This consisted of a housing complex built in 1987 and representative of multifamily projects built in Bogotá at the end of the 20th Century. It featured 227 apartments in 5-7 storey courtyard configurations. A sample of 28 apartments was selected for the study carried out during May 2017.

3.3. Project three.

This was a four-storey school building erected during the early 1940s comprising 37 classrooms, laboratories, offices and special classrooms for art and music classes. The rooms were 62.5m^2 on average with 3.7m high ceilings and placed around two courtyards in a traditional cloister style. The school has a mixed population mainly from middle-income families and with an average occupancy of 32 students per classroom. The teaching format was fairly traditional for the context of Colombia, with students staying in the same room for most of their classes.

3.4. Project four
This was a building mainly constructed during the 1960s with 13 single-storey classrooms. The rooms were 72m^2 on average with 3m high ceilings and placed in a U-shaped block along internal corridors, leaving one paved courtyard in the middle. This was an only-boys school with a population mainly from middle and upper-income families and with an average occupancy of 25 students per classroom. The students had activities in different classrooms with an active teaching and learning format.

4. Results
4.1. Observation phase
The aim of this phase was to test the existing methods and models proposed by ASHRAE Standard 55 for fieldwork in the context of Colombia. The analysis with the static method focused on establishing comfort ranges according to PMV psychometric charts and identifying potential levels of dissatisfaction according to PPD calculations. In project one, this analysis showed that all the studied apartments were outside the recommended comfort ranges. Indoor temperature values went down to 17ºC and 18ºC, which combined with an average 70% of relative humidity resulted in generalised uncomfortable conditions. Additionally, there were considerable indoor temperature fluctuations throughout the day, which related directly to outdoor fluctuations of up to 11ºC, suggesting poor building envelope performance. Overall comfort conditions were the worst for north-facing apartments and for apartments located on top and ground floors. Percentages of occupant dissatisfaction were high at 60%, compared to the recommended maximum of 10-20%. The analysis with the adaptive method confirmed that all the apartments were outside the recommended comfort ranges, even though with this method the ranges were wider. Occupant´s satisfaction was calculated using surveys and rating tables, which were designed for this study based on past research by de Dear and Brager [38], by Langevin, Gurian, and Wen [39] and the Center for the Built Environment [40]. Interval scale questions were used to assess the sensation and thermal perception, whilst multiple choice questions were used to inquire other aspects such as the activities performed, clothes used, air quality and artificial light consumption, among other things. The results revealed worrying levels of dissatisfaction with thermal comfort of up to 80%.

In terms of the method used for the analysis, important overlaps between the comfort levels predicted by the models and the actual data found during fieldwork were noticed. Additionally, diverse results were produced using the same quantitative and qualitative data but different analysis methods (Figure 7). It was found that the adaptive method was slightly more accurate in describing theoretical comfort ranges for the case study, compared to the static method. The levels of dissatisfaction were higher within the surveys compared to the PPD calculations. However, it was observed that the adaptive method on its own was insufficient to fully understand the problem in its context.

The Theory on Environmental Satisfaction suggested by Shin [41], was used here to complement the interpretation of the occupant's responses and to help induce more comprehensive conclusions. This theory suggests that individuals go through four different steps in an effort to mitigate thermal discomfort: 1. environmental modifications to the existing physical elements of the space; 2. behavioural adaptations; 3. adjustments to personal expectations or norms and 4. withdrawal from the space. Evidence of these modes of adaptive behaviour was found in the surveys carried out for the case study. The outcomes indicated that most of the occupants believed that their thermal discomfort originated from elements comprising the apartment's facades, such as wall materials and windows. A significant percentage of occupants expressed their aspiration to install central heating systems, however, the lack of economic resources was a limitation (Figure 8).

The results from this analysis suggest that a facade retrofit could solve the problem passively, avoiding the use of central heating. Various design solutions were initially studied via computer models and dynamic thermal simulations with Energyplus software. In a second stage of the project, two solutions were chosen to be built focusing on increasing thermal mass and improving air-tightness on the inner part of the facades walls and windows. A comparative method was used for the evaluation, where two apartments with similar conditions (apartment A and apartment B) were selected. Apartment A was left alone, whilst apartment B was altered with two interventions. Both apartments were studied over a three-week period in November 2016. Results showed an average temperature increase of 2ºC with these interventions.

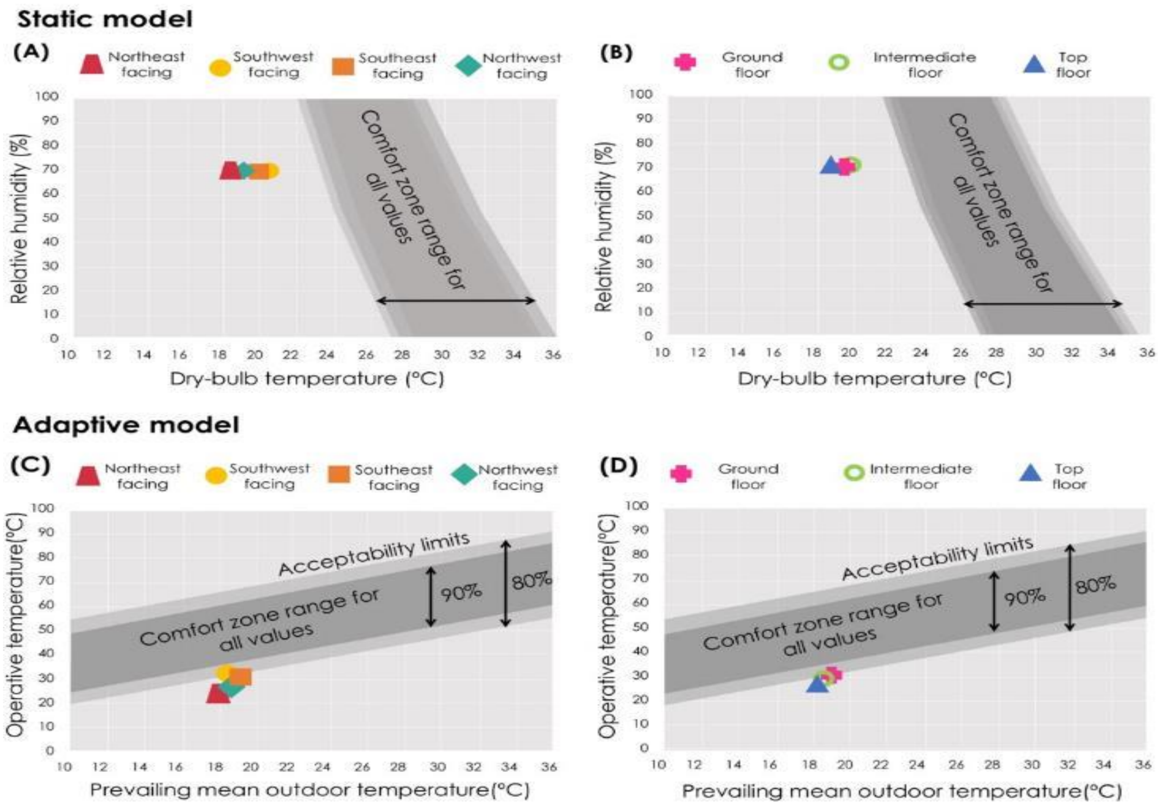


Figure 7. Examples of conflictive results with the static and the adaptive models. Temperature - relative humidity charts based on the CBE tool for the static model (PMV) and adaptive model.

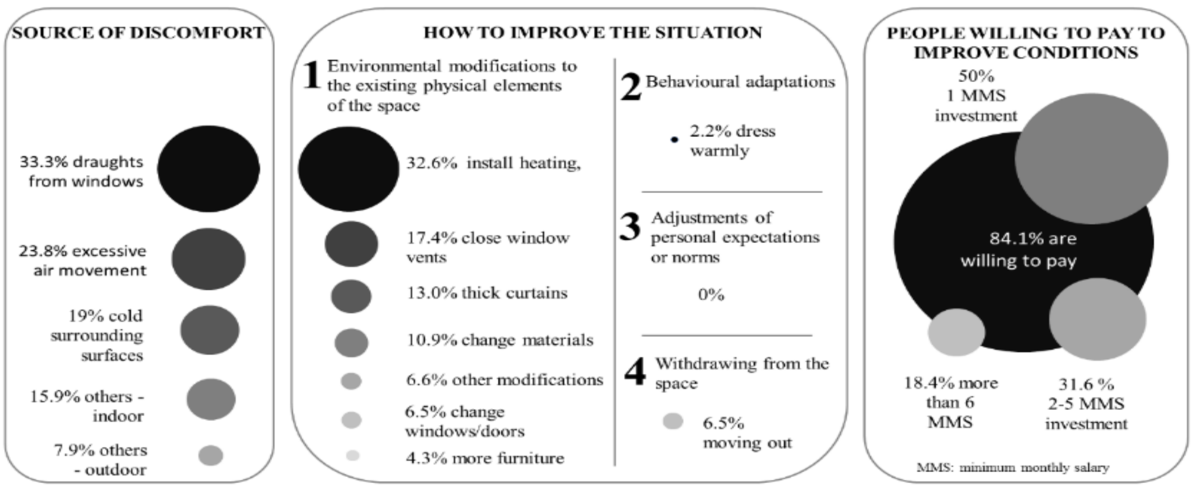


Figure 8. Interpretation of the occupant's responses using the Theory on Environmental Satisfaction by Shin [41]

4.2. Adaptation phase

The typical procedures to acquire data were found to be particularly linear, fragmented and exclusive. The usual sequence comprises the preparation and gathering of data on-site followed by its analysis off-site and subsequent academic publication of the results. Occupants are generally involved only during the survey stage, but the outcomes of the studies are rarely presented to them afterward. It is argued that more cyclical and inclusive procedures that involve the occupants at different stages of the project can greatly improve data collection. For example, it was found that according to the age and social background of the occupants, preparatory activities need to be carried out previous to the application of the surveys, such as informal talks, distribution of literature or staff training. Occupants tend to be more motivated and provide more reliable feedback when they feel rewarded for their efforts, in certain cases with material prizes or with knowledge. Therefore, involving occupants during the analysis and discussion of results proved to be very valuable to improve and refine the outcomes of the studies.

The written surveys recommended by the ASHRAE Standard 55 were initially adapted and used to collect qualitative data from the occupants of project one. However, in practice, the surveys were found to be inadequate for the demographics studied, as they tended to be very long (between 45-60 minutes to complete) and repetitive, which frustrated some of the occupants. In the case of the school buildings, the question´s language, interface, and complexity of the recommended surveys were found to be completely unsuitable for children. Therefore, new surveys were designed and implemented. Additional data-collection tools were also tested in these projects, for example, thermographic photographs, observation logbooks, interviews with focus groups, phone surveys, building management databases, and dynamic thermal simulations. All of these tools allowed the collection of valuable information that contributed to a more holistic understanding of thermal comfort in these buildings. The thermographic photograph and building management databases were particularly useful to detect elements of the building design that were problematic. Likewise, the interviews with focus groups and the observation logbooks demonstrated to be powerful instruments to identify preconceptions, preferences, and adaptational behaviour by the occupants.

5. Conclusions
Data from post-occupancy studies in real constructions have been instrumental in the development of the existing thermal comfort standards. However, the limitations mentioned in this manuscript are considered to be a major flaw in the current pursuit to create universal standards, as they restrict the ability to compare and cross-reference data on a great number of variables. The experiences described in this manuscript show that both the static and the adaptive methods can be used, to a certain extent, to evaluate thermal comfort in Colombia, being the adaptive method more accurate to describe comfort ranges in the particular context of the case studies. However, additional tools and methods are needed in order to fully comprehend occupant´s behaviour and potential solutions in the context of this country. This study advocates for the urgent need of research targeting the following objectives: 1. To develop a method of evaluation and study of thermal comfort in buildings suitable for the Colombian context. 2. To apply and test this method through fieldwork. 3. To make strategic alliances with the construction sector and control entities. 4. To disseminate the research results.

Fieldwork and post-occupancy studies are normally costly, time-consuming and require considerable administrative and academic efforts. Therefore, it is crucial to systematise current practices and joint forces with the aim of better-using research results to improve the means of evaluation and the development of policy. Fieldwork in the context of Colombia illustrates how generalisations and literal applications of the current framework can lead to erroneous assumptions of thermal discomfort, the over-cooling or over-heating of buildings or the implementation of mechanical conditioning where passive solutions are more appropriate. This is an important aspect to address not only from a technical but also from an ethical perspective, as the tropics become more populated and urbanised and energy demands for indoor thermal comfort continue to grow.

Acknowledgment(s)
This work is independent research with the support of two academic institutions. It did not receive any specific grant from funding agencies or commercial bodies. The authors would like to acknowledge the assistance from numerous colleagues in the development of this work. Special thanks to all the people who participated in the case studies.

References
[1] Yang L, Yan H, Lam JC. Thermal comfort and building energy consumption implications - A review. Appl Energy 2014;115:164–73. doi:10.1016/j.apenergy.2013.10.062.
[2] Yau YH, Hasbi S. A review of climate change impacts on commercial buildings and their technical services in the tropics. Renew Sustain Energy Rev 2013;18:430–41. doi:10.1016/j.rser.2012.10.035.

[3] Zhao HX, Magoulès F. A review on the prediction of building energy consumption. Renew Sustain Energy Rev 2012;16:3586–92. doi:10.1016/j.rser.2012.02.049.
[4] Pérez-Lombard L, Ortiz J, Pout C. A review on buildings energy consumption information. Energy Build 2008;40:394–8. doi:10.1016/j.enbuild.2007.03.007.
[5] JRAIA JR and ACIA. World air conditioner demand by region. 2017.
[6] Samson J, Berteaux D, Mcgill BJ, Humphries MM. Geographic disparities and moral hazards in the predicted impacts of climate change on human populations. Glob Ecol Biogeogr 2011;20:532–44. doi:10.1111/j.1466-8238.2010.00632.x.
[7] Ross C, Menezes JR De, Inez T, Svidzinski E. Studies on Fungal and Bacterial Population of Air- conditioned Environments. Brazilian Arch Biol Technol 2004;47:827–35. doi:10.1590/S1516-89132004000500020.
[8] Kishi R, Ketema RM, Ait Bamai Y, Araki A, Kawai T, Tsuboi T, et al. Indoor environmental pollutants and their association with sick house syndrome among adults and children in elementary school. Build Environ 2018;136:293–301. doi:10.1016/j.buildenv.2018.03.056.
[9] Lu Y, Lin S, Lawrence WR, Lin Z, Gurzau E, Csobod E, et al. Evidence from SINPHONIE project: Impact of home environmental exposures on respiratory health among school-age children in Romania. Sci Total Environ 2018;621:75–84. doi:10.1016/j.scitotenv.2017.11.157.
[10] Ismail MR, Barber JM. A Field Study to Determine Inside Design Conditions for Malaysian Air Conditioning Systems. Archit Sci Rev 2001;44:83–99. doi:10.1080/00038628.2001.9697456.
[11] Oves M, Khan MZ, Ismail IMI. Modern age environmental problems and their remediation. 2017. doi:10.1007/978-3-319-64501-8.
[12] Indraganti M. Thermal comfort in apartments in India: Adaptive use of environmental controls and hindrances. Renew Energy 2011;36:1182–9. doi:10.1016/j.renene.2010.10.002.
[13] Edelman A, Gelding A, Konovalov, Elena McComiskie R, Penny A, Roberts N, Templeman S, et al. State of the Tropics: 2014 Report 2014:1–30.
[14] Olesen BW. International standards for the indoor environment. Indoor Air, Suppl 2004;14:18–26. doi:10.1111/j.1600-0668.2004.00268.x.
[15] Roaf S, Nicol F, Humphreys M, Tuohy P, Boerstra A. Twentieth century standards for thermal comfort: Promoting high energy buildings. Archit Sci Rev 2010;53:65–77. doi:10.3763/asre.2009.0111.
[16] Fanger PO. Thermal Comfort. Copenhagen: Danish Technical Press; 1970.
[17] de Dear R, Brager G, Cooper D. Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 1998;104:1–18.
[18] de Dear R, Brager G, Cooper D. Developing an adaptive model of thermal comfort and preference. 1997.
[19] Földváry Ličina V, Cheung T, Zhang H, de Dear R, Parkinson T, Arens E, et al. Development of the ASHRAE Global Thermal Comfort Database II. Build Environ 2018;142:502–12. doi:10.1016/j.buildenv.2018.06.022.
[20] Merkel A. Climate-Data.org. Online 2012.
[21] Al horr Y, Arif M, Katafygiotou M, Mazroei A, Kaushik A, Elsarrag E. Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. Int J Sustain Built Environ 2016;5:1–11. doi:10.1016/j.ijsbe.2016.03.006.
[22] Djamila H. Indoor thermal comfort predictions: Selected issues and trends. Renew Sustain Energy Rev 2017;74:569–80. doi:10.1016/j.rser.2017.02.076.
[23] Ortiz MA, Kurvers SR, Bluyssen PM. A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort. Energy Build 2017;152:323–35. doi:10.1016/j.enbuild.2017.07.060.
[24] Cheng Y, Niu J, Gao N. Thermal comfort models: A review and numerical investigation. Build Environ 2012;47:13–22. doi:10.1016/j.buildenv.2011.05.011.
[25] Mishra AK, Loomans MGLC, Hensen JLM. Thermal comfort of heterogeneous and dynamic indoor conditions — An overview. Build Environ 2016;109:82–100. doi:10.1016/j.buildenv.2016.09.016.

[26] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. Build Environ 2011;46:922–37. doi:10.1016/j.buildenv.2010.10.021.
[27] Djongyang N, Tchinda R, Njomo D. Thermal comfort: A review paper. Renew Sustain Energy Rev 2010;14:2626–40. doi:10.1016/j.rser.2010.07.040.
[28] Mishra AK, Ramgopal M. Field studies on human thermal comfort - An overview. Build Environ 2013;64:94–106. doi:10.1016/j.buildenv.2013.02.015.
[29] Roetzel A, Tsangrassoulis A, Dietrich U, Busching S. A review of occupant control on natural ventilation. Renew Sustain Energy Rev 2010;14:1001–13. doi:10.1016/j.rser.2009.11.005.
[30] UPME. Boletín Estadístico: Minas y energía 2012 – 2016 2016:200.
[31] UPME. ELÉCTRICA Y POTENCIA MÁXIMA EN COLOMBIA Revisión Junio de 2016. Sielgov 2016:55.
[32] Rodriguez CM, D'alessandro M. Climate and Context Adaptive Building Skins for Tropical Climates: a review centred on the context of Colombia. Conf. Adv. Build. Ski. Bressanone, Italy, 2014.
[33] Bernardi L. Effects of high altitude. Prim. Auton. Nerv. Syst., 2012, p. 281–2. doi:https://doi.org/10.1016/B978-0-12-386525-0.00058-5.
[34] Wang H, Hu S, Liu G, Li A. Experimental study of human thermal sensation under hypobaric conditions in winter clothes. Energy Build 2010. doi:10.1016/j.enbuild.2010.06.013.
[35] Hernandez A. Applicability of the Passivhaus Standard for social housing in urban tropical climates (Colombia). University of Bath, 2012.
[36] Gonçalves J, Fernández J. The Environmental Design of Working Spaces in Equatorial Highlands Zones: The Case of Bogotá. Buildings 2015;5:1105–30. doi:10.3390/buildings5041105.
[37] ANSI/ASHRAE. ANSI/ASHRAE 55:2013 thermal environmental conditions for human occupancy. 2013. doi:10.1007/s11926-011-0203-9.
[38] de Dear, Richard Gail Brager S. The adaptive model of thermal comfort and energy conservation in the built environment. Int J Biometeorol 2001;45:100–8.
[39] Langevin J, Gurian PL, Wen J. Tracking the human-building interaction: A longitudinal field study of occupant behavior in air-conditioned offices. J Environ Psychol 2015;42:94–115. doi:10.1016/j.jenvp.2015.01.007.
[40] CBE. Occupant Indoor Environmental Quality (IEQ) Survey and Building Benchmarking. Centre for the Built Environment. Cent Built Environ 2016.
[41] Shin J hye. Toward a theory of environmental satisfaction and human comfort: A process-oriented and contextually sensitive theoretical framework. J Environ Psychol 2016;45:11–21. doi:10.1016/j.jenvp.2015.11.004.
[42] Becqué R, Mackres E, Layke J, Aden N, Liu S, Managan K, et al. Cómo acelerar la eficiencia en la edificación. 2016.