Green Energy and Technology

Laura Marín-Restrepo
Alexis Pérez-Fargallo
María Beatriz Piderit-Moreno
Maureen Trebilcock-Kelly
Paulina Wegertseder-Martínez *Editors*

Removing Barriers to Environmental Comfort in the Global South

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Editors

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Editors
Laura Marín-Restrepo
Architecture et Climat, Louvain research institute for Landscape, Architecture, Built environment (LAB)
Université catholique de Louvain
Louvain-la-Neuve, Belgium

Alexis Pérez-Fargallo
Department of Building Science
Faculty of Architecture
Construction and Design
Universidad del Bío-Bío
Concepción, Chile

María Beatriz Piderit-Moreno
Department Design and Theory
of Architecture
Faculty of Architecture
Construction, and Design
Universidad del Bío-Bío
Concepción, Chile

Maureen Trebilcock-Kelly
Department Design and Theory
of Architecture
Faculty of Architecture
Construction, and Design
Universidad del Bío-Bío
Concepción, Chile

Paulina Wegertseder-Martínez
Department Design and Theory
of Architecture
Faculty of Architecture
Construction, and Design
Universidad del Bío-Bío
Concepción, Chile

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To Mercedes, Hernán, Cristian, Bernando,
and Sebastian

Foreword

What a pleasure it is today, to write the foreword for a book like this, given the immensity of the questions we are all facing.

This book talks about environmental comfort and focuses, in particular, on vulnerable populations. It gives the floor to different experts from the Global South, with the validated results of their research, providing its structure.

Today, to discuss environmental comfort, in the broadest sense, is to consider all the contexts in which a project is developed: climatic, hydric, vegetation, societal, economic, technological, etc. More specifically, both inside buildings and in outdoor public spaces, it is to study and interconnect several objective-measurable physiological phenomena (air temperature, air movement and speed, relative humidity, the activity of the individual and their clothing, air quality, daylighting and sound) and a series of subjective psycho-sensory phenomena (the atmosphere of a garden, the presence of water, the architectural quality, the acoustic protection from external noises, the colors of the environment, the smell of the vegetation, the cleanliness, and the company of the people…).

On the other hand, this work of reference is imperiously engrained within the sustainable development framework, placing humankind at the heart of this concern.

By definition, sustainable architecture is ethically engraved in its environments (contexts), it benefits from their advantages, it protects itself from their disadvantages, it helps them benefit from what it generates, and, ultimately, it protects them from its own troubles.

Thus, new architecture can be born: the location is judiciously chosen, the planning is perfectly defined (mixed functions, mixed populations, and public meeting spaces), the energy design is optimal (summer-winter), the water issue is considered in its entirety (economy, rainwater, natural water cycle), the materials are chosen, respecting the environment and health, the design is thought out, taking into account the waste from the construction site and the end of the building's life.

Thus, this book is a guide for the entire construction sector and helps to respond to ever more pressing issues such as climate change, energy needs, and the comfort needs of occupants.

I would like to thank all the authors for the quality of this book.

October 2022

André De Herde
Professor Emeritus
Université catholique de Louvain
Director Emeritus
Architecture and Climate
Research Group
Louvain-la-Neuve, Belgium

Preface

The concept of environmental comfort is complex. It can be observed from different areas and is dynamic, evolving throughout history as it addresses social, technological, economic, and cultural evolution. Cultural, social, and economic factors, among others, are fundamental to understanding comfort holistically.

In recent years, environmental comfort has made relevant advances through research and the development of standards and policies at the international level. However, in the specific case of the Global South, where the countries with the highest levels of income inequality are concentrated, environmental comfort has its own characteristics and challenges that prevent a clear understanding from the established vision of the Global North.

As researchers linked to environmental comfort, we have found that in the Global South, there are regional barriers that entail approaching environmental comfort from other prisms, with angles tied to social, economic, and cultural realities and even industrial, technological, and constructive development.

However, as researchers in the Global South, we often tend to look at the Global North and believe that there are not many references outside the north, even though the diversity of aspects we have in common –climatic, geographical, social, etc.– confront us with common challenges.

It is precisely from this line that the idea of this book arises, at a latitude of 36°49’41”S and longitude of 73°3’5”W, where the group of editors of this book forms the “Environmental Comfort and Energy Poverty” research group and actively participates in the teaching of the Masters in Sustainable Habitat and Energy Efficiency and the Doctorate in Architecture at the University of Bío-Bío, with students and graduates from a variety of Latin American and Caribbean countries.

After several generations of graduates, we have found that the progress made is often undervalued or even worse, unknown by peers and/or actors of the built environment in our own countries. This is even though, in recent decades, efforts have been made by countries, political leaders, and researchers in the southern hemisphere to begin addressing these issues from our reality.

This is why we find it pertinent to collect part of this progress and make it available to a diverse public, not necessarily experts but those interested in finding ways to improve the quality of people's lives without harming the environment. Therefore, the goal of this book is twofold. First, it seeks to broadly contribute to the development of the concept of environmental comfort, to visualize how from the Global South, progress has been made in understanding the concept from a culturally rooted vision.

Secondly, the book seeks to reach engineers, architects, and researchers from developing countries interested in environmental comfort and its influence on energy consumption, energy poverty, and other related factors, as well as decision-makers and public policy developers associated with the indoor comfort of buildings, making the knowledge generated and applied to this side of the world available.

How to Approach This Book

Our approach in this book has been an attempt to address the main barriers to environmental comfort in the Global South, collecting concepts, theories, arguments, strategies, and tools in a way that leaves them open for discussion, criticism, and understanding.

Environmental comfort is a broad concept still in development, and of which we do not fully know the barriers and how to overcome them. Hence, the concepts and ideas presented in this book are not the definitive answer but rather a first step to recognizing other realities that have their own characteristics and that, therefore, require new reflections. Where possible, we have tried to include the main barriers that are important to address to improve environmental comfort in buildings in the Global South as well as references to many original sources and key thinkers. A careful reading of these ideas may take some time, and we invite you to look at the sources we cite to reflect yet further. We also hope you will identify common aspects and references in countries with similar realities.

Finally, we would like to encourage you to think critically about the barriers, concepts, and ideas presented in this book to reach your own vision using your own social and cultural reality. As we have already indicated, this book is not a definitive text where solutions to all existing problems on environmental comfort are proposed, but rather it should be read as part of the evolutionary process of comfort in buildings in the Global South.

Concepción, Chile
October 2022

Laura Marín-Restrepo
Alexis Pérez-Fargallo
María Beatriz Piderit-Moreno
Maureen Trebilcock-Kelly
Paulina Wegertseder-Martínez

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We would like to thank the Vice-Rector for Research and Postgraduate Studies of Universidad del Bío-Bío, for financing the “Confort Ambiental y Pobreza Energética” (Environmental Comfort and Energy Poverty) research group (GC/C 19450), which was behind the development of this book, and the Ibero-American Program on Science and Technology for Development (CYTED), for financing the “Ibero-American Network of Energy Poverty, and Environmental Well-being” (RIPEBA Thematic Network 722RT0135), through which we have intensified cooperation with other researchers and centers in the Global South.

Laura Marín-Restrepo, while assembling and writing this book, left the Global South, and has been working as a postdoctoral researcher since October 2021 in the Architecture et Climat group, Louvain research institute for Landscape, Architecture, Built environment (LAB) at the Université Catholique de Louvain. Her research is Funded by the Belgian National Fund for Scientific Research (F.R.S.–FNRS).

We also feel it is necessary to thank all the organizations, institutions, centers, and postgraduate training programs that support research on a daily basis, by financing projects, providing technical support, and with advanced human capital training to improve the environmental comfort of buildings in the Global South. In this vein, special thanks go to the graduates of the Masters in Sustainable Habitat and Energy Efficiency and the Ph.D. program in Architecture and Urbanism at Universidad del Bio-Bío, for their contributions from different countries throughout Latin America and the Caribbean.

Finally, this book has only been possible thanks to the extraordinary efforts of the authors, who have shown, from their different countries and continents, an exceptional commitment to improving the comfort of buildings from science, contributing to “Removing Barriers to Environmental Comfort in the Global South.” We are extremely grateful to everyone, and we hope this book meets their expectations.

Special thanks are given to Kevin Wright and Paz Sepúlveda for their support in reviewing the English version of the book and the edition of its texts; to Francisca Jiménez Reyes, for her help revising the format and bibliography; and to Sebastian Giraldi, for his valuable and generous collaboration in formatting and editing the manuscript.

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Contributors

Hanan Al-Khatri Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, Muscat, Sultanate of Oman

Jose Ali Porras-Salazar School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica

Laura Andrade Sepúlveda EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Lucas Arango-Díaz Facultad de Artes Integradas, Universidad de San Buenaventura, Medellín, Colombia

John Arango-Flórez EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Bruno Damián Arballo FAUD, Universidad Nacional de San Juan. CONICET, San Juan, Argentina

Gabriela Magali Arrieta National Council for Scientific and Technical Research (CONICET), Buenos Aires, Argentina

Shady Attia Sustainable Building Design Lab, Department UEE, Faculty of Applied Sciences, Université de Liège, Liège, Belgium

Ariel Bobadilla-Moreno Center for Research in Construction Technologies (CITEC), University of Bío-Bío, Concepción, Chile

Daniela Borja Zuluaga Faculty of Architecture and Engineering, Institución Universitaria Colegio Mayor de Antioquia, Medellín, Colombia

Ivan Julio Apolonio Callejas Federal University of Mato Grosso, Cuiabá, Brazil

Carolina Cano Arroyave EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Elizabeth Castro Burbano EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Francisco Castro Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Daniel Chuk Instituto de Investigaciones Mineras, FI, Universidad Nacional de San Juan, San Juan, Argentina

Silvia de Schiller Research Centre Habitat and Energy, Faculty of Architecture, Design and Urbanism, University of Buenos Aires, Buenos Aires, Argentina

Muriel Diaz Department of Architectural Design and Theory, Faculty of Architecture, Construction and Design, Universidad del Bío-Bío, Concepción, Chile;
Sustainable Building Design Lab, Department UEE, Faculty of Applied Sciences, Université de Liège, Liège, Belgium

Renata Diniz Department of Civil Construction, Postgraduate Program in Civil Engineering, Universidade Tecnológica Federal do Paraná (PPGEC/UTFPR), Curitiba, Brazil

Luciane Cleonice Durante Federal University of Mato Grosso, Cuiabá, Brazil

Evyatar Erell Department of Man in the Desert, Ben-Gurion University of the Negev, Beersheba, Israel

John Martin Evans Research Centre Habitat and Energy, Faculty of Architecture, Design and Urbanism, University of Buenos Aires, Buenos Aires, Argentina

Leandro Fernandes Department of Graphical Expression, Universidade Federal do Paraná, Curitiba, Brazil

Jan-Frederik Flor Faculty of Architecture and Ekistics, Universiti Malaysia Kelantan, Bachok, Malaysia

Raphaela Walger da Fonseca Department of Architecture and Urbanism/CTC, Federal University of Santa Catarina, Florianopolis, Brazil

Suelem Schier de França Department of Architecture and Urbanism/CTC, Federal University of Santa Catarina, Florianopolis, Brazil

Ana Galarza Department of Architecture, Universidad de Piura, Piura, Peru

Ader García-Cardona EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia;
Integrated Arts Faculty, Universidad de San Buenaventura, Bello, Colombia

María José García Vallejo Integrated Arts Faculty, Universidad de San Buenaventura, Medellín, Colombia

Muhammad Luthfi Ghassan Architecture Consultant, Banda Aceh, Indonesia

Alex Gonzalez-Caceres Department of Architecture and Civil Engineering, Chalmers University of Technology, Göteborg, Sweden

Mahendra Gooroochurn Mechanical and Production Engineering Department, Faculty of Engineering, Universityof Mauritius, Reduit, Moka, Mauritius

Emeli Lalesca Aparecida da Guarda Federal University of Mato Grosso, Cuiabá, Brazil

Oscar Guillen Civil Engineering Program, Universidad de Piura, Piura, Peru

Giancarlo Gutiérrez Acoustics Consultant, Medellín, Colombia

Juan G. Gutiérrez Universidad de San Buenaventura, Cali, Colombia

Yury Hernández-Duque Integrated Arts Faculty, Universidad de San Buenaventura, Medellín, Colombia

Elisabeth Herreño-Téllez Integrated Arts Faculty, Universidad de San Buenaventura, Medellín, Colombia

Constanza Ipinza School of Architecture, University of Santiago de Chile, Santiago, Chile;
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Luisa María Jaimes Nova EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Benjamin Jones Department of Architecture and Built Environment, University of Nottingham, Nottingham, UK

Ethieny Rossato Kramer Department of Architecture and Urbanism/CTC, Federal University of Santa Catarina, Florianopolis, Brazil

Eduardo Krüger Department of Civil Construction, Postgraduate Program in Civil Engineering, Universidade Tecnológica Federal do Paraná (PPGEC/UTFPR), Curitiba, Brazil

Ernesto Kuchen FAUD, Universidad Nacional de San Juan. CONICET, San Juan, Argentina

Arturo Raúl Maristany Center for Acoustic and Lighting Research (CIAL), Universidad Nacional de Córdoba, Faculty of Architecture, Urbanism and Design, Córdoba, Argentina

Laura Marín-Restrepo Architecture et Climat, Louvain Research Institute for Landscape, Architecture, Built Environment, Université catholique de Louvain, Louvain-la-Neuve, Belgium

Constanza Molina School of Civil Construction, Pontificia Universidad Católica de Chile, Santiago, Chile

Estefanía Montes-Villalva Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Olga Lucia Montoya Universidad de San Buenaventura, Cali, Colombia

Giobertti Morantes Department of Architecture and Built Environment, University of Nottingham, Nottingham, UK

Abdul Munir Architecture Department, Universitas Syiah Kuala, Banda Aceh, Indonesia

Jorge Muñoz-Fierro Center for Research in Construction Technologies (CITEC), University of Bío-Bío, Concepción, Chile

Moises Obando Robles School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica

David Orozco Gallo EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Cristina Ospina Montoya EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

Cecilia Palarino-Vico Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Lucia Pereira-Ruchansky Institute of Technologies, Faculty of Architecture, Design and Urbanism, University of the Republic, Montevideo, Uruguay

Fernando Oscar Ruttkay Pereira Department of Architecture and Urbanism/CTC, Federal University of Santa Catarina, Florianopolis, Brazil

María Beatriz Piderit-Moreno Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Jose Ali Porras-Salazar School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica

Jesús Pulido-Arcas Center for Research and Development of Higher Education, The University of Tokyo, Tokyo, Japan

Alexis Pérez-Fargallo Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Raúl Ramírez-Vielma Department of Psychology, Universidad de Concepción, Concepción, Chile

Laura Rendón Gaviria Faculty of Architecture and Engineering, Institución Universitaria Colegio Mayor de Antioquia, Medellín, Colombia

David Resano Department of Architecture, Universidad de Piura, Piura Campus, Peru

Rodolfo Rodríguez Department of Basic Sciences, Universidad de Piura, Piura, Peru

Natalia Saavedra Universidad de San Buenaventura, Cali, Colombia

Jorge Hernán Salazar Trujillo EMAT Research Group, School of Architecture, Universidad Nacional de Colombia, Medellín, Colombia

Laina Hilma Sari Architecture Department, Universitas Syiah Kuala, Banda Aceh, Indonesia

Jaime Soto-Muñoz Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Maureen Trebilcock-Kelly Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Álvaro Vargas Olmos EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia

María Isabel Vivanco-Villavicencio Universidad Técnica Particular de Loja, Loja, Ecuador

Paulina Wegertseder-Martínez Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile

Manuela Yepes Ocampo Faculty of Architecture and Engineering, Institución Universitaria Colegio Mayor de Antioquia, Medellín, Colombia

What Are the Barriers to Environmental Comfort in the Global South?

Alexis Pérez-Fargallo and Laura Marín-Restrepo

Abstract Environmental comfort in buildings is a dynamic concept involving architectural, physical, environmental, as well as sociocultural, economic, geographic, and other variables. Today, the Brandt Line is still valid for establishing geographical differences in developments for sustainability, energy efficiency, renewable energy use, climate, altitude, emissions, and access to energy, and for identifying the barriers to environmental comfort. The current gaps in most Global South cases start from historical inequalities, along with geographical, topographical, cultural, and climatic singularities. There have been many and very varied barriers found. However, it is possible to highlight the ones the authors consider are the most important. The concepts related to environmental comfort and sustainable development goals and objectives have mainly been developed in the Global North, meaning for the Global South their definitions require not just conceptual adjustments but also new means of assessment and measurement. As a starting point, the actions and measures being implemented must include local efforts and advances, their available resources and capacities, and, in particular, each country's technological, economic, and social context. The chapters included in this book contribute in this sense.

Keywords Environmental comfort · Developing countries · Building sector · Architecture · SDG

A. Pérez-Fargallo
Department of Construction Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: aperezf@ubiobio.cl

L. Marín-Restrepo (✉)
Architecture et Climat, Louvain Research Institute for Landscape, Architecture, Built Environment, Université catholique de Louvain, Louvain-la-Neuve, Belgium
e-mail: laura.marinrestrepo@uclouvain.be

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1 Introduction

Environmental comfort is relatively novel as an area of study. Its beginnings are linked to the Modern Movement and the introduction of air-conditioning systems within architecture. In 1902, when Willis Carrier invented air-conditioning in New York, looking to keep constant humidity, companies became interested in this invention to reduce problems of high humidity rates in their industrial processes. However, they were not initially interested in making temperatures more tolerable for their workers [1]. However, in 1906, Carrier began to exploit the potential of his invention for spaces with high occupation and little or no ventilation, such as theaters, even though it was not until 1920 that the general public experienced air-conditioning for the first time. From that moment, air-conditioning became an industry, and the first scientific research on thermal comfort was made. In 1923, Houghton and Yaglou [2] worked with the concept of climatic comfort in their study, “Determining lines of equal comfort”, forming part of what today is known as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). In 1956, Carrier launched a window air-conditioning unit, and this type of installation reached homes, even affecting the demographics of the US, with the population in the hottest parts of the country, from Florida to California, rising from 28 to 40%, the so-called “North to South” effect. This influence continues today in cities like Dubai and Singapore. In the 1960s, Victor Olgyay [3] and Baruch Givoni [4] laid down the theoretical and scientific guidelines for human comfort within bioclimatic architecture. It is because of all this that “comfort” has been traditionally associated with thermal comfort.

However, the definition of comfort is complex and varies greatly depending on the area addressing it, be this engineering, architecture, psychology, sociology, or anthropology. This complexity grows further when the social, cultural, political, economic, climatic, and technological realities behind the definitions are radically distinct or start from different levels [5]. Nevertheless, as a starting point for this book, environmental comfort is considered the psycho-physical well-being of people in an environment related to the sensorial perceptions of an individual. It is determined then by factors linked to the environment, such as temperature, humidity, sound, and light [6]. Therefore, environmental comfort typically incorporates four parameters: thermal comfort, indoor air quality (IAQ), acoustic comfort, and visual comfort.

Currently, the main challenges facing the construction sector, such as energy consumption, energy poverty, and climate change, among others, are all linked, in one way or another, to the concept of environmental comfort [7], which is closely tied to the geographic location [8, 9]. For example, in 2018, it was shown that the United States and China represented 54% of the 1932 Terawatts per hour used by residential and commercial air-conditioning devices, which is the equivalent of the annual electricity consumption of Africa. However, Africa is the region of the world that is most exposed to the effects of climate change, even though its inhabitants are the ones who have contributed least to it, as they mainly find themselves in energy poverty, linked to access to energy, and therefore, find it impossible not just to reach a suitable environmental comfort, but to cover their basic energy needs [10].

Unfortunately, this is just one of the examples of the great contrasts between the Global North and the Global South regarding environmental comfort.

2 Global South

The “North-South” terminology arose from an allegoric application of categories to name patterns of wealth, privilege, and development into broad regions, initially driven by the Italian Marxist, Antonio Gramsci, in his essay “The Southern Question” about the differences between the north and south of Italy. Starting from here, the North-South concept began to be included in the international political lexicon, and in the 1980s, the Brandt Line was developed as a means to show how the world was geographically divided between the relatively wealthy and much poorer nations [11].

In this sense, the term, “Global South”, refers to zones with a relevant background of colonialism, neo-imperialism, and differential economic and social changes through which major inequalities remain in the living levels, life expectancy, and access to resources [12]. In general, the Global South refers to regions outside Europe and North America, most with low incomes or substantial economic and social inequalities, which are mainly located in the tropics and the Southern Hemisphere, with the exception of Australia and New Zealand. However, this classification is questionable, as countries like Chile, Uruguay, and Costa Rica have a per capita GDP above the international average, while countries like Ukraine are now found among the set of poorer countries [13]. Even so, the evidence suggests that the Brandt Line is largely intact, as the states of the Global South are just as unsatisfied as they were four decades ago, while differentiated growth rates are remodeling world politics without eroding the North-South divide [14].

Although this division was made from a political point of view, it has been seen that, climatically, there are also relevant differences between north and south, finding, in general, countries with the highest level of horizontal solar radiation in the Global South (see Fig. 1), along with those with the highest temperatures (see Fig. 2), or most of those with the highest altitude cities (see Fig. 3). In this sense, it is important to highlight that more than 120 million people live above 2500 m, with all the countries with over a million inhabitants living at this altitude, in the Global South, with 7 of them in Latin America and the Caribbean [15]. Altitude is an additional factor that needs to be considered in the Global South.

These climatic differences have been fundamental for understanding architecture and its means of adapting to the climate. Examples of this are the Wind Towers or windcatchers in Iran, the house-courtyard of Arabian architecture for regions with a warm-dry climate, vernacular buildings built with heavy earthen walls in adobe or bahareque in tropical climates, intermediate zones that protect against the sun but use the wind for cooling, and architecture with solar protection elements or ventilated facades. This way of adapting architecture, generally to warm climates, unlike the Global North countries, which have less radiation and lower temperatures, is a differentiating aspect that must be considered further. However, in general, the

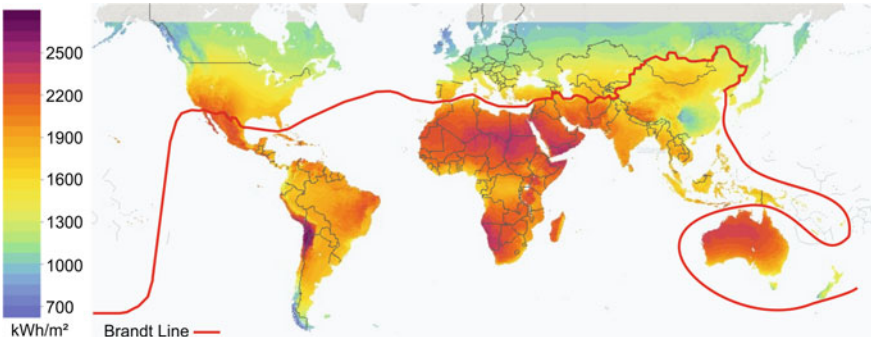

Fig. 1 Global horizontal irradiation (kW h m^2). Own preparation using [16]

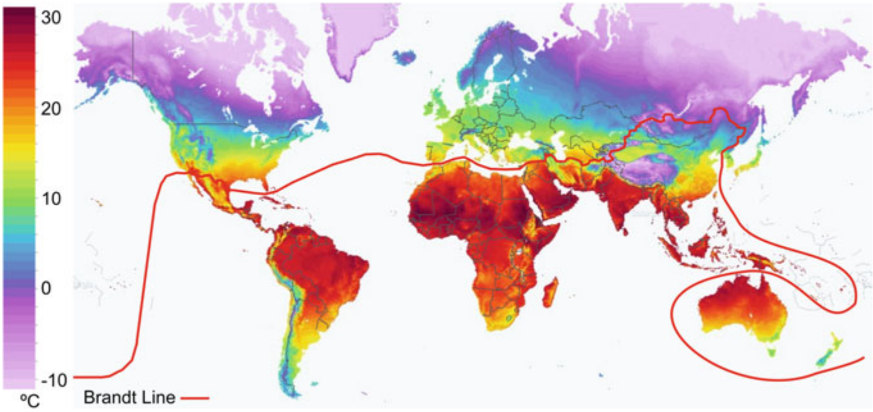

Fig. 2 Air Temperature at 2 m above ground level (°C). Own preparation using [16]

standards developed in recent decades, the energy rating processes, and the sustainability certifications are linked to cold climates and countries with a high economic level.

During the 1973 oil crisis, fears emerged in countries associated with the reduction of energy sources and energy dependence. To face this situation, they would launch incentive programs to reduce energy consumption, with energy efficiency standards later emerging. However, they were all developed in Global North countries. There were also advances in the Global South, such as the programs linked to energy efficiency in Mexico, which began in the 1980s. But it would not be until 2006 that Mexico would begin the Standardization and Labeling Program within the Energy Efficiency Project, and in 2008, issue the Law for Sustainable Energy Use. This shows that between the first experiences in energy efficiency standardization issues in the Global South and Global North, there is a time lag of approximately 30 years.

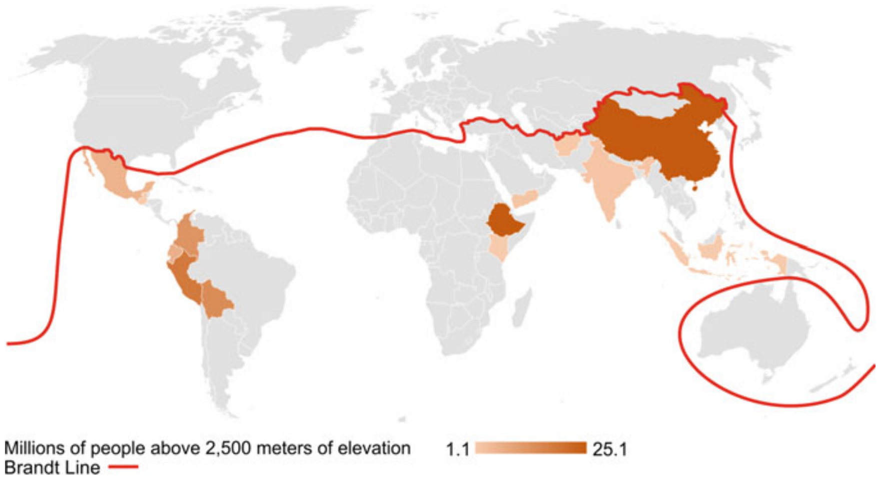

Fig. 3 Countries where more than a million inhabitants live above 2500 m. Own preparation using [15]

In the last two decades, noticeably many countries from the Global South have fostered policies and regulations on access to energy, energy efficiency, and renewable energies, as can be seen in the Regulatory Indicators for Sustainable Energy (RISE) scores of Fig. 4. The RISE scores provide a snapshot of the policies and regulations of a country in the energy sector, organized by the three pillars of sustainable energy: access to energy, energy efficiency, and renewable energy. It can be seen that despite the efforts and the progress there has been, there are still important gaps in the South, mainly in Africa and the Caribbean, with the energy efficiency indicator having the largest difference. This is addressed in greater detail in Chap. 29.

Access to quality energy, the production of renewable energy, energy efficiency, and international cooperation to facilitate access to energy-related research and technologies, promoting investment in clean technologies and energy infrastructure, expanding infrastructure, and improving technology to provide modern and sustainable energy services for everyone in developing countries, are the goals of the United Nations' Sustainable Development Goal N° 7 "Affordable and Clean Energy", and are a priority for Global South countries, linked to improving people's environmental comfort conditions. On the other hand, the goals described by the International Energy Agency [19] establish that, for 2050, more than 85% of buildings are zero-carbon ready, more than 90% of heavy industrial production is low emissions, and almost 70% of electricity generation globally is from solar PV and wind. In the same report, it indicates that

> For many rich countries, achieving net-zero emissions will be more difficult and costly without international cooperation. For many developing countries, the pathway to net zero without international assistance is not clear [19, p. 25].

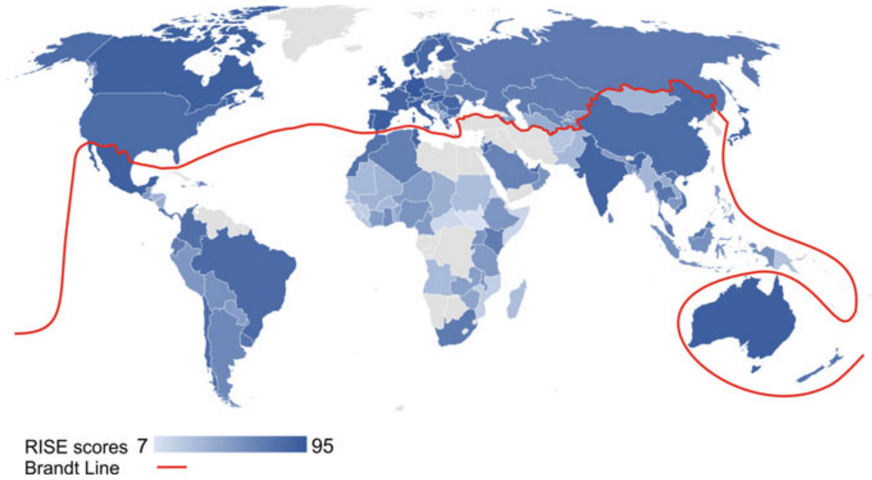

Fig. 4 Regulatory Indicator for Sustainable Energy (RISE) by countries. Own preparation using [17]

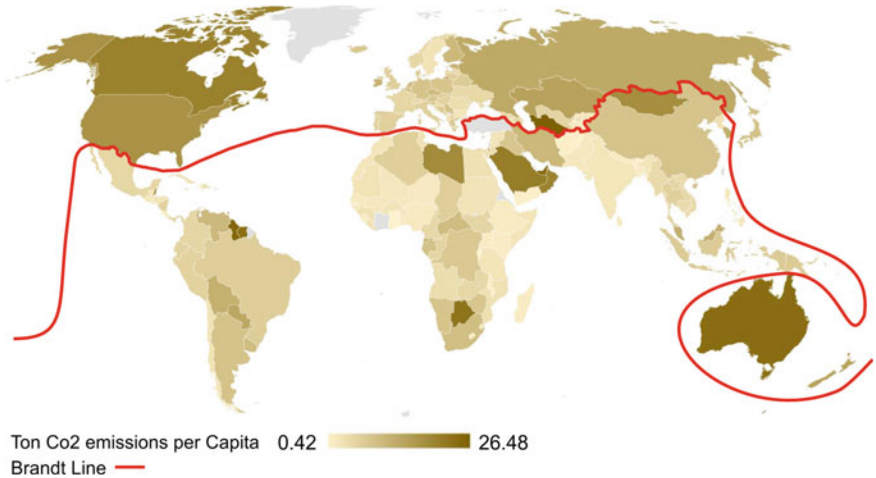

Fig. 5 CO_2 emissions per Capita 2019 (Ton/per Capita). Own preparation using [18]

However, the goals do not consider that in the Global South, there are already many countries whose CO_2 per capita emissions are very close to zero (see Fig. 5), showing a very different reality to most northern countries and, in general, this is not because of high energy efficiency, but rather an issue of access. It must be kept in mind that, in 2020, there were still 773 million people without electricity [20]. Furthermore, we do not know how many people live under conditions of low or zero environmental comfort on not having access to suitable air-conditioning systems, or simply not being able to use them due to energy poverty. Because of all this, the objectives and/or goals marked out by the Global North are very difficult to reach without external financing or developing low-cost technologies for the Global South.

On the other hand, the Global South's socioeconomic context also implies different climate adaptations and responses to the "need" for comfort. Facing a lack of economic resources, extreme weather conditions in many cases, and the impossibility of hi-tech solutions, there is a better adaptation to the environment, namely personal actions that require little or no energy prevail in those places where they cannot afford or do not have access to it. To a certain extent, there are other priorities in the Global South.

As such, it is fundamental that the actions and measures being implemented, whatever their nature may be, must have as their starting point the local advances and efforts, the available resources and skills, and, especially, the technological, economic, and social context of each country.

3 Barriers to Environmental Comfort in the Global South

The beginnings of environmental comfort are relatively recent, linked to the introduction of air-conditioning systems in buildings in the Global North, and related to the main challenges of today for the construction sector. The definition of the concept is complex and varies depending on the social, cultural, political, economic, climatic, and technological variables. However, the methods, tools, and standards generally used in the Global South come from the Global North. In addition, there are common barriers related to geopolitical, economic, development, geographical, cultural, and social aspects, among others, that transcend the concept of environmental comfort but undoubtedly also affect it in many cases.

Although the Brandt Line is over 40 years old, considering the developments in sustainability, energy efficiency, renewable energy use, and other aspects related to environmental comfort, its territorial demarcation seems to be valid in most countries for these issues, also tying in with climatic, altitude, emissions, and access to energy aspects.

Currently, in the Global South's Indicators for Sustainable Energy, a relevant gap compared to the North is seen, which also suggests that for many countries of the South, it is impossible to reach the Sustainable Development Goals or the Net-Zero goals by 2050. The current gaps in most Global South cases start from geopolitical, economic, technological, and social-historical inequalities. The result is the barriers linked to environmental comfort, such as problems accessing energy, the use of contaminating energy sources, limited use of air-conditioning systems, a lack of energy infrastructure, low technological levels, high demand for housing, low standard self-builds, low labor quality, a lack of information on the building stock (thermal properties, use profiles, etc.), a lack of training for professionals on matters related to environmental comfort and energy efficiency, a lack of resources for development, high indoor and outdoor contamination, urban re-densification processes, and a major impact of climate change on the region.

Climate, socioeconomic conditions, and access to energy have a relevant impact on how environmental comfort and the Heating or Eating effect are faced in certain areas of the extreme Global South. This has meant that passive architecture and especially bioclimatic strategies associated with the thermal aspect and user comfort have been taken to the extreme in many cases, identifying important limitations when facing climate change and, on the other hand, being less developed on issues related to acoustic and visual comfort. On the other hand, the lack of environmental comfort regulatory requirements, or the importing of comfort requirements outlined for other climates and other construction, social, and economic realities, has also been seen as an important barrier in the Global South, given that these generate major performance gaps.

Climate change has and will continue to have a very relevant impact on the Southern Hemisphere, entailing, in many cases, a reduction of environmental comfort conditions, and in others, an increase in energy consumption caused by the widespread penetration of HVAC systems. Likewise, it has been seen that researchers have a particular interest in researching and developing low-cost tools and measures that do not increase users' energy dependence or that are easy to use for designers. However, in some cases, a disconnect in the design of the user, the architecture, and the climate has been described, as well as the designers' lack of knowledge of environmental comfort. It has even been discovered that the application of sustainability certifications in buildings does not imply that users have a better perception of environmental comfort.

Many Global South countries are building and modernizing their regulatory framework to improve environmental comfort in buildings. However, these processes, as their starting point, are using the Global North's developments of the last four decades, without fully addressing the technological, economic, and social context of each country, for different reasons. It is fundamental that the programs, laws, requirements, and procedures focused on demanding environmental and energy performance, are socially and economically acceptable in the current and future local reality.

On the other hand, the implementation of regulations on environmental comfort has barriers associated with the investment, the lack of awareness campaigns, a lack of agreements between parties, legislative progress, and the creation of verification and control processes, aspects that need greater political commitment and international support, mainly from the Global North. In addition, the new regulations are closely conditioned by housing shortages, and, therefore, define low demands for environmental comfort, to reduce public investments. In other cases, they focus on reducing demand and not improving environmental comfort through passive systems, thus fostering user energy dependence. In this vein, there are also barriers regarding investment in education and research, focusing attention on other priorities. Finally, there is a lack of connection between researchers and practitioners, between and within countries.

Ultimately, it must be emphasized that there are more and greater barriers in the Global South to improving environmental comfort in buildings than in most Global North countries. The concepts have been developed in the Global North, which means that their definitions often do not face the realities of the Global South, entailing not just adjustments for the concepts but also new ways to evaluate and measure them. The chapters in this book contribute in this sense.

4 An Overview of the Content

This book has been structured considering the four parameters of environmental comfort: Thermal comfort, Indoor air quality, Visual comfort, and Acoustic comfort and its relationship with energy use and energy efficiency, seeking to address different barriers to environmental comfort.

Although the isolated study of comfort is a gap in itself, this structure shows the different angles of the topic, where clearly efforts have focused on the thermal aspect, perhaps fairly, because of its historical background and the specific climate challenges that countries are facing in the Global South.

Weather conditions and their variability in the Global South, and even within countries themselves, finding large countries with a great diversity of conditions, with deserts, coasts, mountains, forests, jungles, paramos, etc., and where often climate change is having a greater impact than in the Global North, is a relevant gap. Thus, the first two parts are dedicated to thermal comfort.

In Part I, with contributions from Costa Rica, Peru, Ecuador, Indonesia, Israel, and Chile, there is research on different building typologies, such as homes, schools, and offices. They assess the thermal environment and its perception in tropical, desert, Meso-Andean, and other climates. Part II has research from Argentina, Colombia, Mauritius, and Oman, on passive systems and resources for architectural and bioclimatic design, and studies of adaptive thermal comfort as a tool.

In Part I, Porras-Salazar et al., in Chap. 2, address vernacular architecture in Costa Rica, assessing the thermal performance of adobe and bahareque buildings to determine whether the thermal mass is effective in maintaining indoor temperatures within acceptable limits in the tropical climate zone. In contrast, Resano et al., in Chap. 3, focus on Peru, where despite being on the tropical strip, a large part of the population lives 3000 m or more above sea level in the Andes and is exposed to intense, cold climatic conditions. This study monitored the thermal performance of a typical Meso-Andean rural dwelling and proposed bioclimatic strategies for a context of resource scarcity. Meanwhile, Vivanco and Trebilcock, in Chap. 4, explore the thermal performance of educational buildings in different typical Andean tropical climates, including the Coastal Lowlands, the Andean Highlands, and the Amazon Rainforest in Ecuador, a context where thermal performance depends solely on the architectural design and occupant behavior.

However, in the Global South, there are many cases where air-conditioning systems are being incorporated into buildings to improve thermal comfort by eliminating the principles of tropical or vernacular architecture in contemporary buildings, as shown by Hilma et al. in Chap. 5. They focus on the current challenges of using air movement to improve thermal perception in Indonesia's warm-humid climate. Since, in some cases, the use of mechanical systems is unavoidable, especially in extremely arid climates such as deserts, Kruger et al. explore in Chap. 6, whether thermal perception can be improved by using low-cost systems for evaporative cooling, such as ceiling-mounted radiant panels coupled to a roof pond.

On the other hand, in Global South countries, sustainable certification systems that aim at reducing the use of resources and the impact of the building on the environment, as well as integrating criteria for improving indoor environmental quality, are starting to be used. In this vein, Trebilcock et al., in Chap. 7, compare occupant satisfaction and comfort between conventional and certified office buildings in Chile.

Moving onto Part II, de Schiller, in Chap. 8, presents bioclimatic design strategies at a layout and morphological level to reduce energy demand while promoting comfort, energy efficiency, and the implementation of solar energy in social housing in 8 Argentinean climates.

The warm coastal region and the colder central plateau of Mauritius are taken as a case study by Gooroochurn in Chap. 9 to review passive measures tested in tropical climates and identify barriers that have prevented their widespread adoption.

Al-Khatri reviews, in Chap. 10, the potential role of adaptive actions to satisfy thermal comfort demands in public buildings, becoming a tool for reducing energy consumption. He also explores the application of artificial intelligence to help this process.

The three final chapters in this section describe bioclimatic design tools, emphasizing passive design for improving thermal comfort. Maristany and Arrieta, in Chap. 11, introduce an adaptive model for homes in non-extreme climates, applied in Argentina. Evans, in Chap. 12, describes the bioclimatic design resources developed over the last 50 years and presents a graphic tool to help designers to use climate data and comfort limits in the initial design stages. Similarly, in Chap. 13, Rendon et al. present an adaptation of Le Corbusier's Grille Climatique to Tropical climates, the Tropical Climate Matrix, a graphic tool for the first stages of building design, tested in two cities in Colombia.

Part III is devoted to IAQ. Molina et al. describe, in Chap. 14, the strategies to improve indoor air quality in Latin American buildings, outlining metrics for determining the most important airborne contaminant sources and the variables that affect IAQ. In this line, and considering the increasing need for indoor air quality control, particularly in hot countries, Kruger and Diniz evaluate in Chap. 15 a low-cost, responsive air-renewal system in a climate chamber equipped with a standard split A/C unit.

Part IV focuses on chapters that address visual comfort and daylight, circadian stimulus, the development and evaluation of metrics, and the design of lighting strategies for classrooms and office environments from Colombia, Brazil, and Chile. Arango-Díaz and Piderit-Moreno, in Chap. 16, suggest a new dynamic daylight metric for the Tropics based on the local context and people's perception. Likewise, in Chap. 17, daFonseca et al. explore the most commonly used daylight metrics and their application in Brazil, a different context from where they were developed.

With building design in mind, Palarino-Vico and Piderit-Moreno describe, in Chap. 18, daylighting strategies to achieve visual comfort in side-lit office spaces, proposing strategies for three Chilean cities with different climates, prevalent skies, and daylight availability. However, daylight is not always guaranteed for existing buildings in the Global South. For this reason, in the final chapter of this section, Chap. 19, Piderit-Moreno and Palarino-Vico study the circadian stimulus potential in Chilean offices that lack windows for daylight and rely only on artificial lighting.

For acoustic comfort, Part V of the book includes advances regarding noise control and the acoustic design of flexible learning spaces. In Chap. 20, Gutierrez and Marin-Restrepo review the most frequent noise sources and architectural design decisions in multi-residential buildings in the tropics that affect acoustic comfort, identifying the situations to avoid, those to promote, and proposing mitigation and control activities to implement when they occur, with particular focus on preventing sleep disturbance. A different approach is presented by Ipinza et al. in Chap. 21, reviewing acoustic design regulations and recommendations with a greater emphasis on sound quality, so necessary in flexible learning spaces.

Part VI, Energy Use and Energy Efficiency, includes contributions on the impact of urban re-densification, energy performance, and energy optimization in buildings, as well as ventilation, passive measures, and climate change, and studies on the use of air conditioning systems, from Ecuador, Argentina, Colombia, Peru, Brazil, Uruguay, and Chile.

In Chap. 22, Montes-Villalva et al. use simulation tools to explore the impact of urban re-densification on solar access, lighting demand, and energy poverty in high-rise dwellings in Ecuador, establishing maximum height recommendations. Finding a balance between comfort and energy savings is the challenge addressed by Arballo et al., in Chap. 23, via a multi-objective optimization tool applied in office buildings in Argentina. Montoya et al. focus on naturally ventilated classrooms in Colombia, and in Chap. 24, they assess the effect of thermal and visual comfort strategies on energy performance. Resano, in Chap. 25, and Callejas et al., in Chap. 26, propose local constructive solutions to optimize thermal comfort and energy efficiency in low-income housing in the desert climate of Peru and the Brazilian Tropical Savannah climate, respectively. Similarly, Pereira-Ruchansky and Perez-Fargallo, in Chap. 27, focus on social housing in Uruguay, evaluating passive design measures using the time in thermal comfort as an indicator in the context of climate change. Finally, in Chap. 28, Munoz et al. built representative housing heating profiles based on environmental monitoring in Central-Southern Chile.

Part VII, the last part of the book, gathers reflections on the concept of environmental comfort: how to define it, how to measure it, how to assess it, and how to improve it. First, Chap. 29 describes existing policies and standards for environmental comfort in the Global South, specifically in Latin America and the Caribbean, providing a context for the following chapters. In Chap. 30, Diaz et al. start from the idea that thermal, acoustic, and visual comfort and indoor air quality should be assessed with a holistic approach. Furthermore, they identify and classify strategies to ensure indoor environmental quality in school classrooms, proposing a workflow for their incorporation in school design. Garcia et al. propose in Chap. 31 a qualitative study looking at comfort and habits of domestic life, seeking to extend the traditional approaches to comfort that tend to ignore complex relationships between architecture, culture, and place, particularly in the Colombian Andean Tropics.

Salazar Trujillo and Arango-Diaz, in Chap. 32, offer a reflection on what is understood by environmental comfort in the Global South, specifically in the intertropical strip, and propose a methodological approach to address it, considering economic and technological constraints.

Finally, in Chap. 33, Marin-Restrepo et al. comment on the main points addressed in the book, showing how barriers are removed and paths are drawn for future research and progress, with a local perspective that is appropriate to the climatic and socio-cultural context of the countries in the Global South.

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References

1. Nagengast B (2002) 100 years of air conditioning. ASHRAE J 44:44–46
2. Houghton F, Yaglou C (1923) Determining equal comfort lines. ASHVE Trans 29:163–176
3. Olgyay V (1963) Design with climate. Princeton University Press, New Jersey, USA
4. Givoni B (1969) Man, climate and architecture. Elsevier Publishing C. L., Amsterdam
5. Brager GS, Dear RJD (2003) Historical and cultural influences on comfort expectations. In: Buildings, culture and environment: informing local and global practices, pp 177–201
6. Riffelli S (2021) Global comfort indices in indoor environments: a survey. Sustainability 13:12784. https://doi.org/10.3390/su132212784
7. Santamouris M (2016) Innovating to zero the building sector in Europe: minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. Solar Energy 128:61–94. https://doi.org/10.1016/j.solener.2016.01.021
8. Pérez-Fargallo A, Pulido-Arcas J, Rubio-Bellido C, Trebilcock M, Piderit B, Attia S (2018) Development of a new adaptive comfort model for low income housing in the central-south of Chile. Energy Build 178:94–106. https://doi.org/10.1016/j.enbuild.2018.08.030
9. Porras-Salazar J, Contreras-Espinoza S, Cartes I, Piggot-Navarrete J, Pérez-Fargallo A (2020) Energy poverty analyzed considering the adaptive comfort of people living in social housing in the central-south of Chile. Energy Build 223:110081. https://doi.org/10.1016/j.enbuild.2020.110081
10. World Meteorological Organization (2022) State of the Climate in Africa. Geneva, Switzerland, https://library.wmo.int/doc_num.php?explnum_id=11304
11. Brandt W (1980) North South: a programme for survival; report of the independent commission on international development issues. MIT, Cambridge, Massachusetts, USA
12. Dados N, Connell R (2012) The global south. Contexts 11:12–13. https://doi.org/10.1177/1536504212436479
13. World Bank Group (2021) Gdp per capita (current us$) | data. https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?name_desc=false&view=map
14. Lees N (2021) The Brandt line after forty years: the more north-south relations change, the more they stay the same? Rev Int Stud 47:85–106. https://doi.org/10.1017/S026021052000039X

15. Tremblay JC, Ainslie PN (2021) Global and country-level estimates of human population at high altitude. Proc Natl Acad Sci 118:e2102463118. https://doi.org/10.1073/pnas.2102463118
16. World Bank Group (2022) Global solar atlas. https://globalsolaratlas.info/map?c=11.609193,8.173828,3
17. World Bank Group (2019) Regulatory indicators for sustainable energy. https://rise.esmap.org/
18. Climate Watch (2019) Historical GHG emissions. https://www.climatewatchdata.org/ghg-emissions?breakBy=regions&calculation=PER_CAPITA&chartType=line&end_year=2019&regions=EAP%2CECA%2CEUU%2CLAC%2CMNA%2CNAR%2CSSA%2CWORLD%2CSAR&start_year=2010
19. International Energy Agency (2021) Net zero by 2050: a roadmap for the global energy sector. Paris, France, https://iea.blob.core.windows.net/assets/063ae08a-7114-4b58-a34e-39db2112d0a2/NetZeroby2050-ARoadmapfortheGlobalEnergySector.pdf
20. EA, IRENA, UNSD, BanK W, WHO (2021) Tracking SDG 7: the energy progress report. Washington DC, USA, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jun/SDG7_Tracking_Progress_2021.pdf

Thermal Comfort

Thermal Performance Assessment of Vernacular Earth Buildings in Tropical Climates: A Case Study in Costa Rica

Jose Ali Porras-Salazar, Jan-Frederik Flor, and Moises Obando Robles

Abstract Thermal mass is a common concept applied in vernacular architecture to keep internal temperatures comfortable by damping and delaying heat transfer through the building envelope. However, despite the widespread presence of large mass buildings in tropical regions, it has been argued in the literature that thermal mass is not efficient in tropical climates due to the minimal difference between night and daytime air temperatures. This study aimed at evaluating the thermal performance of heavyweight buildings to determine whether the use of thermal mass is effective in maintaining internal temperatures within acceptable limits. Six adobe and bahareque buildings with large mass earthen walls were monitored in two tropical climate zones recording internal and external temperatures in both rainy and dry seasons. Three performance indicators were used: general temperature damping, peak temperature reduction, and the proportion of time within 80% thermal acceptability limits. The results showed that the buildings were able to dampen peak high and low temperatures by an average of 5 °C (2.7–9.7 °C), reducing peak outdoor temperatures by up to 5 °C, and increasing the time within thermally acceptable limits. This chapter demonstrates the viability of using thermal mass in tropical buildings as a technique for mitigating global climate change.

Keywords Tropics · Thermal mass · Building envelope · Adobe · Thermal comfort

J. A. Porras-Salazar (✉) · M. Obando Robles
School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica
e-mail: jose.porrassalazar@ucr.ac.cr

M. Obando Robles
e-mail: moises.obando@ucr.ac.cr

J.-F. Flor
Faculty of Architecture and Ekistics, Universiti Malaysia Kelantan, Bachok, Malaysia
e-mail: frederik@umk.edu.my

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1 Introduction

The design of building envelopes plays a key role in the thermal behavior of buildings and has a considerable impact on indoor comfort conditions. Well-insulated building envelopes can help to reduce the need for heating and cooling. However, currently, the air conditioning of buildings contributes around 15% of global electricity usage [1]. The energy use in climate-controlled buildings in the Tropics accounts for 60% alone, thus fuelling climate change with additional CO_2 emissions [2–4]. Even though it is generally agreed that the energy consumption of buildings is lower in the Global South, there is a rising trend due to population growth, urbanization, and lifestyle changes [5]. Extreme weather events associated with climate change, such as prolonged heat waves and droughts, have also contributed to a higher energy demand for cooling [6]. Therefore, reducing energy use in buildings is an important issue to keep global warming below 2 °C.

Vernacular architecture—a term used to categorize methods of construction that use locally available resources to address local needs [7]—is widely acknowledged as having successfully adapted to the prevailing climate of its surroundings via trial and error. Vernacular buildings use passive environmental control methods that make them comfortable and energy efficient [8]. Thermal mass is a common cooling technique in vernacular architecture. It indicates how much mass a building has and, therefore, how much heat it can store. The benefit of thermal mass for indoor thermal comfort is its potential to buffer outdoor air temperature and reduce internal temperature peaks [9]. A building with a large mass can absorb heat from solar radiation and the air during the day and release it at night, providing "inertia" against temperature fluctuations.

Many studies have shown that thermal mass is an effective cooling strategy. Givoni [10] monitored buildings with different mass levels in South California under different ventilation and shading conditions. The author found that on an extremely hot day—outdoor maximum of 38 °C—, the indoor maximum temperature of the high-mass building was only 24 °C. Using simulation models, Shaviv et al. [11] estimated that in four coastal cities in the Middle East—Nahariya, Geva Carnel, Tel Aviv, and Gaza—it is possible to achieve a reduction of 3–6 °C in a heavyweight building. Gauthier et al. [12] analyzed 451 questionnaires made in 26 buildings within the SCAT project and found a significant relationship between building fabric heat capacity and occupants—thermal perception.

However, several studies have postulated thermal mass as an inappropriate design strategy for passive cooling in tropical climates [1, 13]. The main reason given is that the temperature differences between day and night are low. In contrast to what is widely predicted among scholars, the public opinion among the Costa Rican population is that traditional buildings built with heavy earthen walls have better indoor thermal conditions than those built nowadays with light materials. The widespread presence of vernacular adobe or bahareque buildings in Costa Rica underpins the apparent discrepancy between theory and practice.

The question then arises as to whether high thermal mass earthen wall constructions in tropical climates are able to provide acceptable indoor thermal conditions. In order to answer these questions, this research monitored the indoor thermal performance of six adobe and bahareque buildings located in different tropical climatic zones in Costa Rica. To evaluate the thermal performance, three indicators were used: (i) general temperature damping, which is the difference in degrees Celsius between outdoor and indoor temperature oscillation, (ii) peak temperature reduction, which is the difference in degrees Celsius between the maximum outdoor and indoor temperatures, and (iii) the proportion of time within the 80% thermal acceptability limits according to the ASHRAE 55-2017 standard [14]. These indicators have been established in previous studies and, therefore, allow for objective comparison [11, 15].

The importance and originality of this study are that it explores the potential of traditional building techniques to enhance thermal comfort in tropical climates that are increasingly relying on energy-intensive mechanical air conditioning. The tropical region has higher temperatures than the rest of the world, and as their economies develop, their people will demand higher thermal comfort standards with an associated increase in energy consumption. Thus, understanding how passive cooling techniques work and under what circumstances they are effective is crucial to minimizing the use of mechanical cooling. Providing alternative solutions to a region that is home to 40% of the world's population and includes some of the world's largest, most populated, and fastest-growing economies—e.g., India, Brazil, Nigeria, and Indonesia—is, therefore, of significance.

2 Methods

One of the most well-known tools for assessing the thermal performance of vernacular buildings is the in-situ measurement method. This method has been applied previously by many researchers in Taiwan, India, Nigeria, Saudi Arabia, and Japan [16–20]. Thus, a case study approach was adopted using in-situ measurements with dataloggers to understand the thermal conditions of buildings over a prolonged timeframe. An overview of the research workflow is shown in Fig. 1.

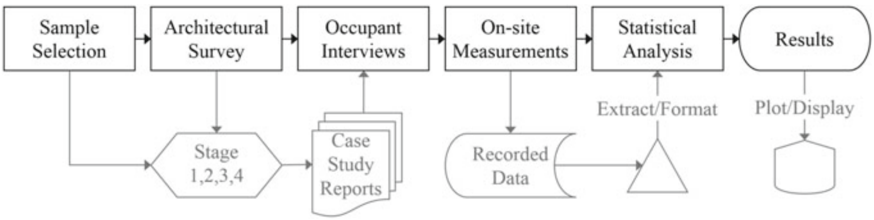

Fig. 1 Methods Flowchart

2.1 Case Studies

The case study presented in this chapter focuses on adobe and bahareque, two raw earth construction techniques with high thermal mass that have been widely used in Costa Rica. Bahareque walls are constructed from interwoven sticks or reeds that are then covered in mud, while adobe walls are formed of bricks made of a mixture of clay, sand, silt, and straw that are dried in the sun. These construction methods became popular during the time of the Spanish colony, from the 16th century onwards, although earth construction techniques had been used since ancient times by Costa Rica's indigenous people. Adobe and bahareque buildings were mainly built in the center and northwest of Costa Rica [21], which were the sites that housed the main colonial settlements. Its application was particularly convenient due to the accessibility of materials close to construction sites and their low cost. However, after an earthquake that affected several adobe buildings in 1910, this construction technique was banned. The use of bahareque was also prohibited in 1974 [22]. Consequently, the vast majority of earth buildings in Costa Rica nowadays were built before those years, which is also the case for the buildings investigated in this study.

A total of six buildings were chosen for this case study using the following eligibility criteria: The foremost important factor was the integrity and original state of the building to ensure that the environmental measurements would predominantly represent the performance of earthen building envelopes. Buildings with too many modifications using modern materials were discarded during pre-screening visits. The second determining factor was accessibility during the measurement periods. Four out of the six buildings chosen were residential houses; therefore, the owners' consent had to be obtained to make site visits and measurements.

Another aspect of importance for the methodological approach was the location of the buildings. To answer the research question, under which environmental conditions of tropical climates do earthen buildings provide better interior thermal conditions, the study surveyed buildings in different climate zones. According to the climate classification of Köppen-Geiger, Costa Rica's climate belongs to the tropical group with three distinctive subgroups (Aw, Af, and Am) [23].

To account for the characteristics of Costa Rica's climatic variance, case study buildings were located across the territory in different climate zones. Comparability of the results was ensured by limiting the maximum distance between the case study buildings in each zone to less than 5 km. Accordingly, case study buildings CC1 and CQ1 were located in Cartago and Quircot, in the province of Cartago, representing the tropical monsoon climate (Am) with dry subtropical winters. HSD1 and HSD2, located in Santo Domingo, Heredia, were in the same climate zone (Am). Buildings LG1 and LG2 found in Liberia, Guanacaste, were chosen as representative case studies for the tropical savanna climate with dry-winter characteristics (Aw). Due to the geographical distribution of the earth buildings, none of the case studies was located in the tropical rainforest climate zone (Af). Figure 2 shows pictures and Table 1 provides basic information about each of the selected case study buildings.

Fig. 2 Case study earth buildings from left to right, CC1 and CQ1 in Cartago, HSD1 and HSD2 in Heredia, GL1 and GL2 in Guanacaste

Table 1 Data summary of case study buildings

Code	Location	Geographical location	Meters above sea level (m)	Building typology	Building footprint area (m^2)	Building Envelope Earth Ratio (*wall only) (%)	Earthen walls construction method
CC1	Cartago, Cartago	9°51′N, 83°55′W	1443	Terraced family house	215	16 (*55.4)	Bahareque
CQ1	Quircot, Cartago	9°53′N, 83°55′W	1486	Church	173	35 (*85.7)	Adobe
HSD1	Santo Domingo, Heredia	9°58′N, 84°5′W	1150	Terraced family house	140	13 (*55.1)	Adobe
HSD2	Santo Domingo, Heredia	9°58′N, 84°5′W	1135	Terraced family house	119	19 (*59.1)	Adobe
GL1	Liberia, Guanacaste	10°38′N, 85°26′W	143	Terraced family house	238	27 (*69.7)	Adobe
GL2	Liberia, Guanacaste	10°38′N, 85°26′W	143	Church	355	36.8 (*94.1)	Adobe

2.2 Architectural Survey

A prerequisite for the environmental measurements was to conduct a qualitative case study. Hence, none of the buildings chosen had previously been investigated in detail. Consequently, construction plans or information about building modifications were not available, but for the measurements, it was considered crucial to identify those parts of each building with the original earthen building fabric. Therefore, a detailed architectural survey was carried out based on the description and image approach [13], documenting the building conditions in-situ with measured drawings and photos. The combined information was later used to generate three-dimensional models and provide criteria to determine the exact location of the measurement devices.

2.3 On-Site Measurements

Environmental measurements were taken directly in the occupied case study buildings to understand how earthen wall constructions regulate internal temperatures. To assess whether different seasonal weather patterns would affect the thermal performance, the environmental conditions were monitored in the dry—January and February— and rainy season—October. These periods were chosen considering the historical climate data of Costa Rica [24]. Each building was monitored with dataloggers for several days in all three periods. However, due to logistical requirements and a limited amount of dataloggers, during the rainy season, buildings were monitored chronologically, one after the other, while during the dry season, the buildings were monitored simultaneously. This approach allowed placing, during the rainy season, twelve dataloggers in each building, increasing the spatial distribution and obtaining a more comprehensive picture of the thermal performance. While during the dry season, the focus was set on the effect of the weather conditions depreciating spatial resolution in favor of enhanced data comparability, placing only two dataloggers in each building. Table 2 shows the measurement periods for each building.

Table 2 Measurement periods for each case study building

CC1	CQ1	HSD1	HSD2	GL1	GL2
03/10–09/10/2010	10/10–16/10/2010	19/09–25/09/2010	26/09–02/10/2010	17/10–23/10/2010	24/10–30/10/2010
13/01/2011	13/01/2011	13/01/2011	13/01/2011	13/01/2011	13/01/2011
13/02–19/02/2011	13/02–19/02/2011	13/02–19/02/2011	13/02–19/02/2011	13/02–19/02/2011	13/02–19/02/2011

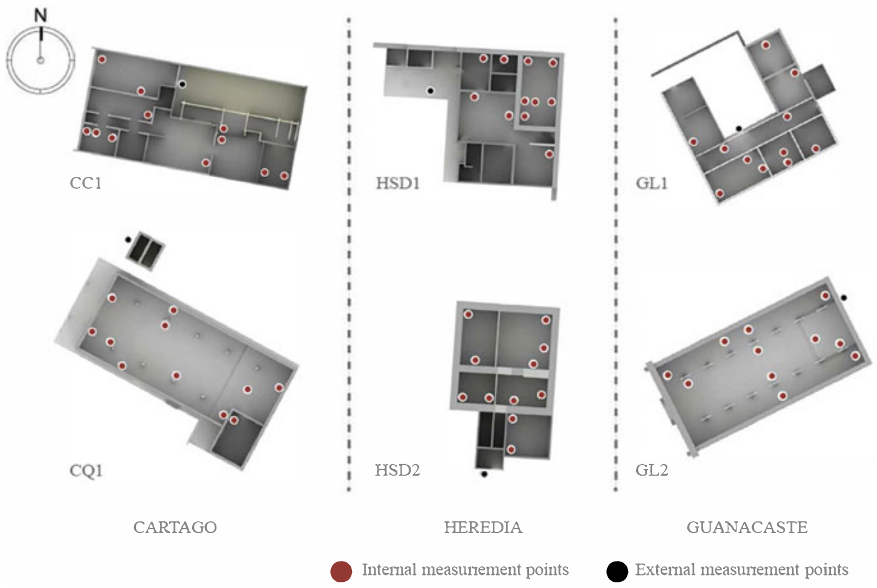

Fig. 3 Positioning of dataloggers in the case study buildings (October measurement period)

The placement of the dataloggers followed the EN 13799 standard [25], placing the dataloggers at 1.1–1.7 m above the floor. Figure 3 shows key plans for each of the case study buildings with the location of the dataloggers during the rainy season.

Once the dataloggers were marked, placed, and launched, the indoor air temperature, humidity, and illuminance were recorded. However, only the temperature measurements were processed for this study. During the monitoring periods, the residents and managers operated the building openings as usual, and all other occupation activities were carried out normally. The outdoor conditions were also monitored with the same type of dataloggers placed outside, covered from rain and direct solar radiation.

2.4 Measurement Equipment

The equipment used for the environmental measurements consisted of twelve HOBO, model U12-012 type mobile dataloggers. The parameters measured were temperature and relative humidity with an accuracy of ±0.35 °C from 0° to 50 °C and ±2.5% from 10% to 90% RH, respectively. The resolution for the temperature measurements was 0.03 °C at 25 °C and 0.05% RH for the relative humidity measurements. Illuminance was recorded in a range of 0 to 32,000 lx. All twelve devices were calibrated previously by the supplier. The logging frequency was set at 10 min. The HOBOware monitoring data software (Version 3.7.23) was used for programming and launching the dataloggers, reading out, and plotting.

2.5 Statistical Analysis

To estimate if the differences between (i) outdoor and indoor temperature oscillation and (ii) outdoor and indoor peak temperature were statistically significant; first, a normal Q-Q plot and a Shapiro-Wilks test with a P-value criterion of 0.05 were used to decide whether the data subjected to statistical tests were normally distributed. As the results showed that the data under both conditions were normally distributed, an unpaired two-sample t-test was used with the statistical significance set at $p = 0.05$. The data were assumed to be independent even though the same buildings were measured in different months.

The effects of outdoor temperature oscillation on (i) indoor temperature oscillation and (ii) peak indoor temperature damping were estimated using different linear models: linear, quadratic, cubic, and LOESS. The model with the highest prediction accuracy—determined by the highest determination coefficient (R^2) and the lowest Mean Absolute Error (MAE)—was selected. Statistical analysis was performed using R software (version R 4.1.3).

3 Results and Discussion

Table 3 summarizes indoor and outdoor conditions measured for seven consecutive days per season in each building. Cartago (CC1 and CQ1) was the coldest site, with an outdoor temperature range of 14.1–28.5 °C in February. Indoor temperatures ranged from 16.5 to 24.9 °C. Heredia presented outdoor temperatures from 16.2 to 29.1 °C and indoor temperatures from 20.4 to 27.5 °C. Of all three, Guanacaste was the warmest site, with outdoor conditions ranging from 22.2 to 35.8 °C and indoor temperatures from 23 to 33 °C. Inter-seasonal oscillation of outdoor temperatures at all sites was below 15 °C, characteristic of tropical climates. In the case of outdoor relative humidity, values ranged from 40 to 100% at all sites. The indoor relative humidity range was smaller in Cartago (62–90%) and Heredia (60–82%) and higher in Guanacaste (46–97%). Coinciding with the rainy season, October was the most humid month for all sites.

The temperature and humidity data collected during each monitoring period were consistent with typically prevailing seasonal trends in the chosen sites. Hence, monitoring in October reflected the characteristics of the rainy season, and measurements in January and February mirrored the characteristics of the dry season.

The difference between outdoor and indoor temperature oscillation across all seasons is shown in Fig. 4a. There is a significant difference ($p < 0.001$) between the mean outdoor temperature oscillation (mean = 10.3 °C, sd = 2.7 °C) and the

Table 3 Summary of indoor and outdoor temperature and relative humidity conditions for each case study building

Code	Location	Month	Indoor conditions				Outdoor conditions			
			T_{min} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)	T_{min} (°C)	T_{min} (°C)	RH_{max} (%)	RH_{min} (%)
CC1	Cartago	October	24.9	19.4	85	67	25.9	15.7	95	58
CC1	Cartago	January	20.5	18.3	90	78	22.0	15.6	97	74
CC1	Cartago	February	23.7	19.0	81	62	28.5	14.1	94	48
CQ1	Cartago	October	23.3	17.5	89	71	28.2	15.5	96	51
CQ1	Cartago	January	19.6	17.0	90	77	24.3	14.9	97	63
CQ1	Cartago	February	22.4	16.5	86	67	26.0	14.1	94	48
HSD1	Heredia	October	27.5	21.6	82	63	29.1	16.2	95	57
HSD1	Heredia	January	22.8	20.4	79	69	24.9	17.5	89	60
HSD1	Heredia	February	24.2	20.6	79	61	28.1	17.1	93	48
HSD2	Heredia	October	27.5	21.6	82	63	29.1	16.2	95	57
HSD2	Heredia	January	23.3	20.7	77	65	23.3	17.6	90	65
HSD2	Heredia	February	24.5	21.0	78	60	25.6	17.3	93	78
GL1	Guanacaste	October	31.8	24.9	87	65	32.6	23.0	95	61
GL1	Guanacaste	January	30.8	26.4	66	53	32.7	25.1	73	48
GL1	Guanacaste	February	33.0	25.2	69	46	33.8	22.8	78	45
GL2	Guanacaste	October	32.1	23.0	96	65	35.6	22.2	98	43
GL2	Guanacaste	January	30.1	25.5	70	54	32.2	24.9	73	49
GL2	Guanacaste	February	31.2	24.7	69	50	35.8	22.7	79	41

T_{max}: Maximum Temperature
T_{min}: Minimum Temperature
RH_{max}: Maximum Relative Humidity
RH_{min}: Minimum Relative Humidity

mean indoor temperature oscillation (mean = 5.0 °C, sd = 2.0 °C). The buildings were able to dampen peak high and peak low temperatures by an average of around 5 °C during the three monitored periods. The damping range fluctuated from 2.7 to 9.7 °C. A similar trend was observed for the variation between peak high outdoor (mean = 28.8 °C, sd = 4.2 °C) and peak high indoor temperatures (mean = 26.3 °C, sd = 4.3 °C) (Fig. 4b). Up to 5 °C lower indoor temperatures were measured, as can be seen in Fig. 5b. However, this difference was not significant ($p = 0.08$).

This 5 °C maximum peak temperature reduction is small if compared to, e.g., the 14 °C measured by Givoni in South California [10]—Hot-summer Mediterranean climate (Csa) according to Köppen-Geiger—, and the same can be said about the temperature oscillation damping. At first sight, these findings seem to be consistent with what many researchers have postulated; that thermal mass as a cooling strategy is not so efficient in warm-humid climates [13].

However, the results are similar to those obtained by researchers in Middle-Eastern cities also with Mediterranean climates (Csa). Saleh et al. [15] monitored three

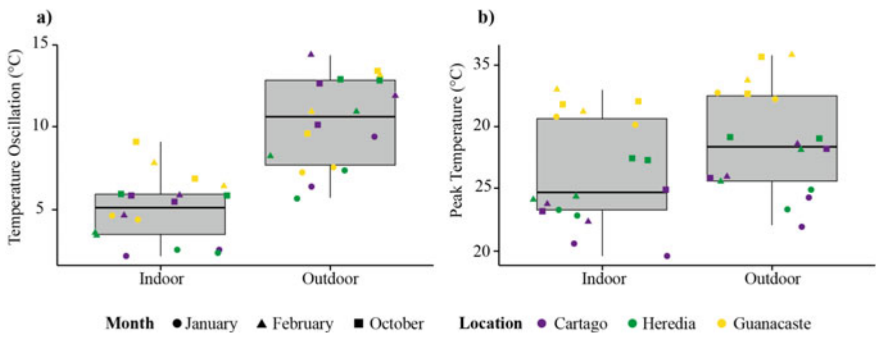

Fig. 4 Boxplot showing differences between **a** indoor and outdoor temperature oscillation at the six sites, **b** peak outdoor and peak indoor temperatures. The data correspond to the averages of a week (7 days) of measurement with Hobos U12-12 at each site and in each season of the year. Each data point represents the measurements of a building during a season. Jitter was used to prevent data points from overlapping

heavyweight residential apartments during the summer season in Lebanon, finding that temperature fluctuation was reduced from 9 °C outdoors to 4 °C indoors and that internal day temperatures were 2 to 4 °C cooler. Shaviv et al. [11] used computer simulations to examine the effect of thermal mass on buildings located in several coastal Middle-Eastern cities finding that it is possible to achieve a reduction of 3–6 °C.

Building use patterns may provide a credible explanation for the discrepancies in thermal performance. The case study buildings—and in general, tropical high thermal mass buildings—are more permeable than their counterparts in arid and semi-arid climates, and owners tend to ventilate them naturally both during the day and at night. Therefore, indoor temperatures, albeit dampened through the effect of the building's thermal mass, follow the same pattern as the exterior. Another aspect that could have influenced these results is that the roofs, which are the parts of the building that receive most solar radiation and represent more than 40% of the building envelope surface, were built with low thermal mass materials. This constructive particularity could have additionally contributed to an accelerated heat transfer [26].

As proof of this hypothesis, Fig. 5a shows that indoor temperatures (ITO) are linearly related to outdoor temperatures (OTO) (Model: ITO = 0.49 OTO–0.07, R^2: 0.66, MAE: 1.2). The higher the outdoor temperature differential between day and night at the location, the higher the internal temperature oscillation. The difference between the indoor and outdoor temperature peaks (DP) can also be explained partly by the outdoor oscillation, as shown in Fig. 5b. The outdoor temperature oscillation can explain up to 57% of the variability of the temperature peak (Model: DP = 0.35 OTO–1.076, R^2: 0.57, MAE: 1.2). These findings are underpinned by similar results discovered by [11] for the highest indoor temperature, which was found to depend linearly on the site's difference between day and nighttime temperatures.

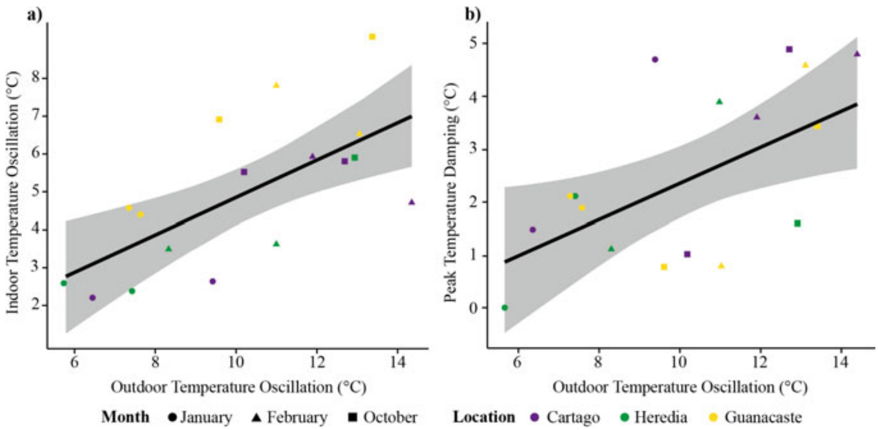

Fig. 5 Relationship between **a** outdoor and indoor temperature oscillation. Temperature oscillation was estimated as the difference in °C between mean maximum temperature and mean minimum temperature; **b** outdoor temperature oscillation and peak temperature damping. Peak temperature damping is the difference in °C between maximum outdoor and maximum indoor temperatures. Mean maximum and minimum temperatures were estimated from data collected for 7 days at each site and in each season. Each data point represents the measurements of a building during a season

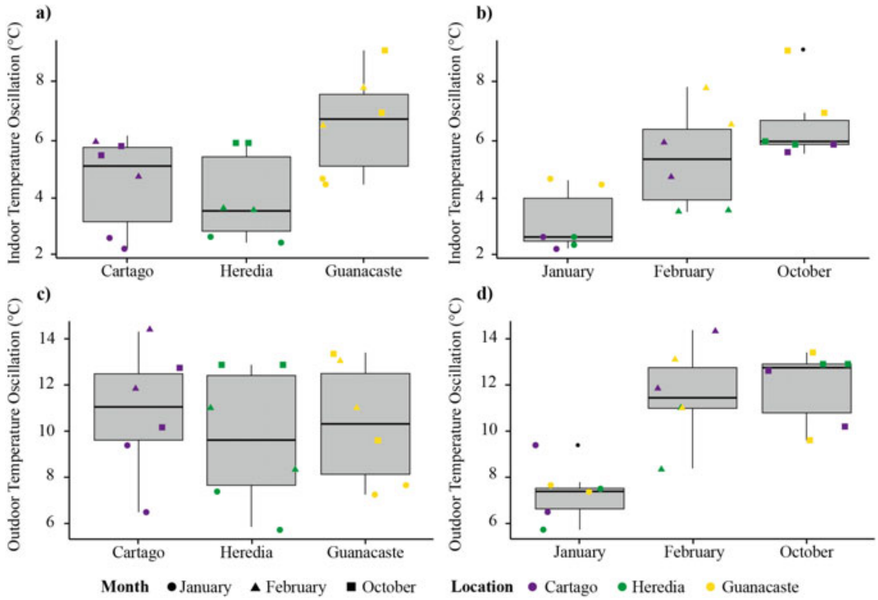

Fig. 6 Boxplots showing indoor and outdoor temperature oscillation according to the site (**a** and **c**) and season (**b** and **d**). The data correspond to the averages of a week (7 days) of measurements with Hobos U12-12 at each site and in each season of the year. Each data point represents the measurements of a building during a season. Jitter was used to prevent data points from overlapping

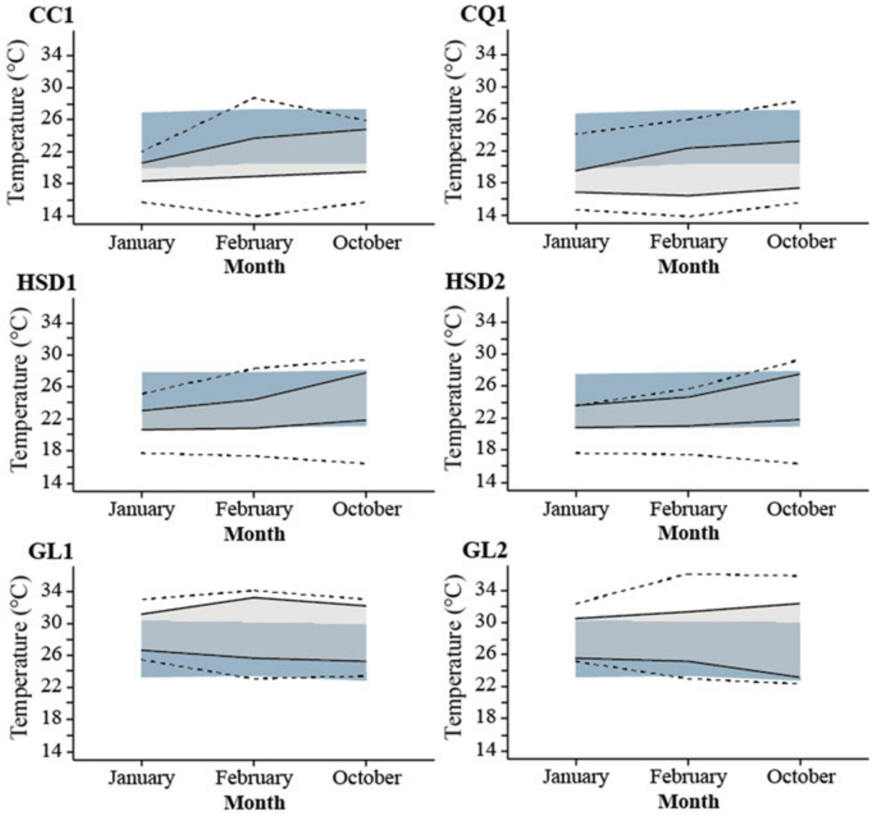

Fig. 7 Temperature behavior outside and inside the six buildings overlapped with the 80% thermal acceptability zone. The dashed lines represent the maximum (top) and minimum (bottom) average outdoor temperatures. The solid lines represent the average maximum (top) and minimum (bottom) indoor temperatures. The blue zone represents the 80% thermal acceptability zone according to the adaptive thermal model

Temperature damping was not uniform throughout the year or the sites studied. The interior oscillation was lower in January and in Heredia and higher in October and Guanacaste (See Fig. 6a, b). There could be two possible explanations for these differences. First, October was the month with the highest outdoor temperature fluctuation, and January the month with the lowest (See Fig. 6d), and second, the tropical climate, often perceived as uniform, tends to differ greatly from one place to another, despite short distances, due to factors such as orography and height above sea level—e.g., in Heredia, the interior oscillation is lower than in Guanacaste, regardless of the time of year (See Fig. 6a).

The indoor and outdoor temperature behavior of the six buildings and its relationship with the thermal acceptability zone—calculated according to the adaptive comfort model [14]—is illustrated in Fig. 7. In all buildings, the envelope acts as

Table 4 Percentage of annual hours where the temperature at each case study city is above and below the 80% thermal acceptability limits

Percentage of annual hours where outdoor air temperature is:	Cartago, Cartago (CC1, CQ1) (%)	Santo Domingo, Heredia (SDH1, SDH2) (%)	Liberia, Guanacaste (GL1, GL2) (%)
Above the upper 80% acceptability limit	0.2	0.3	24.0
Below the lower 80% acceptability limit	56.6	44.2	6.7
Percentage of annual hours between 8 a.m. and 8 p.m. within the 80% thermal acceptability limits	84.0	92.0	76.0

Note: The 80% thermal upper and lower acceptability limits were estimated according to the method specified in the ANSI/ASHRAE 55-2017 Standard: Thermal Environmental Conditions for Human Occupancy [14]. For each case study city, an Energy Plus Weather file (epw) was interpolated using Meteonorm 8.0

a buffer, keeping the internal temperature within a smaller range than the outer. It should be highlighted that the bandwidth between the maximum and minimum temperature conditions narrows toward both extremes.

However, the buildings in Heredia are the only ones that, during both seasons, are within the thermal acceptability zone. This could be attributed not only to the thermal mass but also to the favorable conditions of the local climate. Table 4 shows that in Heredia, the percentage of hot hours—above the upper 80% acceptability limit—throughout the year is less than 1%; while the percentage of cold hours—below the lower 80% acceptability limit—is 45%. Between 8 a.m. and 8 p.m., more than 90% of the time, the internal conditions are situated within the thermal acceptability zone. From this, it could be inferred that the envelope of the two buildings studied in this region could be accumulating heat during the day—when outdoor temperatures are comfortable—and releasing it at night—when dropping below the comfortable limits.

According to the Adaptive model, the temperatures in Guanacaste are 24% of the time above the thermal acceptability zone—upper 80% acceptability limit—and despite the buffering in the hottest hours, indoor temperatures are not comfortable. However, it can be seen that in January, when temperatures are lower, the indoor temperatures of the two buildings located in this area are within the comfort range. Therefore, damping is still beneficial.

In contrast to Guanacaste, the opposite occurs in Cartago, temperatures are low at night, and despite the damping provided by the buildings, releasing heat accumulated during the day at night, the coldest hours are outside the thermal acceptability range. A solution would be to supplement the thermal mass with direct radiation for a short period to improve the interior thermal conditions at this location. The combination of thermal mass and passive heating is a common strategy in upland tropical climates such as Cartago [9].

3.1 Limitations

This research has several limitations, with the main ones listed below:

(i) Due to the method chosen—case studies— it was not possible to isolate the effects of thermal mass. Some factors could not be controlled across all buildings, such as orientation, wall shading, window area, and pattern of use. These elements may affect the rate of heat transfer and the efficiency of thermal mass [27] and might account for the discrepancies found in the thermal behavior of, e.g., churches and family houses in Cartago and Guanacaste.

(ii) Thermal lag—peak delay—is also a good indicator of massive building performance [28]. However, this could not be estimated with the data available.

(iii) The mean radiant temperature (MRT) was not measured due to a lack of instruments. Therefore, to determine thermal acceptability limits, it was assumed that the MRT and air temperature were equal, which is not necessarily true. Due to the effect of thermal mass and ventilation, it is likely during the first hours of the day. The temperature of the walls was lower than that of the air, while the opposite might have happened at night. Future studies should include the measurement of MRT to better approximate thermal comfort conditions.

(iv) A better understanding of the thermal behavior of heavyweight buildings would be possible by comparing them to lightweight buildings located in the same areas, as well as by completing the case studies with computer simulations studies where some of the prior limitations can be overcome.

4 Conclusions

This study set out to determine whether the use of thermal mass in tropical climates increases thermal comfort or not. The thermal performance of six vernacular earth buildings was evaluated, monitoring four houses and two churches in both dry and rainy seasons. The results showed that the buildings were able to dampen peak high and low temperatures by an average of 5 °C (range: 2.7–9.7 °C). Outdoor temperatures were reduced by up to 5 °C at their peak, and the time within the thermal acceptability limits was increased.

The results of this research support the idea that thermal mass can significantly enhance the interior thermal comfort conditions of tropical buildings. However, the achievable improvements cannot be compared with the thermal behavior of archetypal desert dwellings, widely used by academics to represent thermal mass. In the Tropics, due to the climatic conditions, the inside-outside relationship, and thus, ventilation, is part of daily life and the way of living, and, therefore, a determining factor in how buildings will perform. As a result, this study rejects the common argument that thermal mass does not work in the Tropics; it just works differently. This new understanding should help to recalibrate expectations of thermal mass's impact on thermal comfort in the Tropics and open avenues to reintroduce this passive strategy to the repertoire of climate-continuous architects in the Global South.

However, the generalizability of these results is subject to certain limitations. For instance, due to the in-situ measurement method, thermal mass effects on thermal performance could not be isolated. Additionally, due to the limited equipment and data, radiative effects and thermal lag were not assessed. Notwithstanding these limitations and the relatively small sample, this work offers valuable insights into the thermal performance of earthen, large mass buildings in the Tropics. A natural progression of this work would be to investigate the impact of user patterns idiosyncratic to the Tropics and analyze their effect on thermal mass as a passive strategy. More broadly, further research is also needed to determine how these high thermal mass buildings would perform in progressing climate change scenarios to ensure future readiness.

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References

1. Santamouris M, Kolokotsa D (2013) Passive cooling dissipation techniques for buildings and other structures: the state of the art. Energy Build 57:74–94. https://doi.org/10.1016/j.enbuild.2012.11.002
2. González-Cetz M, Gómez-Azpeitia G (2018) Thermal comfort in classrooms in Mexico's hot and humid climate. In: Proceedings of the windsor conference, p 1117
3. Katili A, Boukhanouf R, Wilson R (2015) Space cooling in buildings in hot and humid climates – a review of the effect of humidity on the applicability of existing cooling techniques. In: 4th international conference on sustainable energy technologies – SET 2015, https://doi.org/10.13140/RG.2.1.3011.5287
4. Law T, Fay R (2009) Thermal comfort, productivity and energy consumption in the tropical office environment: a critical overview. In: 43rd annual conference of the architectural science association, ANZAScA 2009, vol 6
5. Santamouris M, Vasilakopoulou K (2021) Present and future energy consumption of buildings: challenges and opportunities towards decarbonisation. e-Prime 100002:100002. https://doi.org/10.1016/j.prime.2021.100002
6. Mastrucci A, van Ruijven B, Byers E, Poblete-Cazenave M, Pachauri S (2021) Global scenarios of residential heating and cooling energy demand and co_2 emissions. Climatic Change 168:14. https://doi.org/10.1007/s10584-021-03229-3
7. Coch H (1998) Chapter 4—bioclimatism in vernacular architecture. Renew Sustain Energy Rev 2:67–87. https://doi.org/10.1016/S1364-0321(98)00012-4
8. Chandel S, Sharma V, Marwah BM (2016) Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions. Renew Sustain Energy Rev 65:459–477. https://doi.org/10.1016/j.rser.2016.07.038

9. Butera F, Adhikari R, Aste N (2015) Sustainable building design for tropical climates. UN-Habitat - UNON, Publishing Services Section
10. Givoni B (1998) Effectiveness of mass and night ventilation in lowering the indoor daytime temperatures. Part I: 1993 experimental periods. Energy Build 28:25–32. https://doi.org/10.1016/S0378-7788(97)00056-X
11. Shaviv E, Yezioro A, Capeluto IG (2001) Thermal mass and night ventilation as passive cooling design strategy. Renew Energy 24:445–452. https://doi.org/10.1016/S0960-1481(01)00027-1
12. Gauthier S, Teli D, James P, Stamp S (2017) Are heavyweight buildings more comfortable? The potential of thermal mass in increasing thermal comfort. In: Proceedings of PLEA2017 passive and low energy architecture, pp 1084–1091
13. Nguyen AT, Tran QB, Tran DQ, Reiter S (2011) An investigation on climate responsive design strategies of vernacular housing in Vietnam. Build Environ 46:2088–2106. https://doi.org/10.1016/j.buildenv.2011.04.019
14. ASHRAE (2017) ANSI/ASHRAE Standard 55-2017 Thermal environmental conditions for human occupancy
15. Saleh PH, Schiano-Phan R, Gleeson C (2017) What heavy weight buildings in hot climates can tell us about their thermal performance. In: Proceedings of the 33rd passive and low energy architecture, p 9
16. Chiou YS, Elizalde JS (2019) Thermal performances of three old houses: a comparative study of heterogeneous vernacular traditions in Taiwan. Sustainability 11:5538. https://doi.org/10.3390/su11195538
17. Dili A, Naseer M, Varghese TZ (2010) Passive control methods of Kerala traditional architecture for a comfortable indoor environment: comparative investigation during various periods of rainy season. Build Environ 45:2218–2230. https://doi.org/10.1016/j.buildenv.2010.04.002
18. Maimagani SS, Majid RA, Leng PC (2022) Thermal performance of classroom block: a comparison of Hobo datalogger and design-builder. J Inf Syst Technol Manag 7:224–237. https://doi.org/10.35631/JISTM.725019
19. Mohamed M, Klingmann A, Samir H (2019) Examining the thermal performance of vernacular houses in Asir region of Saudi Arabia. Alexandria Eng J 58:419–428. https://doi.org/10.1016/j.aej.2019.03.004
20. Yoshino H, Hasegawa K, Matsumoto S (2007) Passive cooling effect of traditional Japanese building's features. Manag Environ Qual Int J 18:578–590. https://doi.org/10.1108/14777830710778337
21. Gutiérrez Rojas ME (2007) La casa de adobes costarrise, 2nd edn. Editorial UCR
22. CFIA (2011) Código sísmico de Costa Rica
23. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130
24. Germer J (1986) Estrategias pasivas para Costa Rica: Una aplicación regional del diseño bioclimático. Imprenta Carcemo
25. CEN (2007) EN 13779-2007. Ventilation for nonresidential buildings, performance requirements for ventilation and room conditioning systems
26. Porras-Salazar JA, Contreras-Espinoza S (2019) Efecto de los revestimientos fríos sobre la temperatura superficial de las cubiertas en el clima cálido-húmedo. REVISTARQUIS 9:70–81. https://doi.org/10.15517/ra.v9i1.40232
27. Du X (2019) Space design for thermal comfort and energy efficiency in summer: passive cooling strategies for hot humid climates, inspired by Chinese vernacular architecture. A+BE — Architecture and the Built Environment
28. Gagliano A, Patania F, Nocera F, Signorello C (2014) Assessment of the dynamic thermal performance of massive buildings. Energy Build 72:361–370. https://doi.org/10.1016/j.enbuild.2013.12.060
29. Flor JF, Espinoza MG, Ramírez FM, Robles MO, Mora VR, Quesada AV (2011) Diseño de la envolvente y sus implicaciones en el confort higrotérmico. Master's thesis, Universidad de Costa Rica

Bioclimatic Comfort Strategies for Typical Meso-Andean Dwellings in Peru

David Resano, Rodolfo Rodríguez, Oscar Guillen, and Ana Galarza

Abstract The Himalayan and Andean mountain ranges are home to some of the highest cities on Earth. According to National Geographic, the highest city in the world is La Rinconada, which is located 5000 m above sea level in the Peruvian Province of Puno. Peru is home to 17 of the 109 world cities located 3000 m or more above sea level with more than 1000 inhabitants. Despite such extreme climatic conditions, the dwellings in these locations do not provide thermal comfort, which can cause respiratory diseases and sometimes lead to premature deaths. An examination of the distribution of the Peruvian population in the Andes shows that most live between 3000 and 4000 m above sea level in the strip known as the Meso-Andean zone. It is a rural area with a low socioeconomic level. This study describes the construction of a typical dwelling in the Meso-Andean rural area and monitors and analyzes its hygrothermal behavior for 1 year. It includes a discussion of the barriers to thermal comfort in the Peruvian Meso-Andean. Several bioclimatic comfort strategies are proposed based on the indoor and outdoor climate.

Keywords Andean weather · Comfort climogram · Energy poverty · Dwellings at altitude

D. Resano (✉) · A. Galarza
Department of Architecture, Universidad de Piura, Piura Campus, Piura, Peru
e-mail: david.resano@udep.edu.pe

A. Galarza
e-mail: ana.galarza.p@udep.edu.pe

R. Rodríguez
Department of Basic Sciences, Universidad de Piura, Piura Campus, Piura, Peru
e-mail: rodolfo.rodriguez@udep.edu.pe

O. Guillen
Civil Engineering Program, Universidad de Piura, Piura Campus, Piura, Peru

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1 Introduction

Due to the geographical location and topographical altitude, several Peruvian regions suffer from extreme weather. The Andean highlands are home to 17 of the 109 world cities located 3000 m above sea level (masl) with more than 1000 inhabitants. The Andes and the Himalayan Mountain ranges have the largest number of high-altitude inhabited municipalities. According to National Geographic, La Rinconada in Peru at 5099 m above sea level is the highest city on the planet [1]. Despite the extreme geographic and climatic conditions, most of the dwellings in Peru have a conventional construction and are not fit for the climatic conditions. Every year, people who live in the high-altitude areas of the Andes in Peru suffer from diseases derived from cold or frost, which can lead to premature death.

Historically, the materials used by Andean cultures to build their settlements have been stone, wood, and vegetable fibers. Evidence of this has been found in archaeological remains, such as those found at Kuelap (Chachapoyas culture, eleventh century, 3000 masl) and in the Inca settlements at Machu Picchu (Inca culture, fifteenth century, 2420 masl). According to the Sociodemographic Profile of Peru, [2], the prevailing materials used in housing construction are brick for facades (55.8%) and reinforced concrete (42.8%) for roofs. After brick, adobe is the most common wall material (27.9%) with corrugated metal or cement fiber panels used for roofing (39.2%) [2, p. 297]. This data shows the constructive reality for the country in general, with brick and slabs predominating in urban areas, and adobe and corrugated panels being used in rural areas (see Fig. 1).

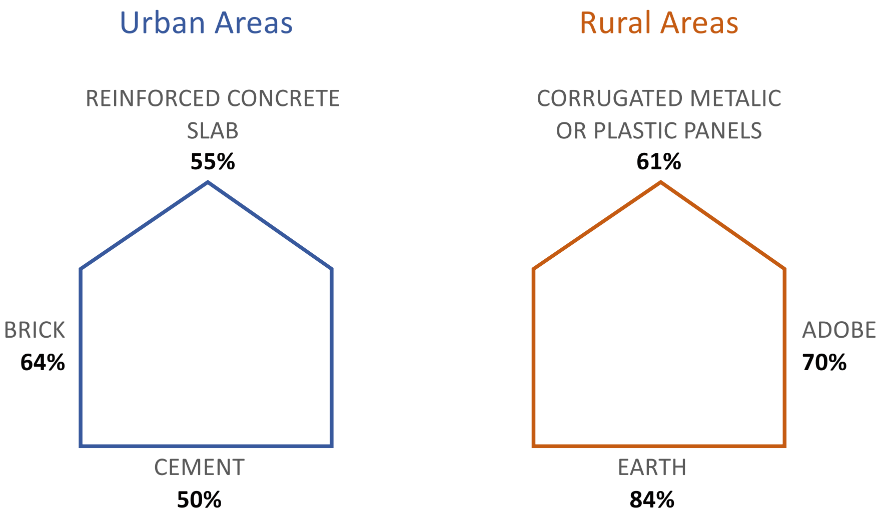

Fig. 1 Prevailing materials for Peruvian dwellings [2]

Currently, Peruvian housing construction generally lacks bioclimatic criteria and construction solutions that have been adapted for the country's climatic diversity. In Peru, there are eight bioclimatic zones distinguished according to their temperature, relative humidity, wind speed and direction, solar radiation, hours of sunshine, precipitation, and altitude. Among them are four cold climate zones located in the Andes, classified by their topographic height as follows: Internandina Baja (2000 to 3000 masl, 12 municipalities), Mesoandina (3000 to 4000 masl, 69 municipalities), Alto Andina (4000 to 4800 masl, 29 municipalities), and Nevado (> 4800 masl, 17 municipalities) [3].

The Meso-Andean strip of Peru has 69 municipalities, the highest number in the country. In this study, a typical dwelling located in Altos de Poclús 3086 masl), in the Andean Plateau of Piura, has been used as the case study. Figure 2 shows an aerial view of this municipality. To improve the quality of life and increase the region's socioeconomic development, it is important to understand the construction and climatic behavior of these dwellings. This is the first step before proposing design strategies to help improve thermal comfort.

Fig. 2 Altos de Poclús, 3086 masl. Frías District, Ayabaca Province, Piura Region, Peru

2 Methodology

The main objective of this study is to establish the most relevant bioclimatic design strategies to be applied to a typical Peruvian Meso-Andean dwelling to overcome barriers to thermal comfort. To do this, the study consists of four phases: typological and constructive analysis of a typical Meso-Andean dwelling, climate analysis, a discussion of bioclimatic strategies based on indoor comfort, and conclusions regarding the main barriers to thermal comfort in these dwellings.

The first phase considers two sources, the national statistical data on buildings in Peru [2] and the measured and redrawn data from a typical dwelling in the Meso-Andean area of the Piura region (Altos de Poclús). This is used as the model to specify functional issues and the constructive execution for this type of dwelling.

The outdoor climate data is taken from meteorological station number 104097, located in Altos de Poclús, which is owned by the Peruvian National Service for Meteorology and Hydrology (Senahmi). This data complements sensors installed inside and outside the model dwelling to monitor temperature, relative humidity, and soil temperature. A FLIR-T540 camera has been used to take thermographic photographs.

The bioclimatic design strategies are for annual humidity and temperature conditions. The Givoni diagram (see Fig. 8) shows the indoor comfort areas (summer and winter) following the Ashrae 2005 standard, and, where possible, other bioclimatic strategies will be applied to establish thermal comfort levels. This diagram was produced using Climate Consultant 6.0 software.

Finally, based on the three previous phases, the study concludes with a summary of the main barriers to energy comfort considered as most relevant for a typical dwelling in the Meso-Andean area of Piura.

3 Construction and Typology of Typical Meso-Andean Housing

For this study, the climatic behavior of a typical rural dwelling at 3,086 masl in Altos de Poclús, in the Andean Plateau of the Piura region (Peru), has been monitored and analyzed. The altitude used corresponds to that of the Meso-Andean strip. Beyond variations in size or room layout, the dwelling has the typical building methods used in rural Andean areas, with adobe on the walls and metal or fiber cement corrugated panels on the roofs (see Fig. 3).

Figure 4 shows the Tocto family dwelling's floor plan and elevations. It was built with 26-cm-thick adobe load-bearing walls, and a wooden beam structure covered with corrugated fiber cement sheets. The walls and partitions are load bearing. The dwelling consists of interior habitable spaces such as bedrooms, kitchen, dining room, and living room. It has inner non-habitable corridors and storerooms, and next to the entrance there is a partially covered outdoor patio. Mr. Tocto designed the layout

Fig. 3 Tocto Family Dwelling in Altos de Poclús, September 2021

considering his family's current needs and allowing for growth. Thermal comfort was not considered, as outlined in Sect. 2.

Given that Peru is home to some of the highest populated areas on the planet, it is remarkable that most dwellings are still without specific thermal insulation or waterproofing layers. In addition, these dwellings do not have active environmental conditioning installations either, having, in the best of cases, a wood-burning hearth or a similar device dedicated fundamentally to cooking, but without consideration for indoor thermal comfort.

Scarce or low levels of public infrastructure development make it difficult to implement active energy production systems in these areas. Consequently, bioclimatic design strategies to achieve indoor comfort are important, as shown in Sect. 5.

4 Outdoor and Indoor Climate Monitoring

In this section, the monitoring of the outdoor climate and the thermal behavior of the model dwelling is explained.

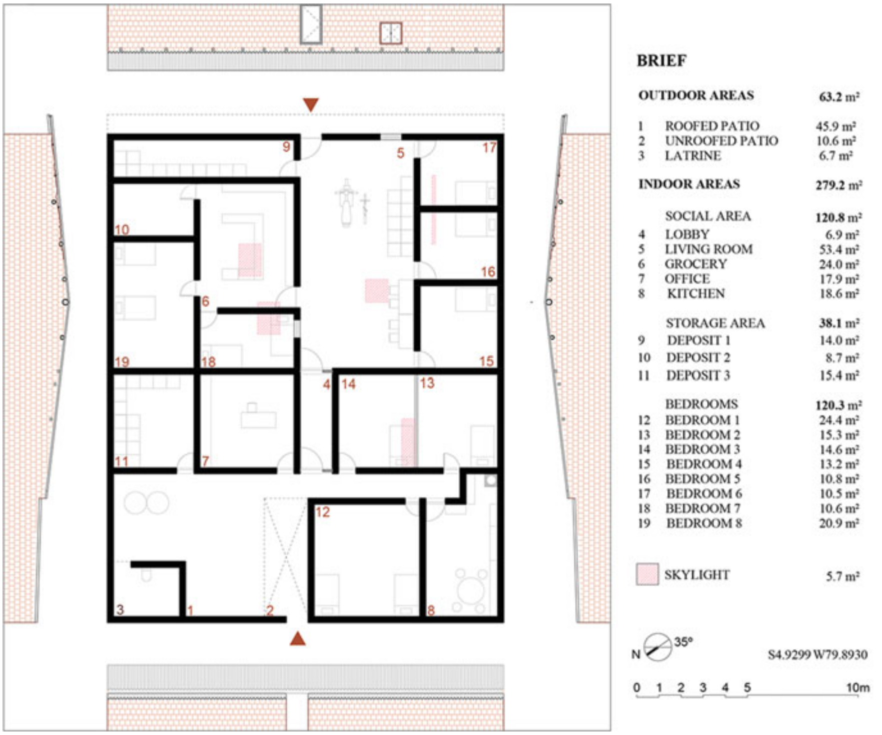

Fig. 4 Floor plan and elevations of the Tocto family dwelling

4.1 Outdoor Climatic Conditions in the Meso-Andean Strip

The climogram in Fig. 5 for Alto de Poclús shows the data collected and reported by the SENAMHI meteorological station—Ordinary Climatology code 104097, latitude 04°55′01″S, longitude 79°53′25″W, altitude 3086 msnm, Frias District—for the Ayabaca Province, Piura Region Basin, and Yapatera River.

The maximum temperature reaches 19 °C, while the minimum is above 2 °C. The average temperature of around 10 °C is practically stable throughout the year. As for rainfall, there is a dry season between May and August, with rain falling during the rest of the year.

4.2 Hygrothermal Behavior of the Typical Dwelling

Figure 6 shows the results from monitoring the indoor climate of the model dwelling for 1 year against the outdoor climate. The measurements are monthly absolute

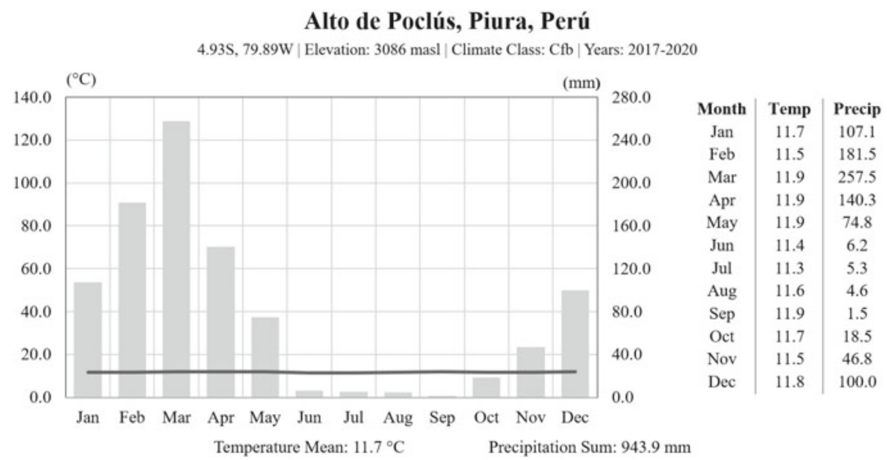

Fig. 5 Climogram for Altos de Poclús based on data from SENAMI (Station 104097)

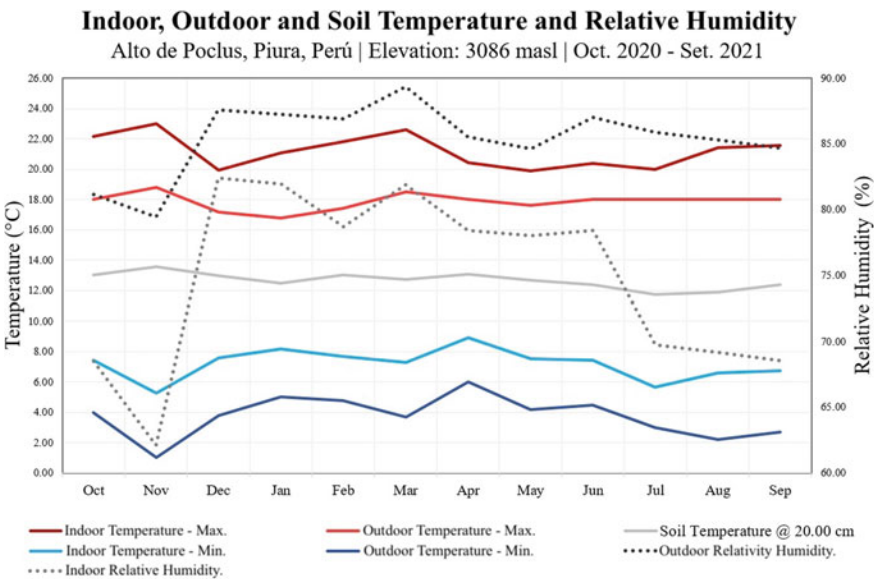

Fig. 6 Indoor hygrothermal behavior of the model dwelling compared with outdoor climate. The values indicated are monthly absolute maximums and minimums. Data from October 2020 to September 2021

maximum and minimum values with the following parameters: air temperature, soil temperature at 20 cm, and average relative humidity.

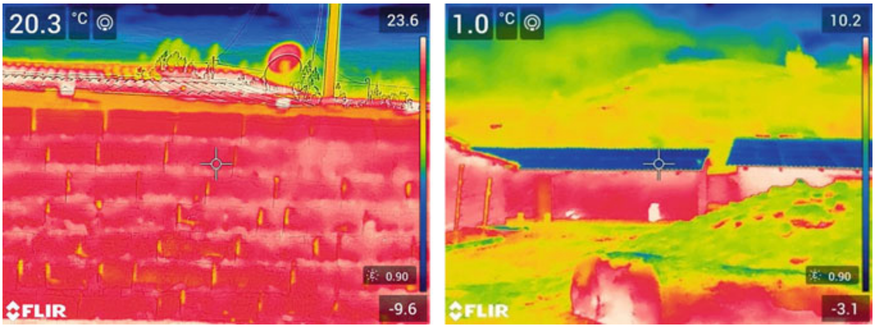

Fig. 7 Thermal photographs of dwellings in Altos de Poclús. On the left, the reference dwelling during the middle of the day. On the right, at dawn on October 3, 2020, at 3:43 am

The ground temperature remains almost constant at 12 °C, while the air temperature fluctuates widely between day and night. This is a clear sign that the dwelling has low thermal insulation due to the roofing material. In addition, the indoor temperature oscillates almost in unison with the outdoor with hardly any lag, due to the low general thermal inertia in the dwelling. Indeed, the indoor thermal amplitude is practically the same as the outdoor almost every month, resulting in a thermal stability coefficient (t.s.c) of around one, typical for constructions without thermal inertia. During the night, the indoor air temperature is only a couple of degrees higher than the outdoor, which indicates the poor performance of the dwelling against the cold. However, the maximum indoor air temperature values during the day exceed those taken outside. The building collects solar radiation, mainly because of the roof's light fiber cement and plastic material, losing it at night.

The thermal envelope of these dwellings has two deficiencies, evident in the thermographic photographs shown in Fig. 7. The walls are not airtight and the ceilings show a lack of thermal performance.

It is striking that the vertical enclosures of the dwelling have hardly any windows. As can be seen in Fig. 4, there is only one in the social area on the southeast façade. This could indicate that the dwelling is airtight but lacks the necessary ventilation to renew the air. However, in fact, the opposite occurs. The envelope is not airtight, fundamentally due to the constructive joints between each element—the roof and walls, the walls and doors, and between the adobe blocks. The thermographic photograph on the left in Fig. 7 shows this. This lack of tightness is a barrier to thermal comfort in such a relatively cold climate.

As for daylight, this enters through the translucent corrugated plastic skylights that have replaced the usual fiber cement ones, as indicated in red in Fig. 4. The roof of the dwelling has an area of 360 m^2, of which the surface of the illuminated ceilings is 5.6 m^2. These translucent roofs help to capture solar radiation, which heats the interior air in the middle of the day, Fig. 6. However, the roofing becomes a cold spot at night due to its low mass and thermal resistance. The thermal photograph on the right in Fig. 7 shows how the roof reaches radiant temperatures below zero at night when the outdoor air temperature is between 2 and 6 °C (see Fig. 6).

5 Bioclimatic Strategies for the Peruvian Meso-Andean Strip

This section focuses on bioclimatic strategies to improve the hygrothermal behavior of a typical Meso-Andean dwelling. It is important to stress the term bioclimatic, as the goal of this study is not to provide additional energy to improve comfort. Instead, it is about profiting from climate conditions through construction and architectural design. This approach is aligned with the global trend toward energy efficiency to mitigate climate change. In this case, it is also imperative given the scarcity of economic resources and infrastructure in the Peruvian Andean rural context.

The main design strategies to adapt these dwellings to their climate are shown in the Givoni diagram in Fig. 8. The summer and winter comfort zones are indicated in blue, taking the indoor comfort parameters from the ASHRAE 2005 standard [4]. The diagram shows that the outdoor climate corresponds to comfort conditions only 2.6% of the time. During the remaining 97.4%, it is necessary to implement hygrothermal conditioning measures, whether active (46.1%) or passive (51.3%). Among the passive bioclimatic design measures, the greatest impact is from internal solar gain (40.45%) and heat capture through thermal inertia (11.85%). These two bioclimatic measures are related to the specific dwelling in this study.

The Givoni diagram in Fig. 8 and the temperatures indicated in Fig. 6 show how the maximum temperatures are not an inconvenience, being within the comfort zone nearly all year round except for July and August. However, the outdoor average and minimum air temperatures are only comfortable for 225 h a year. Consequently, as mentioned, the most relevant passive strategy to achieve climatic comfort in the Meso-Andean climate is clear, which is to take advantage of solar gains and limit energy loss due to the thermal envelope. Indoor comfort is possible almost half of the year by capturing solar energy. That is why this section mainly focuses on measures of this type, such as the following five: the layout and orientation of the outdoor glazed openings, both on façades and roofs; the avoidance of obstacles that cast shadows on the building; consideration of the thermal properties of the opaque enclosure, fundamentally the insulation and thermal inertia; an evaluation of the degree of compactness of the dwellings; and the study of the distribution of the layout to optimize the location of living spaces.

The next paragraphs discuss how these five measures can be viably implemented in the type of dwelling studied.

Solar gains could be increased by placing more north-facing windows, for the coldest months of the southern winter. In this sense, roof skylights are suitable since they favor solar capture throughout the year [5]. According to Givoni's diagram, the solar protection of the facade and roof openings would only be necessary for 19 h in

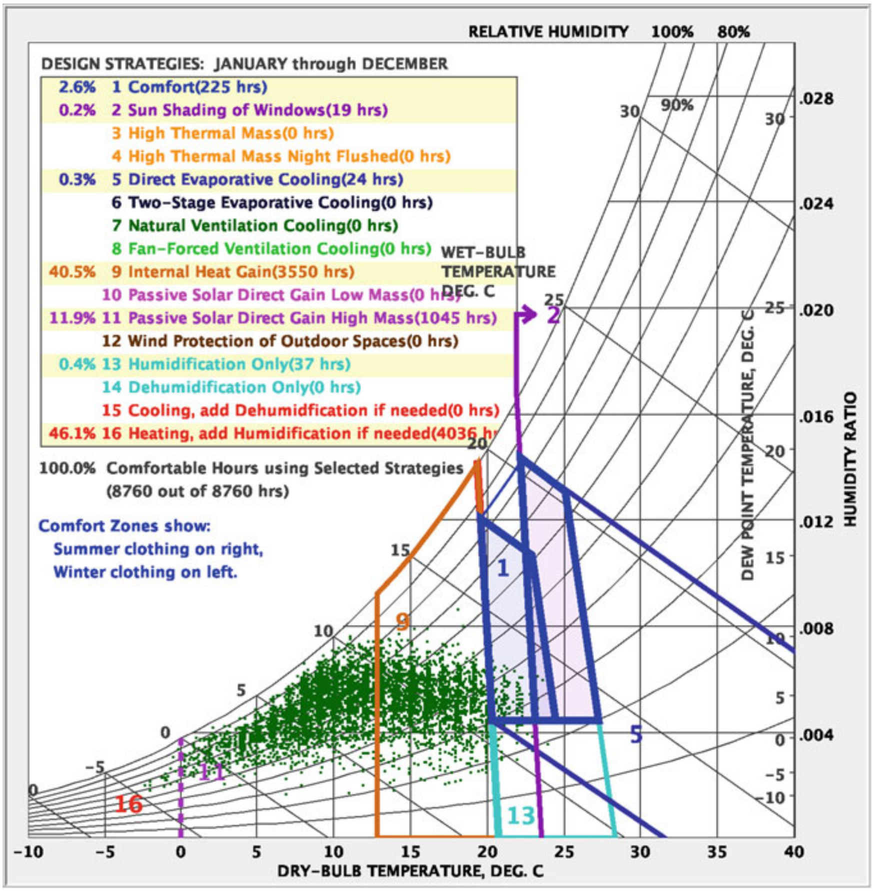

Fig. 8 Givoni climogram for the Meso-Andean climate indicating the main bioclimatic strategies and the percentage of annual time where they would be effective (Climate Consultant 6.0)

summer, so it would not be an essential measure. Additionally, natural or artificial obstacles that produce shade on the glass enclosures should be avoided. The low temperatures during almost the entire year in the Meso-Andean areas indicate that it is essential to collect solar heat through windows or skylights at higher topographic altitudes and that solar gains are welcome all year round.

But this solar capture would be useless without adequate thermal resistance that allows heat to be conserved until the coldest hours of the day and night. Considering a thermal conductivity of 0.9 W K/m for adobe, according to data from the RNE-EM.110 standard, the thermal transmittance (U) of a 26 cm adobe wall is 2.33 W/(m^2 K). Regarding the 5 mm roofing fiber cement corrugated panel for the thermal conductivity indicated in RNE-EM.110 of 0.225 W K/m, the U-value is 6.16 W/(m^2 K). Undoubtedly, thermal ceiling insulation in this type of dwelling is urgently needed.

In the second instance, wall transmittance could be reduced, following the thermal inertia effect, as discussed later. In addition to thermal insulation, another fundamental measure to conserve the solar radiation captured is to increase the compactness of dwellings. Reducing the thermal envelope surface considering the volume of interior space would reduce the heat transfer process gained by radiation between the outside and inside, and favor heat conservation. The studied dwelling's interior volume is 782.4 m^3, and the envelope surface is 849.7 m^2, obtaining a compactness factor of 0.92. It would be advisable to look for compactness levels of at least above one [6].

According to the Givoni climogram, improving thermal inertia would result in a possible increase of 1045 h/year in thermal comfort. The adobe wall thermal-useful mass (mtu) is 1.81 × 106 kg/J, with a thermal lag (DT) of 4.02 h. Their behavior could be optimized so that the DT would not arrive until the night hours. Undoubtedly, the weak point in these dwellings is the roof. The fiber cement sheets used for the roofs have hardly any thermal mass, 0.18 x 106 kg/J, and their thermal lag is almost zero, 0.16 h. As mentioned in Sect. 2, the current thermal stability coefficient (t.s.c) for the dwelling is around one, typical of indoor environments without thermal inertia. The recommendation would be to reduce the t.s.c of the dwelling to 0.5, to ensure that the indoor thermal amplitude is at least half that of the outside. Using covers with greater mass could solve this issue. Designing roof construction systems with resistance and thermal inertia adapted to the socioeconomic levels of these populations would be a relevant measure to achieve thermal comfort.

The thermal comfort of habitable areas is optimizable through two fundamental strategies. First, by placing rooms that are not thermally conditioned, such as garages or storerooms, next to the outside walls facing the predominant winds, which in this study is southeast. Secondly, the inclusion of sunny and wind-protected yards next to living rooms would help heat the outdoor air for indoor ventilation.

Finally, it must not be forgotten that above 3000 masl, it is difficult to achieve comfortable conditions without additional energy inputs. According to the Givoni climogram, there are 4036 h/year when it is necessary to use active heating systems. Insofar as most of these hours correspond to the night and early morning, the objective would be to maximize heat capture by radiation during the day and then transfer it to the dwelling at night.

6 Conclusions

As mentioned in the previous section, the analysis of a typical Meso-Andean dwelling and its behavior in its climate highlights the need to adopt bioclimatic strategies at the design stage to achieve thermal comfort. Undoubtedly, some barriers hinder the implementation of these thermal comfort measures. To improve the quality of life for the population who live in dwellings in this region, the challenge is to gradually overcome the barriers with solutions adapted to their socioeconomic and cultural realities. A discussion of those that are most relevant follows.

The high altitude is a factor that determines the fundamental parameters of the climate. The higher the altitude, the greater the need to heat dwellings, and the less possible it is to achieve thermal comfort with only passive measures. Therefore, active heating measures become more essential as the altitude increases. However, the low economic resources of the population in these areas, as well as the lack of energy infrastructure, constitute energy barriers for conventional active systems. To achieve hygrothermal well-being inside homes throughout the year at higher altitudes, it is necessary to study heating systems based on renewable energies, such as solar radiation.

The construction materials currently used in the dwellings are not suitable for cold climates. Adobe has good behavior for thermal inertia, but a relatively high thermal conductivity compared to other insulating materials [7]. The materials used for the roof are even worse since their thermal resistance is almost zero, and they also lack thermal inertia. The limit value set by the current Peruvian standard for voluntary compliance for thermal transmittance in the Meso-Andean climate is 2.36 W/(m^2 K) for walls and 2.21 W/(m^2 K) for ceilings [3]. The 25 cm adobe walls have a transmittance rate of 2.33 W/(m^2 K) and the corrugated fiberboard ceilings of 6.16 W/(m^2 K). The values for the Peruvian standard are conservative, and yet still, the construction systems of the current Meso-Andean dwellings are a long way from complying with them. In this case, implementing thermal insulation in opaque enclosures, especially roofs, is an essential measure. Without the appropriate insulation thickness, the possible gains obtained from the capture of solar radiation would not affect indoor comfort.

In addition, some improvements in how the work is executed are essential. Generally, Meso-Andean villagers build their own homes, sometimes with the support of a local builder. It is crucial that they pay attention to fundamental issues such as air leaks from the thermal envelope. As mentioned, it is common to leave unsealed joints where the ceiling meets the walls, where the carpentry meets opaque enclosures, and even in the construction joints between adobe sections. Therefore, it is necessary to educate and make the builders and users of these dwellings aware of behaviors favoring a use regime that improves thermal conditions and indoor comfort.

Peru is a diverse country, where three main ecosystems coexist: the Pacific desert coast, the high Andean Mountain zone, and the Amazon jungle zone. In fact, according to the Thornthwaite classification [8], there are 38 different climates in Peru. Despite this geographic and climatic diversity, statistical studies of Peruvian dwellings show that their construction does not consider the climate to which they are exposed. The official bodies do not collect statistical data about weather and climatic zone information that would help address the relationship between current construction systems and their suitability from the point of view of thermal comfort.

Undoubtedly, it is necessary to investigate the application of thermal insulation systems and installations adapted to these climates, as well as the socioeconomic and cultural reality. Generally, communities dedicated to agriculture, livestock, or mining live in the Andean areas and do not have the resources or technology to overcome the barriers to thermal comfort. Investigating insulation, airtightness, and hygrothermal conditioning systems that are of low cost and a constructive implementation adapted to a particular way of life is essential for overcoming the current barriers to thermal comfort in these dwellings.

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References

1. West JB (2002) Highest permanent human habitation. High Altitude Med Biol 3:401–407. https://doi.org/10.1089/15270290260512882
2. Instituto Nacional de Estadística e Informática (2018) Perú: Perfil Sociodemográfico. Informe Nacional. Censos Nacionales 2017: XII de Población, VII de Vivienda y III de Comunidades Indígenas. https://www.inei.gob.pe/media/Menu-recursivo/publicaciones_digitales/Est/Lib1539/
3. Ministerio de Vivienda Construcción y Saneamiento (2014) RNE-EM.110. Reglamento Nacional de Edificaciones de Perú. Confort térmico y lumínico con eficiencia energética
4. ASHRAE (2005) 2005 ASHRAE HANDBOOK. Fundamentals
5. Hamdan MA (1994) Thermal gains through windows. Energy Convers Manag 35:501–506. https://doi.org/10.1016/0196-8904(94)90091-4
6. Catalina T, Virgone J, Iordache V (2011) Study on the impact of the building form on the energy consumption. In: 12th conference of international building performance simulation, pp 1726–1729
7. Cagnon H, Aubert J, Coutand M, Magniont C (2014) Hygrothermal properties of earth bricks. Energy Build 80:208–217. https://doi.org/10.1016/j.enbuild.2014.05.024
8. Servicio Nacional de Metereología e Hidrología del Perú (2020) Climas del Perú. Mapa de clasificación climática nacional, Resumen ejecutivo

The Thermal Behaviour of Educational Buildings in the Tropical Andes. A Case Study of the Millennium Educational Units of Ecuador

María Isabel Vivanco-Villavicencio and Maureen Trebilcock-Kelly

Abstract Studies show that children are more vulnerable than adults to the effects of low and high temperatures. They spend a lot of time every day in educational buildings, making it essential to take steps to mitigate health and comfort risks in school classrooms. In this context, this chapter addresses the thermal behaviour and comfort of school buildings located in the tropical Andes. The case study is the "Millennium Educational Units" (Unidad Educativa Milenio-UEM) school typology, which has been built in different climates throughout Ecuador. An evaluation was made of three UEM cases, which integrated passive strategies, considering the different climates found in the country. The methodology was based on an analysis of UEMs and their occupants, using observation and evaluating thermal behaviour. The database used for the analysis was obtained from climate files; the calculation of the adaptive comfort range and thermal simulation, based on domestic and international standards. This study demonstrates the importance of including sustainable passive strategies in educational buildings and thereby contributes to improving the comfort and performance of its occupants.

Keywords Environmental comfort · Educational buildings · Tropical Andes

1 Introduction

People spend 80–90% of their lives inside buildings [1], hence the relevance of studying environmental comfort as an important factor for health. In Latin America,

M. I. Vivanco-Villavicencio (✉)
Universidad Técnica Particular de Loja, Loja, Ecuador
e-mail: isabelvivancoarq@gmail.com

M. Trebilcock-Kelly
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mtrebilc@ubiobio.cl

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Fig. 1 UEM Bernardo Valdivieso de Loja Millennium Educational Unit

67.5% of buildings are uncomfortable [1], so there is a need to improve design processes, construction standards and regulations, as well as to guide their users so that comfortable and healthy indoor environments can be achieved.

However, studies have shown that children are more vulnerable than adults to the effects of low and high temperatures. They spend a lot of time every day in educational buildings, making it essential to take steps to mitigate health and comfort risks in school classrooms [2]. Studies recommend that standards consider the impact of both temperature and CO_2 levels on perceived indoor environmental quality, as these affect children's overall comfort and fatigue levels.

Since 2012, Ecuador has established a public policy to provide school infrastructure to all the country's regions. The Ministry of Education and the Undersecretariat of School Administration—the entity in charge of planning and improving educational infrastructure—promoted a standardized infrastructure called Millennium Educational Units (Unidad Educativa Milenio—UEM) (see Fig. 1), to offset the lack of educational infrastructure in underdeveloped sectors. The aim was to improve educational quality and equity. The UEM typology consists of a classroom block that has been built across the country with little variation in terms of design and building properties. It has been located in different climatic regions of Ecuador, without properly assessing its ability to provide thermal comfort to students.

The typologies are based on different education levels with four variants: a Major Educational Unit with a capacity of 1140 students per day; a Minor Educational Unit with a capacity of 570 students per day; Multi-teacher Exception Infrastructure and Two-Teacher Exception Infrastructure [3, 4]. To face the increasing student demand, the Ecuadorian Ministry of Education built 65 UEMs until 2016, from a total of 324 UEMs planned throughout the country. According to Ponce and Drouet [5], the investment in standardized public infrastructure is significant. Each major UEM benefits 1140 students at a cost of around US$6.3 million, while every minor UEM benefits 570 students at a cost of around US$4 million. The planning process includes specific urban planning consultations to determine requirements for services and urban infrastructure. However, it does not consider aspects of thermal comfort and climate adaptation.

This paper aims to assess the integration of passive design strategies to improve the thermal performance of the UEM classroom block prototype for three natural regions in Ecuador's zone 7: El Oro, Loja, and Zamora Chimchipe. It is expected that this study can contribute to the future development of UEMs with quality standards that consider indoor environmental quality and student comfort.

2 Methodology

To achieve the goal outlined, the methodology consisted of making thermal simulations of three case studies of Millennium Educational Units and proposing appropriate passive design strategies for each case/climate.

2.1 Case Studies

Continental Ecuador is located on the northwestern coast of South America and is divided into four natural regions: the Coast Lowlands (Región Costa), Andean Highlands (Región Sierra), the Amazon Rainforest (Región Amazónica) and the Island Region (Región Insular), which in this chapter will be referred to as the Coast, Sierra, Amazon and Insular regions. Several factors such as altitude, the equatorial line and the Andes mean the country has a variety of climates and microclimates throughout each of its regions, where temperatures can exceed 38 °C and reach as low as 2 °C. The three case studies are located in administrative zone 7 in southern Ecuador, comprising the provinces of El Oro, Loja, and Zamora Chinchipe. This zone is the only one that covers three natural regions—Coast, Sierra and Amazon—with short distances between them. The UEMs are not heated or cooled, so thermal behaviour depends purely on architectural design and occupant behaviour (see Fig. 2 and Table 1). To evaluate the case study, the calculation of comfort range limits is made based on the ASHRAE 55 adaptive model, considering average outdoor temperatures [6]. It is important to note that in these tropical climates there is no temperature variation throughout the year, so the annual average temperature determines the adaptive comfort range (see Table 2).

2.2 Thermal Simulation

With the data obtained from the comfort range limits and the classroom block's technical parameters, a thermal simulation analysis was carried out using the TAS "Thermal Analysis Simulation" software, which allowed diagnosing the thermal behaviour of each UEM classroom block. Each block has 12 classrooms of 70 m^2

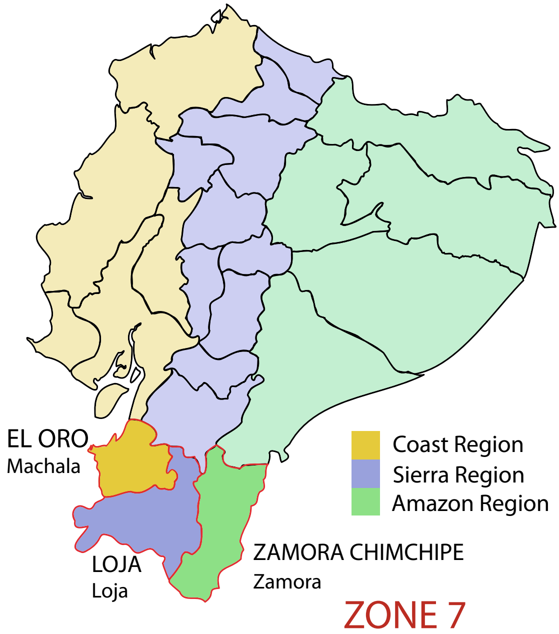


Fig. 2 Location of the case studies in three climatic regions of Ecuador's zone 7

Table 1 Location of the case studies

Case study	City	Natural region	Admin zone	Climate zone (NEC 2011)	Climate zone (NEC 2018)
UEM 9 de Octubre	Machala	Coast	El Oro	ZT6	1
UEM Bernardo Valdivieso	Loja	Sierra	Loja	ZT3	2
UEM Arutam	El Pangui	Amazon	Zamora Chinchipe	ZT5	3

NEC 2011: NEC-11 Chapter 13, 2011 [7]. NEC 2018: NEC-HS-EE, 2018 [8]

that are 4 m high. Each classroom is used by 40 students and 1 teacher in three shifts. The thermal simulation parameters for each case are detailed in Table 3.

2.3 Passive Design Strategies

The last stage of the methodology consisted of developing a passive design strategies matrix to improve the typology considering the specific characteristics of each climatic region. The strategies comprised the thermal protection of the envelope (roof,

Table 2 Climatic data and calculation of comfort range

NATURAL REGION/City/Case	Alt. (masl)	T_{min} (°C)	T_{aver} (°C)	T_{max} (°C)	$T_{Comfmin}$ (°C)	$T_{Comfmax}$ (°C)
COAST/Machala/UEM 9 de Octubre	5	19.00	25.21	29.15	22.12	29.12
SIERRA/Loja/UEM Bernardo Valdivieso	2145	11.50	16.35	21.4	19.37	26.37
AMAZON/El Pangui/UEM Arutam	775	17.10	22.80	28.15	21.37	28.37

Note: Data obtained from the National Meteorology and Hydrography Institute—INAMHI
T_{min}: minimum outdoor temperature
T_{aver}: average outdoor temperature
T_{max}: maximum outdoor temperature
$T_{Comfmin}$: minimum comfort temperature
$T_{Comfmax}$: maximum comfort temperature

Table 3 Parameters for thermal simulation

Location of the UEMs	Coast Region Machala	Sierra Region Loja	Amazon Region El Pangui
Ventilation systems	Natural	Natural	Natural
Average wind speed (m/s)	0.31	0.83	0.56
Metabolic rate (MET)	1.30	1.30	1.30
Clothing (CLO)	0.50	1	0.50
Occupancy	Monday to Friday (07:00 to 22:30)	Monday to Friday (07:00 to 22:30)	Monday to Friday (07:30 to 20:30)
Window-to-wall ratio (%)	32.4	32.4	32.4
Floor area (m^2)	70	70	70
Wall area (m^2)	40	40	40
Window area (m^2)	12.9	12.9	12.9

Note: Data obtained from the 2015 Technical Standards for the Design of Educational Environments

wall, floors and windows), passive solar energy and natural ventilation. This was developed based on domestic and international regulations.

Using the TAS software tool, the thermal behaviour of the improved educational units was evaluated and analysed based on the strategies proposed in the matrix, determining indoor temperatures.

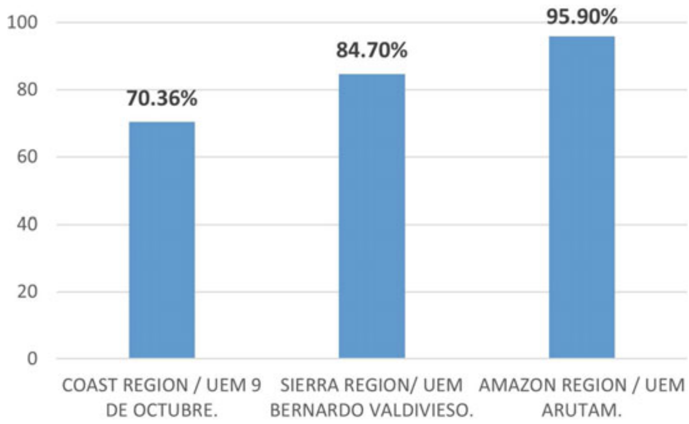


Fig. 3 Percentage of time within the adaptive comfort range

3 Results

The results of the first thermal simulation of the three cases are shown in Fig. 3. The percentage of time that the indoor temperature remains within the comfort range established by the adaptive method [6] for each climate shows important differences between the three cases. The UEM Arutam case in the Amazon Region has the best thermal performance with 95.9% of the occupancy time within the 21.37–28.37 °C range. In contrast, UEM 9 de Octubre, located in the Coast Region, has the worst thermal performance with 70.36% of the occupancy time within the 22.12–29.12 °C range.

According to the simulation, the UEM located in the Coast Region, with indoor temperatures reaching 38 °C, does not adequately reach thermal comfort for its occupants, while the UEMs in the Sierra and Amazon require some improvements. The application of passive strategies that look to improve the thermal comfort of school classrooms is key. Passive strategies were proposed based on domestic and international studies and regulations: Ecuadorian Construction Standard [7], Chilean Thermal Regulation Standard [9], Energy Efficiency Guide for Educational Establishments [10] and the Manual for Passive Design and Energy Efficiency in Public Buildings [11].

A set of different strategies was foreseen, including solar shading, cross ventilation, improved thermal transmittance and ventilated walls. The best strategies for each case are highlighted in Fig. 4.

The results of the thermal simulation are shown in Fig. 5, which compares the base case against the improved case with passive strategies. The UEM in the Coast Region, with a comfort range between 22.12 and 29.12 °C, showed an improvement

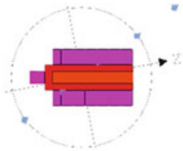
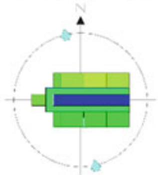
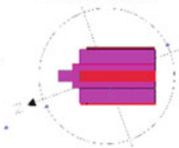
	Orientation	Thermal transmittance U-value (W/m^2K)	Glazing properties
COAST REGION			
BASE CASE	EAST-WEST	U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
NEC-11 Ch. 13		U roof: 0.74 U wall: 2.76 U floor: 2.84	SINGLE TS: 0.69 U: 5.7
NRTC		U roof: 0.82 U wall: 2.76 U floor: 2.07	DOUBLE TS: 0.05 U: 3.46
STRATEGY 2 (Solar shading and cross ventilation)		U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
STRATEGY 2+3+6 (Solar shading, cross ventilation, U value, and ventilated walls)		U roof: 0.21 U wall: 0.43 U floor: 3.83	SINGLE TS: 0.05 U: 6.39
SIERRA REGION			
BASE CASE	NORTH-SOUTH	U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
NEC-11 Ch. 13		U roof: 1.59 U wall: 1.53 U floor: 1.44	SINGLE TS: 0.69 U: 5.7
NRTC		U roof: 0.56 U wall: 2.76 U floor: 0.88	DOUBLE TS: 0.19 U: 2.13
STRATEGY 3 (Thermal transmittance)		U roof: 0.56 U wall: 0.52 U floor: 3.83	DOUBLE TS: 0.19 U: 2.13
AMAZON REGION			
BASE CASE	EAST-WEST	U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
STRATEGY 2 (Solar shading and cross ventilation)		U roof: 1.59 U wall: 2.76 U floor: 3.83	SINGLE TS: 0.69 U: 5.7
STRATEGY 2+6 (Solar shading, cross ventilation, and ventilated walls)		U roof: 1.59 U wall: 0.58 U floor: 3.83	SINGLE TS: 0.69 U: 5.7

Fig. 4 Passive strategies matrix for each region

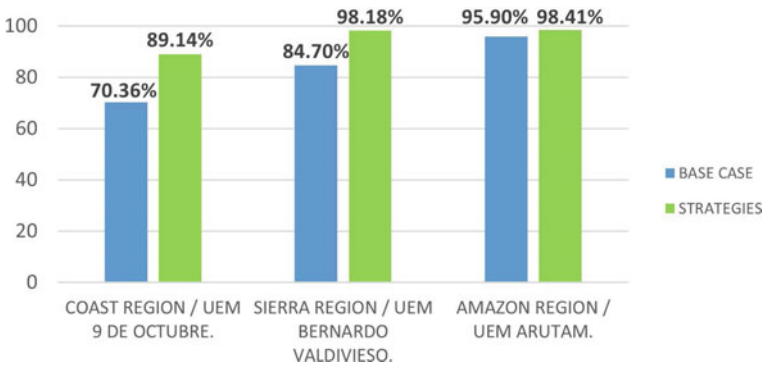


Fig. 5 Percentage of time within the adaptive comfort range

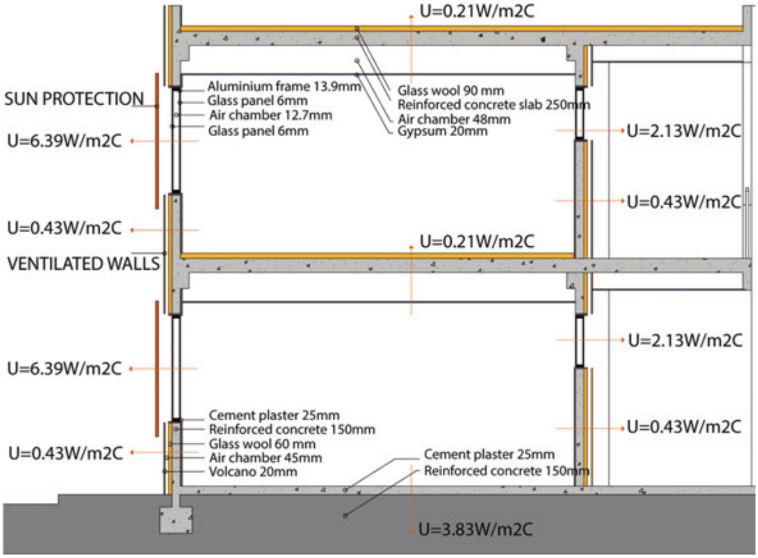


Fig. 6 Passive improvement strategies for the Coast Region classroom block

of 18.78%, while the maximum temperature dropped from 35 to 29 °C. The UEM in the Sierra Region, with a comfort range between 19.37 and 26.37 °C, improved by 13.48%, and was nearly all the time within the comfort range, while the minimum temperature increased from 14 to 19 °C. Finally, the UEM in the Amazon Region, had a comfort range between 21.37 and 28.37 °C, the percentages increased by 2.51% and the temperature decreased from 28 to 25 °C.

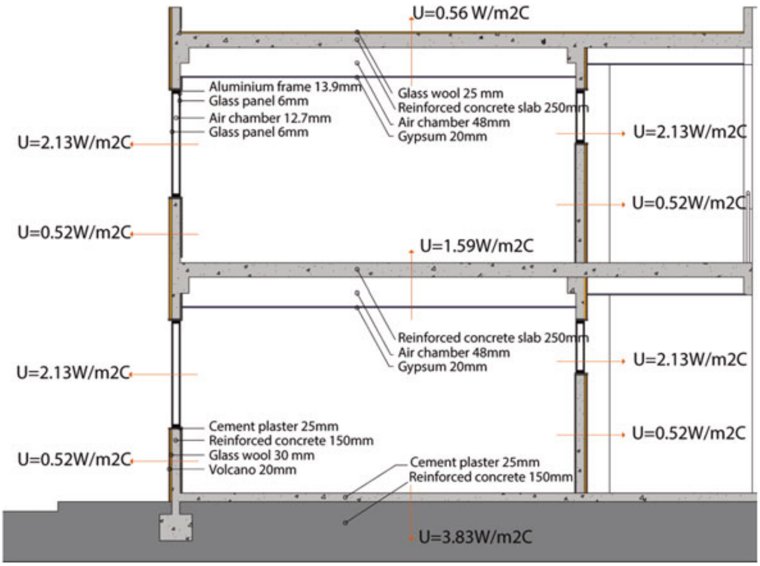


Fig. 7 Passive improvement strategies for the Sierra Region classroom block

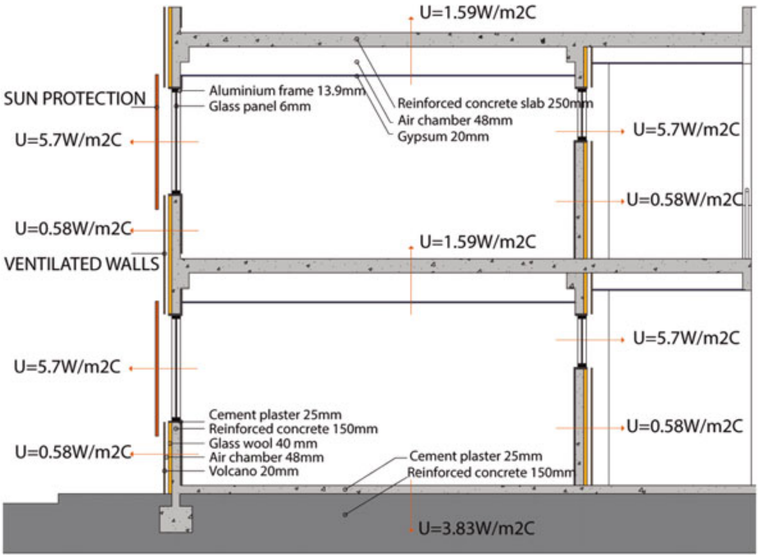


Fig. 8 Passive improvement strategies for the Amazon Region classroom block

Regarding the recommendations to improve the thermal performance of UEMs, Fig. 6 shows that in the Coast Region, STRATEGY 2+3+6, which includes solar shading, cross ventilation, improved thermal transmittance and ventilated walls, ensures comfortable temperature conditions and indoor air renewal, and, therefore, improves student performance and comfort.

In the Sierra Region, STRATEGY 3, which includes improved thermal transmittance (See Fig. 7), allows increasing the percentage of time that children would be within the comfort range, avoiding the phenomenon of cold walls, and reducing air movements.

Figure 8 shows the strategies proposed for the Amazon Region (STRATEGY 2 + 6) that include solar shading and ventilated walls and would allow reducing relative humidity conditions, which is an important factor in this region.

4 Conclusions

Considering the locations of the study, chosen based on their most extreme climates, altitude and humidity of the three natural regions of Zone 7, it is concluded that the UEM typology performs better in the Amazon Region and worse in the Coast Region. The application of passive design strategies such as solar shading, cross ventilation, thermal transmittance and ventilated walls allows improving the thermal performance of UEMs by 18.78% in the Coast Region. Therefore, the application of passive improvement strategies should be considered, which will serve as a guide for future standardized UEM construction in Ecuador.

In this context and considering that children are more vulnerable than adults to high- and low-temperature conditions, it is not appropriate to standardize the construction of UEMs in Ecuador, since the climatic conditions are different for each natural region; therefore, there must be a specific design that takes into consideration aspects such as context and climate and can meet the comfort requirements inside the classroom.

Finally, this research can contribute as a guide for the applicability of similar studies for public infrastructure standards of other state entities in the country or other similar contexts that allow removing environmental comfort barriers.

References

1. Valderrama-Ulloa C, Silva-Castillo L, Sandoval-Grandi C, Robles-Calderon C, Rouault F (2020) Indoor environmental quality in Latin American buildings: a systematic literature review. Sustainability 12:643. https://doi.org/10.3390/su12020643
2. Korsavi S, Montazami A, Mumovic D (2021) Perceived indoor air quality in naturally ventilated primary schools in the UK: impact of environmental variables and thermal sensation. Indoor Air 31:480–501. https://doi.org/10.1111/ina.12740
3. Ministerio de Educación (2016) Criterios de ubicación y tipologías ecuador. http://educacion.gob.ec/criterios-de-ubicacion/, Accessed 17 Jan 2016
4. Ministerio de Educación (2016) Unidades educativas del milenio, construidas, en construcción y por construirse. http://educacion.gob.ec/uem-en-construccion/, Accessed 18 Jan 2016

5. Ponce J, Drouet M (2017) Documento de Política No 01-2017 (MINEDUC). Evaluación de Impacto del Programa de Escuelas del Milenio. Ministerio de Educación. https://educacion.gob.ec/wp-content/uploads/downloads/2017/08/Evaluacion-de-Impacto-del-Programa-de-Escuelas-del-Milenio.pdf
6. ASHRAE (2010) ANSI/ASHRAE 55–2010: thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers
7. Ministerio de Desarrollo Urbano y Vivienda (2011) NEC-11: Norma Ecuatoriana de Construcción. Capítulo 13: Eficiencia Energética en la Construcción en Ecuador, Decreto Ejecutivo Nro. 705. Ecuador
8. Ministerio de Desarrollo Urbano y Vivienda (2018) NEC-HS-EE: Norma Ecuatoriana de Construcción. Eficiencia Energética en Edificaciones Residenciales (E), Acuerdo Ministerial Nro. 004-18. 05. Ecuador
9. Ministerio de Vivienda y Urbanismo (2006) Normativa de Reglamentación Térmica Chile. Manual de aplicación. Reglamentación Térmica, Ordenanza General de Urbanismo y Construcción, Chile
10. Trebilcock M, Piderit M, Diaz M, Guzmán F, Bobadilla A, Figueroa R, Muñoz C, Arriagada R, Besser D, Hatt T (2012) Guía de Eficiencia Energética de Establecimientos Educacionales. Agencia Chilena de Eficiencia Energética (AChEE)
11. CITEC-UBB (2012) Proyecto Innova Chile Código: 09CN14-5706. Manual de Diseño Pasivo y Eficiencia Energética en Edificios Públicos. Centro de Investigación en Tecnologías de la Construcción, Universidad del Bío Bío. https://arquitectura.mop.gob.cl/centrodocumental/Documents/Manual-de-diseno-pasivo-y-eficiencia-energetica-en-edif%20Publicos_Parte1.pdf

Air Movement to Remove Barriers and Provide Thermal Comfort in the Global South: A Case Study of a Classroom in the Warm Humid Tropics, Banda Aceh, Indonesia

Laina Hilma Sari, Muhammad Luthfi Ghassan, and Abdul Munir

Abstract Warm tropical climates are typical of the Global South. Achieving thermal comfort in the tropics, especially in a warm humid climate, is challenging due to its main barrier: the high relative humidity exacerbated by the high outdoor air temperature. In southeast Asia, such as in Indonesia, traditional dwellings had been built on stilts, adopting many openings either in walls, gables, or floors to get natural air circulation. The old architectural designs are relevant for scientific knowledge as their air movement decreases the relative humidity, hence improving the thermal comfort sensation. However, providing excellent air movement throughout rooms in contemporary buildings is arduous with design not considering tropical architectural principles. This chapter discusses the challenges for adequate air movement throughout rooms in the tropics. Although buildings in the tropics have been designed to be naturally ventilated, some have switched to air conditioning. This phenomenon was assessed using field measurements in an educational building located in Banda Aceh, Indonesia. Measurements of air velocity, temperature, and relative humidity were collected, while the air movement was predicted using an ANSYS simulation. The effect of air movement on thermal comfort was assessed to explore why there was a shift from naturally ventilated to air conditioning setups.

Keywords Thermal comfort · Air movement · Warm-humid climate · Indonesia

L. H. Sari (✉) · A. Munir
Architecture Department, Universitas Syiah Kuala, Banda Aceh, Indonesia
e-mail: laina_hilma@unsyiah.ac.id

M. L. Ghassan
Architecture Consultant, Banda Aceh, Indonesia

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1 Introduction

The Global South is quite large and comprises many countries in Africa, the Middle East, Asia, and the Pacific [1]. In Asia, Global South nations are characterized by warm tropical climates [2]. The warm climate has a high energy demand for cooling loads, especially during outdoor temperature peaks [2, 3]. This climate in South East Asia is primarily humid, characterized by high relative humidity and high air temperature [4]. Traditional dwellings across the equator, in dealing with this, give an excellent lesson on how to cope with the climate. Just as in Indonesia, most traditional houses in South East Asia have stilt floors and lightweight materials. They have many window openings and a clerestory along the top of the roof, as cross-ventilation is essential for circulating natural air throughout the rooms, pushing the hot air outside, and reducing relative humidity [5].

However, the current architectural styles have shifted toward modernism by predominantly adopting a bulky style and using heavy-weight materials and glass. In many cases, public buildings in the tropics are designed with a sealed façade, resembling buildings from a colder zone. The glass-sealed façade directly rejects the natural cooling air and daylight. While some others, which are designed in a tropical style, have also switched to using air conditioning. As a result, the Asian global south suffers from over-cooling and is expected to triple its cooling energy demand while doubling its built footprint by 2050 [2].

As mentioned above, air movement is essential to induce thermal comfort. In addition, our body adapts to the natural environment in some circumstances. This can be triggered by providing natural airflow to induce a thermal comfort sensation. However, air circulation has often been disregarded for today's buildings. As a result, this chapter discusses the challenges for adequate air movement throughout rooms in the tropics.

The case study was carried out in classrooms in the engineering faculty's educational building, at Universitas Syiah Kuala' (See Fig. 1). The building is in Banda Aceh, Indonesia, specifically at 5°33′28″N, 95°19′20″E. Although the building was designed to be naturally ventilated, part of it has been shifted to be air-conditioned under bioclimatic principles. This phenomenon was assessed through field measurements, namely, air velocity, temperature, and relative humidity, while air movement was predicted using an ANSYS simulation. The effect of air movement on thermal comfort was assessed to explore the reasons behind the shift from naturally ventilated to air-conditioned.

Banda Aceh, located in Aceh province, has an average relative humidity of 79% with two seasons: a dry season (March-August), and a rainy season (September-February). Its location, close to the equator, has a mean temperature of 28 °C, while temperatures can reach 33 °C. The Engineering faculty building was designed with a tropic-style architectural character with many courtyards to catch the wind and shading to cool the local environment (See Fig. 1).

Fig. 1 The façade of the engineering faculty

1.1 Air Movement and Thermal Comfort

In hot and humid climates, air movement is a cheap method. It plays a significant role in inducing a comfortable indoor climate [6, 7]. Natural air movement can be achieved by full cross-ventilation and building openings considering orientation and internal layout, which provides a cooling effect that can enhance evaporation from the skin's surface [8].

In Indonesia, the thermal comfort standard is categorized based on Effective Temperature (ET) following the Indonesian National Standard (SNI 03-65722001):

1. Cool comfort—ET between 20.5 and 22.8 °C
2. Optimal comfort—ET between 22.8 and 25.8 °C
3. Warm comfort—ET between 25.8 and 27.1 °C

Zhai et al. [9] indicate that thermal comfort could be maintained up to 30 °C and 60% RH in warm tropics with personally controlled air movement.

1.2 Tropic Architectural Design

A traditional or vernacular dwelling is believed to be adaptive to the local environment when it creates indoor thermal comfort. Therefore, architectural design in the tropics, especially in Aceh, where the case study is located, can learn from the traditional Acehnese house. Acehnese traditional houses are built on stilts running from east to west. They have many north-facing windows, while south-facing sides are shaded with large canopies. The house has lightweight timber walls and a low thermal transmittance palm leaf roof. Compared to the current Aceh houses built from heavy-weight materials such as concrete, an Acehnese traditional house can have a lower indoor air temperature during the day and night.

The traditional house, especially at night, can have an air temperature closer to the outdoor temperature. Under the same conditions, the concrete house has an air temperature of up to 5 °C above the outside one. As a result, modern houses mainly have air conditioning installed for night-time indoor cooling, the result of heat released by the concrete wall, which has a high thermal mass [10, 11].

Iqbal [12] shows that having many windows in Acehnese traditional houses circulates the air thoroughly through the rooms. When the average outdoor airspeed is 1.86 m/s, the airspeed running throughout the openings is around 0.2–1.2 m/s, which is a nice flow felt by the occupant [13]. The ANSYS Workbench simulation indicated that the westerly wind, which is the fastest incoming air orientation in Aceh, helps airflow throughout the rooms (See Fig. 2).

2 Research Method

This study used quantitative research, collecting data from field measurements and running a simulation in ANSYS Workbench. The thermal comfort measurements were made in naturally ventilated and air-conditioned rooms. The windows of the Engineering Faculty building, the case study, had been sealed using glass and plastic sheets to optimize the air conditioning system's operation. Only the classrooms on the second floor were unsealed and operated a hybrid operation, i.e., air-conditioned and naturally ventilated (See Fig. 3). Hence, the study measured the rooms specified on the second floor, namely, A1, A2, A3, A4, and A5 (See Fig. 4).

The data collected in this study are Air Temperature (Ta) and Relative Humidity (Rh), which were measured by a Wet Bulb Globe Temperature (WBGT) meter. Another parameter was Air Velocity (Av), measured by a hot-wire anemometer. Due to the limited time and tools, the measurement was made only on sunny days from 8.00 to 16.00, once the rooms were empty. The evaluation uses ET applied in the Indonesian Standards to determine thermal comfort standards. ET views a combination of Ta, RH, and Av, creating the thermal sensation.

To indicate ET, the Wet Bulb Temperature (WBT) value is needed, which is defined by tracing the Ta and Rh on the psychometric chart (See Fig. 5a). Ta is also known as Dry Bulb Temperature (DBT). Further WBT, DBT, and Av are outlined in the Nomogram Effective Temperature (Basic-0.5 clo, the usual clo value in Aceh) to indicate the Effective Temperature (ET) (See Fig. 5b).

An airflow simulation is also run to evaluate airflow and the amount of air received by the rooms. The simulation is run in Ansys Workbench, which is a CFD simulation. In particular, ANSYS Fluent, a computer-aided software for Computational Fluid Dynamics (CFD) was used to model fluid flow and heat transfer in complex geometries.

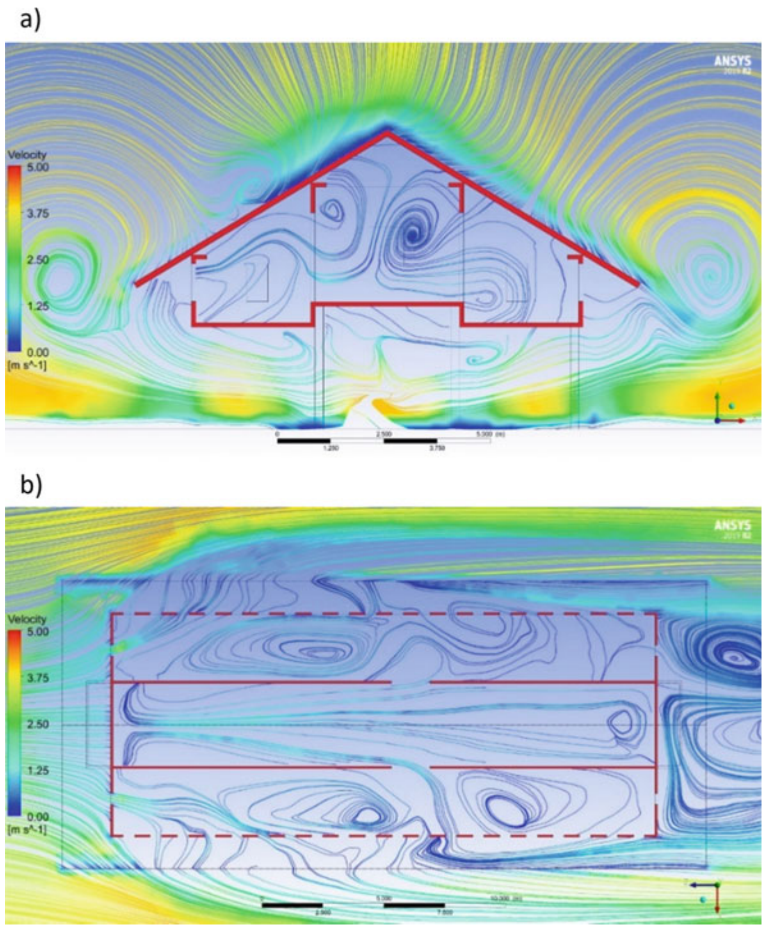

Fig. 2 The airflow in an Acehnese traditional house. **a** Vertical section; **b** Floor plan

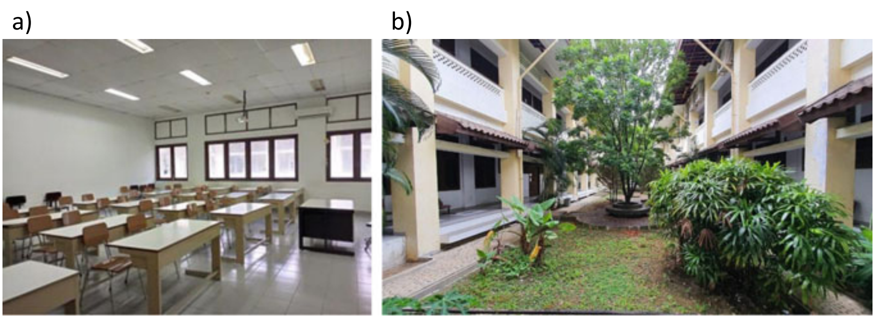

Fig. 3 Case study. **a** classroom; **b** Courtyard. Adapted from [14]

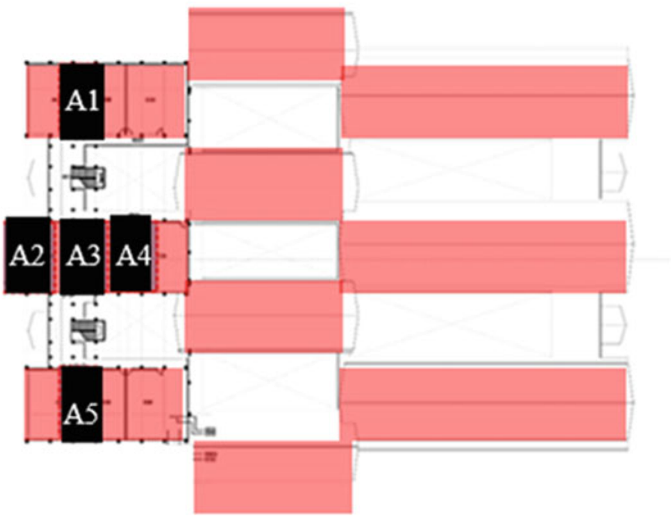

Fig. 4 The second-floor classrooms measured in this study

3 Results

3.1 Indoor Thermal Performance

The field measurements show that even though the indoor air temperature is conditioned and set by the air conditioning at 18 °C, the indoor air temperature rose 5 °C, ranging from 23.5 to 27.1 °C. However, this temperature is still lower than outdoors, which fluctuated from 26.3 to 33.1 °C. Once the air conditioning is off and there is natural ventilation, the indoor air temperature sits at an average of 30.5 °C. At the same time, the outdoor temperature is 30.6 °C (See Fig. 6). This is the natural effect of natural ventilation. The indoor air temperature will be very close to the outdoor air temperature.

The relative humidity in the air-conditioned room is higher than the outdoor relative humidity, in contrast to naturally ventilated rooms (See Fig. 7), where the absence of AC provokes a higher air temperature and slightly lower relative humidity.

The unexpected result occurs in air velocity. Once natural ventilation is used, the airspeed value is lower than when the air conditioner is on (See Fig. 8). Further data is shown on Effective Temperature. Figure 9a shows that the effective temperature in the air-conditioned room is lower than in a naturally ventilated room (See Fig. 9b). Most of the afternoon, the effective temperature stands outside the range, at too hot. Optimal comfort only occurs in the morning from 8.00 to 9.00.

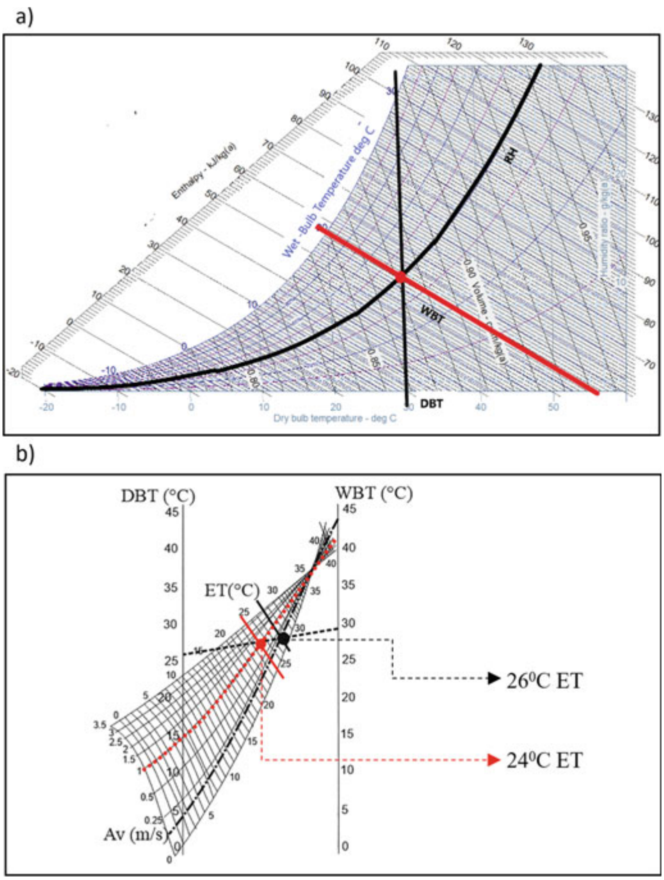

Fig. 5 **a** The psychrometric chart. Adapted from [15]; **b** Nomogram Effective Temperature. Adapted from [16]

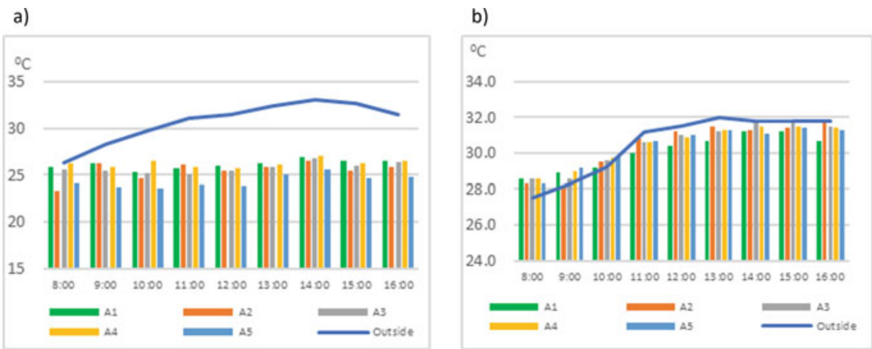

Fig. 6 Air temperature in **a** air-conditioned rooms **b** naturally ventilated rooms

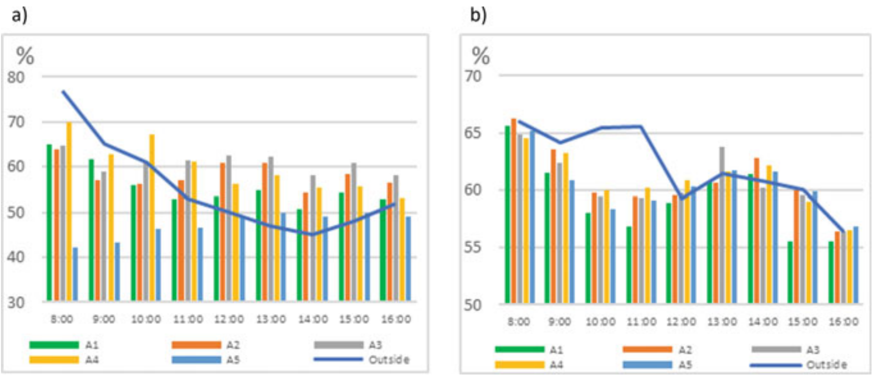

Fig. 7 Relative Humidity in **a** air-conditioned rooms **b** naturally ventilated rooms

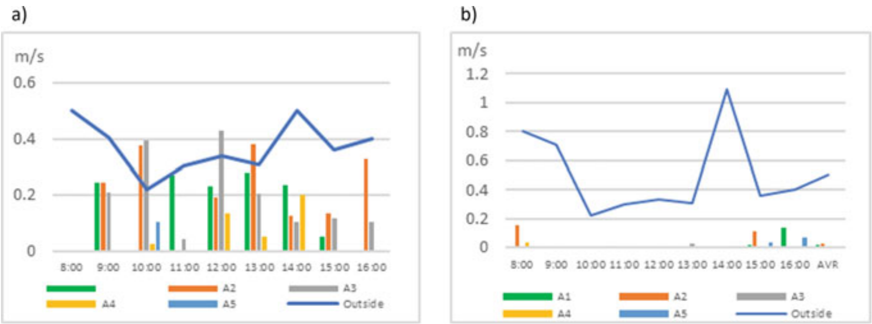

Fig. 8 Air velocity in **a** air-conditioned rooms **b** naturally ventilated rooms

3.2 Result of Airflow Simulation

The CFD ran the airflow simulation in Ansys Workbench. The airspeed set in the software was 3.59 m/s, the average airspeed in Banda Aceh recorded by the Aceh meteorology office. The simulation created a west-facing wind tunnel, the dominant wind flow in Aceh. The windows are set to have an airflow of 75% since they are designed with a casement-top hung type. Figure 10 shows the simulation of the second floor where the case study is located. It can be seen that the wind can work best in the circled room, at around 0.53 m/s. Whereas in the measured room, the simulation predicted that A1 received the wind speed at 0.26 m/s.

In contrast, A2, A3, A4, and A5 received an airspeed of 0.52 m/s near the windows, while the center of each room remained close to 0.05 m/s. CFD also simulated the airflow on the ground and first floors in this study. The simulation indicates how the airflow works if the windows on the ground and the second floor remain open. Figures 11 and 12 show that the wind flow was stronger, particularly near the west-

a) Air-conditioned rooms ET°C

	Hours	A1	A2	A3	A4	A5
1	8:00	23	20.8	22.6	23.5	20
2	9:00	23.2	22.5	22.4	23.2	20
3	10:00	22	21.5	22.2	24	19.6
4	11:00	22	22.5	22	22.5	19.8
5	12:00	22.2	22.5	22.4	22.2	20
6	13:00	22.5	22.8	22.6	22.8	21
7	14:00	22.8	22.8	23	23.2	21.5
8	15:00	22.8	22.2	22.8	22.5	21
9	16:00	22.5	22.4	22.8	22.4	21

b) Naturally ventilated rooms ET°C

	Hours	A1	A2	A3	A4	A5
1	8:00	25,7	25,5	25,7	25,7	25,5
2	9:00	25,8	25,3	25,5	25,8	25,8
3	10:00	25,6	25,9	26	25,6	25,6
4	11:00	26,1	27	26,8	26,9	26,9
5	12:00	26,6	27,6	27,2	27,2	27,2
6	13:00	27	27,7	27,6	27,6	27,6
7	14:00	27,4	27,7	27,7	27,7	27,4
8	15:00	27	27,8	27,7	27,6	27,6
9	16:00	26,5	27,8	27,3	27,2	27,1

<20.5	Too cool
20.5-22.8	Comfortable- cool
22.8-25.8	Optimal comfort
25.8-27.2	Comfortable- warm
>27.2	Too hot

Fig. 9 Effective temperature in **a** air-conditioned rooms **b** naturally ventilated rooms

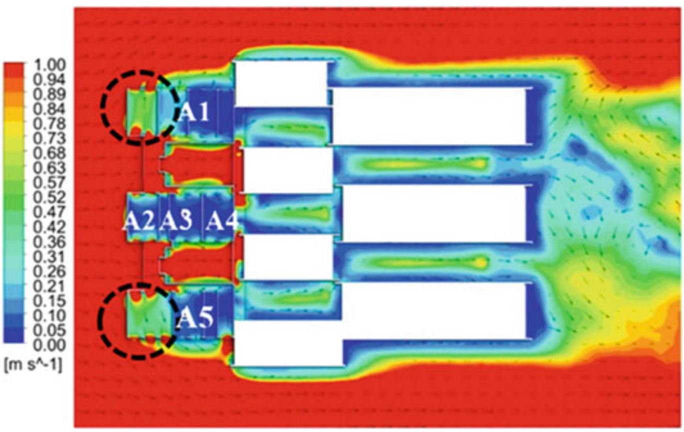

Fig. 10 CFD simulation result of the second floor

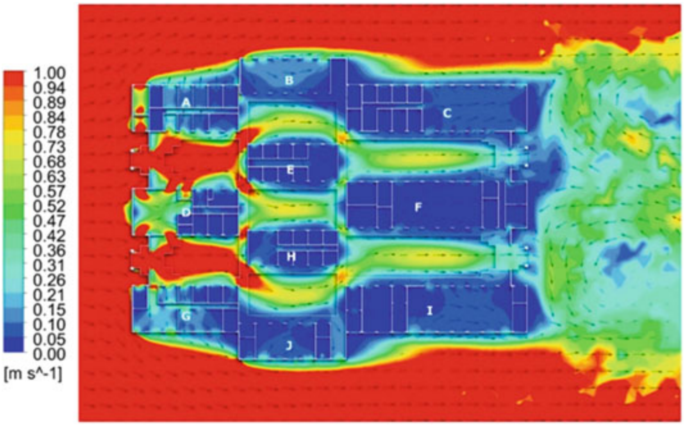

Fig. 11 CFD simulation result of the Ground Floor

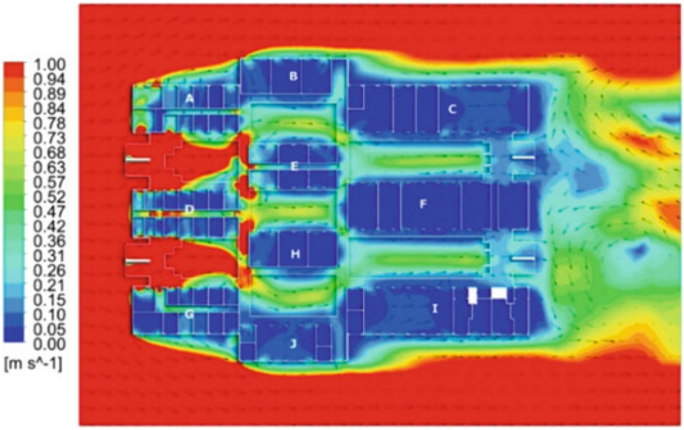

Fig. 12 CFD simulation result of the first floor

facing side on the ground and first floor, reaching up to 0.57 m/s. The remaining rooms had an airspeed of 0 to 0.21 m/s circulating throughout the rooms.

4 Discussion

In this study, the evaluation of airflow movements seeks a thermal comfort sensation through the ET. As mentioned previously, the SNI-based comfort range is within an ET of between 20.5 and 27.1 °C. This study found that ET in naturally ventilated rooms is mostly outside the comfort range (See Fig. 9b). The airspeed measured in these rooms was deficient and stood at 0 m/s. The Nomogram Effective Temperature indicates that surface air velocity creates a higher ET. Figure 5b shows that the Nomogram ET will decrease the ET once the airspeed is faster. For example, the 26 °C ET can be decreased to 24 °C by enhancing the airspeed at 1 m/s. The limited airflow was also seen in the CFD simulation, where the air is not thoroughly circulated. Figures 10, 11 and 12 show that the airflow throughout the buildings is uneven, and many rooms had airspeed levels below 0.25 m/s.

The cause of this may be because the west-facing windows are closed sometimes, thus rejecting the incoming airflow. The casement-top hung window works to circulate 75% of the airspeed [17]. However, most windows are closed and thus reject the flowing air. An open plan is seen as being very effective for airflow. The simulation shows that near corridors and stairs, the airspeed is around 0.25 m/s. Whereas in the courtyard, the airspeed is up to 0.73 m/s. The buildings have courtyards with and without vegetation. Different vegetation in the courtyard is essential to create a cool local climate, and there have been studies demonstrating that vegetation will create low air temperatures [18, 19]. Some treeless spaces in the courtyard may be the reason for the higher outdoor air temperature. However, the air is not flowing into the rooms as windows are closed or not fully open at times. The simulation, which applies an infiltration rate of 75%, indicates that the airflow is not evenly circulated. However, it can supply at least 0.05–0.25 m/s of airspeed into the rooms. This means that it is recommended to open the windows to let air circulate well. The effective temperature indicates that a higher speed will decrease the temperature.

Figure 9b shows that half the time, sensors had recordings as thermally comfortable cool, and comfortable warm. Only some periods, i.e., from 11 am to 4 pm, were sensed as thermally too hot. The quick switch to making the room air-mechanically conditioned was not wise. It increases the possibility of making the room excessively cold. People in warm climates tend to set the AC thermostat at its lowest temperature [20, 21], which causes excessive energy use and rising global temperature. In addition, many studies also show that our bodies can actually acclimatize to the local climate [22, 23]. This works best if it is supported by the aforementioned air movement that can help people overcome a too hot and humid environment.

Returning to the Global South, creating thermal comfort by relying entirely on natural air in warm-humid areas is an urgent issue to reduce the barrier to creating thermal comfort. The hot and warm climate characterizes the global south climate. This change will also reduce energy use by being less dependent on air conditioning and will be a greener alternative for the Environment.

5 Conclusions

This chapter addresses the challenge of providing thermal comfort in the global south, especially in a warm, humid climate. Here, air movement is critical in reducing relative humidity to induce a thermal comfort sensation. Classrooms in the Engineering

Faculty Building in Aceh, Indonesia, are evaluated, as a case study, on using air conditioning despite the building's design having a tropic architectural style. From this study, it is concluded that a change away from installing air conditioning in the Engineering Faculty Building's classrooms would be because of the following:

- Thermal comfort defined by ET in naturally ventilated classrooms is higher than the Indonesian standard due to the high air temperature and relative humidity, and low air velocity.
- The cause of the low air velocity entering the classrooms is the lack of west-facing openings, which reduces the speed of incoming air.
- Windows are mainly closed, meaning that they do not circulate the air, creating an absence of air velocity.
- The shading or vegetation is insufficient. Therefore, it does not create a cool local climate to induce low air temperature.

This study shows that air velocity could help to reduce high air temperatures and high relative humidity. A further study to propose how to introduce the air temperature into the rooms would be beneficial for promoting passive natural cooling in this type of buildings, especially in the tropics.

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References

1. World Population Review (2021) Global south countries 2021. https://worldpopulationreview.com/country-rankings/global-south-countries
2. Alnuaimi AN, Natarajan S (2020) The energy cost of cold thermal discomfort in the global south. Buildings 10:93. https://doi.org/10.3390/buildings10050093
3. Cheung C, Fuller R, Luther M (2005) Energy-efficient envelope design for high-rise apartments. Energy Build 37:37–48. https://doi.org/10.1016/j.enbuild.2004.05.002
4. Nguyen AT, Singh MK, Reiter S (2012) An adaptive thermal comfort model for hot humid South-East Asia. Build Environ 56:291–300. https://doi.org/10.1016/j.buildenv.2012.03.021
5. Ramli NI, Saji ND (2021) Adaptation of architectural design features traditional Malay houses at Kampung Morten for Malacca contemporary houses. Prog Eng Appl Technol 2(1):234–245, https://doi.org/10.30880/peat.2021.02.01.022
6. de Dear R, Brager GS (2001) The adaptive model of thermal comfort and energy conservation in the built environment. Int J Biometeorol 45:100–108. https://doi.org/10.1007/s004840100093
7. Prianto E, Depecker P (2003) Optimization of architectural design elements in tropical humid region with thermal comfort approach. Energy Build 35:273–280. https://doi.org/10.1016/S0378-7788(02)00089-0
8. Tanabe S, Kimura K (1994) Effects of air temperature, humidity, and air movement on thermal comfort under hot and humid conditions. In: American society of heating, refrigerating, and air conditioning engineers (ASHRAE) annual meeting. Orlando, FL, USA
9. Zhai Y, Zhang H, Zhang Y, Pasut W, Arens E, Meng Q (2013) Comfort under personally controlled air movement in warm and humid environments. Build Environ 65:109–117. https://doi.org/10.1016/j.buildenv.2013.03.022

10. Sari LH, Hasan I, Irwansyah M, Meutia E (2017) An environmental assessment of vernacular housing in Banda Aceh. Tesa Arsitektur 15:1–12. http://103.243.177.137/index.php/tesa/article/viewFile/573/760
11. Sari LH, Harris D (2013) Indoor thermal assessment of post-tsunami housing in Banda Aceh, Indonesia. Int J Hous Sci 37:161–173. https://scholar.google.com/citations?view_op=view_citation&hl=en&user=Yn6oegcAAAAJ&citation_for_view=Yn6oegcAAAAJ:bFI3QPDXJZMC
12. Iqbal M (2021) Analisis sistem ventilasi alami pada rumah tradisional Aceh dengan metode simulasi CFD. Master's thesis, Universitas Syiah Kuala
13. Szokolay SV (2012) Introduction to architectural science: the basis of sustainable design. Architectural Press, Elsevier
14. Ghassan M, Sari L, Munir A (2021) An evaluation of the tropical architectural concept on the building design for achieving thermal comfort (case study: engineering faculty of Syiah Kuala university). In: IOP conference series: materials science and engineering, p 1. https://iopscience.iop.org/article/10.1088/1757-899X/1087/1/012013/meta
15. Koenigsberger OH, Ingersoll TG, Mayhew A, Szokolay SV (1974) Manual of tropical housing and building. Longman, London
16. Lippsmeier G (1994) Bangunan tropis. Penerbit Erlangga
17. Heiselberg P, Dam H, Sørensen LC, Nielsen PV, Svidt K (1999) Characteristics of air flow through windows. Indoor Environmental Engineering R9940. https://vbn.aau.dk/en/publications/characteristics-of-air-flow-through-windows-2
18. Picot X (2004) Thermal comfort in urban spaces: impact of vegetation growth: case study: Piazza della Scienza, Milan, Italy. Energy Build 36:329–334. https://doi.org/10.1016/j.enbuild.2004.01.044
19. Gatto E, Buccolieri R, Aarrevaara E, Ippolito F, Emmanuel R, Perronace L, Santiago JL (2020) Impact of urban vegetation on outdoor thermal comfort: comparison between a Mediterranean City (Lecce, Italy) and a Northern European City (Lahti, Finland). Forests 11:228. https://doi.org/10.3390/f11020228
20. Sikram T, Ichinose M, Sasaki R (2019) Thermal adaptive behavior of occupants in air-conditioned office buildings in Thailand. In: IOP conference series: earth and environmental science: sustainable built environment conference 2019 Tokyo (SBE19Tokyo). Built environment in an era of climate change: how can cities and buildings adapt?, The University of Tokyo, Tokyo, Japan, vol 294
21. Wright MK, Hondula DM, Chakalian PM, Kurtz LC, Watkins L, Gronlund CJ, Larsen L, Mallen E, Harlan SL (2020) Social and behavioral determinants of indoor temperatures in air-conditioned homes. Build Environ 183:107187. https://doi.org/10.1016/j.buildenv.2020.107187
22. Salata F, Golasi I, Ciancio V, Rosso F (2018) Dressed for the season: clothing and outdoor thermal comfort in the Mediterranean population. Build Environ 146:50–63. https://doi.org/10.1016/j.buildenv.2018.09.041
23. Lam CKC, Lau KKL (2018) Effect of long-term acclimatization on summer thermal comfort in outdoor spaces: a comparative study between Melbourne and Hong Kong. Int J Biometeorol 62:1311–1324. https://doi.org/10.1007/s00484-018-1535-1

Occupant Thermal Perception of a Cooling System Based on Ceiling-Mounted Radiant Panels Coupled to a Roof Pond

Eduardo Krüger, Leandro Fernandes, and Evyatar Erell

Abstract Roof ponds can provide modest structural cooling and stabilization of surface and indoor air temperatures in hot-dry climates, with special relevance to the Global South, where most desert areas are found. Thermal performance may be improved if they are coupled to radiant ceiling panels circulating water chilled by evaporative cooling in the pond. The objectives of this study, conducted at an experimental facility in Sde-Boqer, Negev Desert, Israel, were to demonstrate the operation of such a system in practice and to evaluate its cooling performance. Volunteers exposed to two distinct thermal environments—a room cooled by a roof-pond system coupled to ceiling-mounted radiant panels, and a nearly identical room cooled by a conventional split air-conditioning system—were consistently able to sense differences between the two rooms, which had nominally similar thermal conditions (calculated by their respective PMVs).

Keywords Roof pond · Radiant cooling · Thermal comfort · Questionnaire survey · Mean radiant temperature

1 Introduction

Arid climates (Köppen's "B" dry climate types) comprise almost one-third of the Earth's land surface and include the northern part of the African continent, much of

E. Krüger (✉)
Department of Civil Construction, Universidade Tecnológica Federal do Paraná, Curitiba, Brazil
e-mail: ekruger@utfpr.edu.br

L. Fernandes
Department of Graphical Expression, Universidade Federal do Paraná, Curitiba, Brazil

E. Erell
Department of Man in the Desert, Ben-Gurion University of the Negev, Beersheba, Israel
e-mail: erell@bgu.ac.il

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Central Asia, vast regions of the Middle East, and the western parts of Latin America, including inland regions in Northeast Brazil. Most desert areas are thus in countries often referred to as the 'Global South'.

In passive building design, evaporative cooling is strongly indicated for arid regions, as evaporation rates are the highest where it is drier. Indirect evaporative cooling systems can improve indoor comfort in single-storied buildings through several mechanisms, including thermal stabilization, structural cooling, and significant lowering of daytime indoor air and surface temperatures. In the case of roof pond systems, the pond's water temperature will typically be close to the average daily wet-bulb temperature outdoors and the ceiling, cooled by the pond, acts as a heat sink to the space underneath. Roof ponds are capable of only modest reductions of the water temperature, yet as the cooling is provided continuously (even when the room is not occupied), even small reductions in ceiling temperature may result in a non-negligible reduction in the mean radiant temperature (T_{MRT}), thus contributing to indoor comfort.

Hydronic radiant cooling panels, when coupled with a roof pond, can further improve thermal performance due to reduced distribution losses [1]. Unlike standard air-conditioning (all-air) systems, heat transfer occurs mainly by radiation, with limited air movement. ASHRAE defines Radiative Heating and Cooling systems (RHC) as those where radiant heat transfer accounts for more than 50% of heat exchange within a conditioned space [2]. There are two main types of hydronic systems with radiant heat exchange, namely: (1) low thermal inertia systems, including suspended ceiling panels; and (2) high thermal inertia systems, including Thermally Activated Building Systems (TABS), where pipes are embedded into the building envelope, typically ceiling slabs [3].

Commercial radiant cooling systems reduce draft discomfort due to reductions in air movement and have several advantages over all-air systems such as higher energy efficiency, long-term thermal stability, lower noise levels, and better air-quality control. Nevertheless, such systems also present problems related to moisture condensation, difficulties in adjusting cooling output for space zoning, and time delay in achieving cooling, which has lately prompted the development of novel hybrid cooling systems [4–6].

Studies comparing radiant and convective cooling systems show small differences between them [4]. However, a review by Karmann et al. [7] found only two studies comparing occupant perception of such systems in full-scale of office environments. Schellen et al. [8] reported that in thermal environments with differing passive (convection in different air speeds) and active cooling systems (radiation or convection), subjects' thermal sensation showed substantial variance despite being exposed to conditions where PMV ≈ 0 [9]. Results, however, were found to be inconclusive regarding which of the systems had a higher performance in terms of occupant comfort perception. In a study comparing the thermal perception of occupants in a meeting room with a suspended radiant ceiling panel and an air-handling unit (AHU) that simulated a conventional all-air cooling system, both set to within ± 0.5 of neutral PMV (ISO 7730), Imanari et al. [10] found that the radiant cooling mode yielded a higher percentage of positive comfort votes than the AHU with humidity control—even though thermal conditions were set to be equivalent.

After their literature review, Karmann et al. [11] conducted a comprehensive field study in 60 office buildings and found that radiant systems are potentially more advantageous than all-air systems in terms of occupant satisfaction. However, a field survey on occupant satisfaction in LEED-certified buildings using radiant systems [12] found that the lack of control and the slow system response were recurrent complaints, despite an overall favorable assessment of their performance.

The objective of this study is therefore to contribute to the discussion on the advantages and disadvantages of radiant versus all-air systems for cooling, particularly for locations in the Global South that are characterized as having Köppen's B climate types. Here we compare occupant thermal perception in a test room cooled by ceiling-mounted radiant panels coupled with a roof pond to thermal perception assessed in a similar room cooled by a conventional air-conditioning system.

As radiant systems are generally more economical than all-air systems and as the system evaluated here is based on passive cooling, many of the challenges in the Global South regarding necessary investments to implement such systems can have very short payback periods.

2 Methods

The study compares two otherwise similar rooms with different cooling strategies: passively through radiant cooling, using ceiling panels coupled to a roof pond cooled by evaporation and nocturnal radiative heat loss; and actively with a conventional air-conditioning system. In the latter, cooling is achieved more quickly with respect to air temperature, whereas in the former, cooling is the result of small radiant fluxes acting continuously, even when the room is not occupied.

The study was performed in two stages: First, different configurations of a passive cooling system were tested to identify the most effective means for providing chilled water and cooling the experimental room. The system chosen for this study is based on evaporative processes with high evaporation rates to ensure superior cooling output under arid conditions. Several alternatives that demand less water consumption, such as using 'dry' roof ponds, where water is contained in plastic bags or gunny bags, shaded ponds (cool ponds), or water-spraying schemes that operate only during night-time hours are described in Erell et al. [13].

During the second stage, thermal conditions in both rooms were monitored concurrently and evaluated by occupants, who were exposed one by one to both thermal environments and asked to report their thermal perception. In this chapter, we focus only on the thermal sensation reported by survey participants. Other aspects related to thermal perception such as thermal comfort and thermal preference were examined in previous publications [14, 15].

2.1 Test Facility

The two rooms are part of a test facility located at the Sde-Boqer Campus of the Ben-Gurion University of the Negev, in Midreshet Ben Gurion, Israel (30.8°N, 35°E, 478 meters asl). The climate (Köppen "Bsh", mid-latitude steppe and desert) is characterized by large diurnal and seasonal thermal fluctuations, dry air, and a clear sky with intense solar radiation. Summer conditions are extremely stable: temperature differences from day to day are minimal, with a typical maximum of 32–33 °C and a minimum of 17–18 °C. The average wet bulb temperature in July is 16.8 °C. Global horizontal radiation averages 7.7 kW h/m^2 per day during June and July [16].

The facility, built in 1991 for experiments in passive cooling and solar control [17, 18], incorporates three nearly identical test rooms (270 cm wide, 350 cm long, and 305 cm in height) with a white-painted interior. In our study, one room was equipped with an insulated roof pond ('RP room'). whereas a second ('AC room') had equivalent roof thermal insulation but was fitted with a split AC unit. The AC unit was operated by remote control by the researchers to adjust the desired set-point temperature. The fan speed was kept at the lowest setting. The evaporator of a similar AC unit was used as a fan in the RP room to provide air movement, with the external casket closely resembling the AC equipment used in the AC room but providing no sensitive cooling. In the RP room only, two aluminum radiant cooling panels were suspended from the ceiling, each with a 1.6 m^2 surface area.

2.2 Test Configuration and Thermal Monitoring

The roof comprised a conventional flat roof (10 cm-thick concrete slab with 6 cm extruded polystyrene insulation and 3 cm gravel ballast above) covered by a 755-liter roof pond (average water depth 9 cm) shaded by a white PVC panel suspended 1.5 m above the pond. The water from the pond was circulated by an electric pump to the two ceiling-mounted radiant panels in the RP room. The pond was also fitted with floating polystyrene insulation and sprayed from sprinklers above the pond on a 24-h basis (See Fig. 1).

The study was carried out during two summer months (July and August 2017). During test days, indoor air and surface temperatures were recorded in both rooms by Type T thermocouples. Globe temperature was likewise measured by thermocouples, inserted in 38 mm diameter spheres (ping-pong balls), painted grey (RAL 7001). Relative humidity was measured with Vaisala HMP-60 Temperature/Relative Humidity sensors and air velocity with a Kurz Portable Air Velocity Meter (Series-441) hot-wire anemometer. In both rooms, the surface temperatures (ceiling, floor, walls, radiant cooling panels, and at two heights of the window panes) were also recorded. In each room, the air temperature was measured at four different heights (10, 60, 110, 280 cm above the floor) and in the center of each room; due to the small internal volume, negligible horizontal variations in air temperature were assumed.

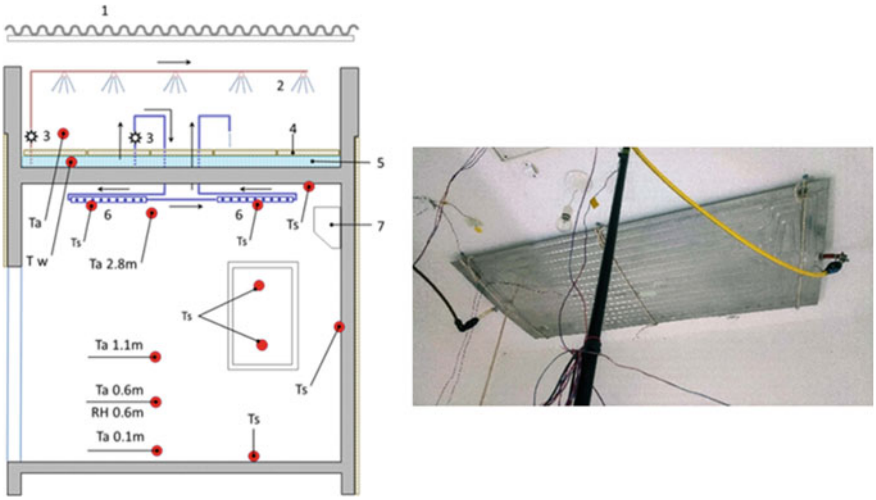

Fig. 1 *Left:* Section in the roof pond room showing sensor locations/T_a: air temperature; T_s: surface temperature; T_W: water temperature; RH: relative humidity. *Right:* One of two radiant cooling panels in the ceiling of the roof pond room

Relative humidity, air velocity, and globe temperature were recorded at 60 cm height, corresponding to a seated position [19]. All sensors were connected to a Campbell Scientific datalogger CR23X via Multiplexer AM-32. Readings were made every 30 s, and averages were calculated at 10-min intervals.

The set-point temperature of the AC unit was adjusted 30 min before the arrival of each of the research participants so that thermal conditions in the air-conditioned room were as close as possible to conditions in the roof pond room.

2.3 Questionnaire Survey

Participants were recruited by personal invitations as volunteers among students and staff of Ben-Gurion University. Very little information was disclosed about the true purpose of the study. Participants spent approximately 30–35 min in the building, first in one room (30 min), then in the other (for an additional 5-min period), at random. During the experiments, participants filled out thermal comfort questionnaires (handed out as printed copies) at three timestamps: (1) within the first five minutes upon arrival in the first room, (2) after 30 min in the room, (3) within the first five minutes upon arrival in the second room. It was assumed that, due to the thermal similarity of the rooms, a shorter stay would be sufficient in the second room for thermal assessment.

The questionnaire was designed following ISO 10551 [20] and recorded personal data including thermal history (biometrics, length of residency in Israel, country of

Comparing this environment with the previous environment, this second environment is:

( )	( )	( )
1	2	3
Less comfortable than the previous	Similar to the previous	More comfortable than the previous

Comparing this environment with the previous environment, this second environment is:

( )	( )	( )
1	2	3
Colder	Similar	Hotter

Fig. 2 Survey questionnaire—comparing both rooms

origin, previous thermal environment, transport mode to the test building); clothing information (from a look-up table); and questions on thermal perception at the three timestamps. Personal data were filled out by participants at the start while clothing insulation was estimated visually by the researchers. Thermal sensation (TS) was assessed by a 7-point Likert scale with a neutral midpoint, with TS votes ranging from cold (–3) to hot (+3).

Upon their arrival, the subjects were given an overview of the experimental procedure, which included filling in a demographic form followed by thermal comfort questionnaires. This also allowed them to settle in and experience conditions in the test room. The subjects then received the first part of the questionnaire to fill out and were left alone in the room. They were allowed to read, study, or chat on the phone, but were requested to remain seated at all times and not greatly alter the position of the chair. Approximately 25 min later, subjects filled out the second part of the questionnaire. They were then led to the second room, where they were asked to fill out the third part of the questionnaire after a brief period of exposure. The intention was to assess their immediate impression when entering the second room to allow a direct comparison to the first one; it was assumed that since rooms had similar thermal conditions there was no need for further acclimatization. The starting room could be either the AC room or the RP room, in a random order, according to a simple randomization procedure. Sessions took place during the daytime at the participant's convenience, one at a time.

When the participants finished their brief stay in the second room, two additional questions were posed for a direct comparison between rooms (See Fig. 2).

3 Results

3.1 Thermal Conditions in the Rooms

Figure 3 shows air and mean radiant temperature in both rooms on a typical day (August 21). During the sessions (five per day, from about 9:30 am through 5:30 pm,

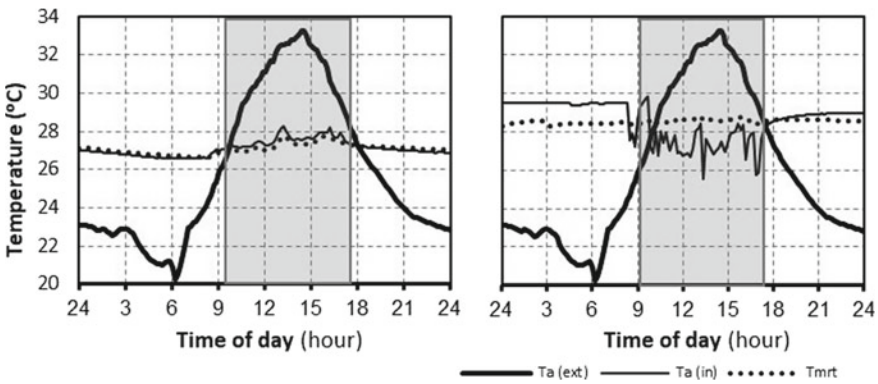

Fig. 3 Mean radiant temperature [Tmrt], air temperature indoors [Ta (in)] and outdoors [Ta (ext)]: **a** in the roof pond room (left) and **b** in the AC room (right) on August 21. The shaded area indicates the operation of the AC unit (or the fan in the RP room)

as indicated by the shaded rectangle in the graphs), surface temperatures presented contrasting behaviors, despite similar air temperatures: in the air-conditioned room, surface temperatures were 1.4 °C above indoor air temperature, on average, whereas in the roof pond room they were 0.2 °C lower. In the AC room, the system remained in continuous operation during sessions to provide thermal comfort. Minor fluctuations in air temperature were observed due to the nature of the controller (ON-OFF), but differences in PMV scores between the rooms were negligible.

Objective thermal sensation indoors was assessed by the PMV, calculated from monitored data using mean radiant temperature initially obtained from globe temperature data. The aim was that all experiments would be carried out at approximately neutral thermal conditions (PMV $\approx$ 0) indoors, and conditions were in fact within PMV ±1 of neutral throughout all sessions. A total of 45 sessions also complied with our (arbitrary) requirement that the absolute difference in PMV between the two rooms should be no greater than 0.35, as confirmed by one-way ANOVA tests.

3.2 Survey Results

Surveys began on July 26 and ended on September 5. Participants (n = 45, 20 male, 25 female) were on average 33.5 years old and with a Body Mass Index (BMI, calculated as body weight divided by the square of body height, expressed in units of kg/m^2) ranging between 18.4–35.5, thus varying from 'underweight' to 'obese' according to WHO categories [21]. Participants came from 15 different countries and their residency in Israel varied from less than one year (13%) to over 20 years (49%). The majority had just come from non-AC thermal environments (67%), some

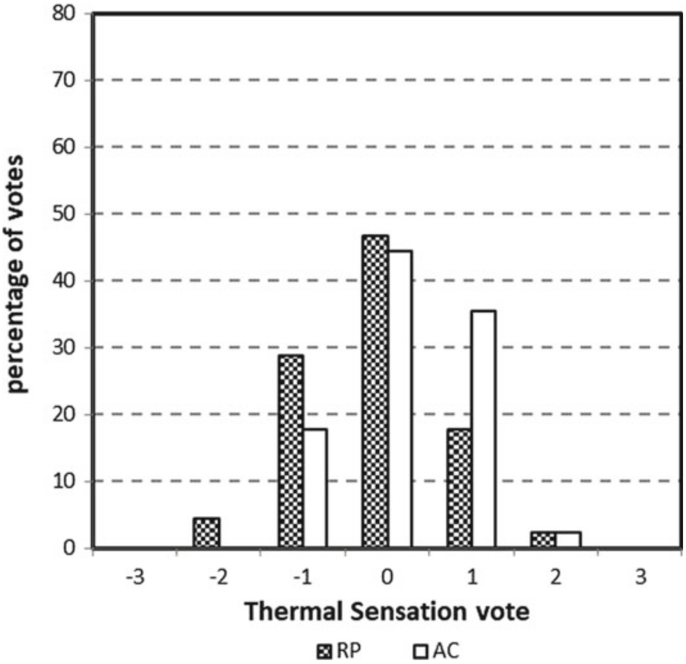

Fig. 4 Thermal sensation (TS) votes in the Roof-pond (RP) and Air-conditioned (AC) rooms

from an air-conditioned space (29%), and the remainder from public transport/car (air-conditioned).

Despite both rooms having thermal conditions with similar PMV, reported votes showed differences between rooms in terms of subjective thermal sensation, TS (See Fig. 4). In the RP room, 47% of responses indicated thermal neutrality while 33% indicated some degree of cold sensation (TS votes −3, −2, −1), compared with 44% who indicated neutrality and 18% who felt cold in the AC room. Correspondingly, a rise in heat sensation increased from 20 to 38%. The difference is statistically significant ($p < 0.05$).

A more detailed analysis of TS votes given at the three timestamps showed that respondents changed their initial vote after spending some time in the starting thermal environment. The comparison between the first two stamps showed a p-value lower than the significance level of 0.05 for the AC room and above significance ($p = 0.10$) in RP, which suggests more consistent TS votes by the respondents in the latter, possibly due to its long-lasting thermal stability.

Statistically significant differences in TS for participants transiting from one room to another were only found when the subjects moved from the RP to the AC room (with a p-value of 0.009 and a corresponding rise in TS vote of 0.65). For the opposite transition, despite a drop in TS of 0.14, the p-value was well above the significance level.

Table 1 Calculated PMV and PPD versus occupant thermal sensation (TS) votes in the test rooms

	PMV	Reported TS	Diff	PPD (%)	Percentage dissatisfied (%)	Diff
RP	0.04	−0.16	0.19	6.43	6.67	−0.24
AC	0.01	0.22	−0.22	6.18	2.22	3.96
Difference	−0.03	0.38		−0.24	4.44	–

Table 2 Changes in TS votes for variations in timestamps (*$p < 0.05$, **nearing significance level of 5%)—transition from AC to RP room and vice-versa

Changes	TS		
	Offset	p-value	Effect size (r)
Timestamp 1 to 2 (in AC)	−1.05	5.09E-05*	0.07
Timestamp 1 to 2 (in RP)	−0.57	0.062521**	0.47
Timestamp 2 to 3 (from AC to RP)	−0.14	0.525139	−0.19
Timestamp 2 to 3 (from RP to AC)	0.65	0.00859*	0.19

Reported thermal sensation (TS) votes of −3, −2, +2, and +3 were assumed to indicate thermal dissatisfaction. Comparison of reported sensation with estimated values for PMV and PPD (‘Predicted Percentage Dissatisfied’, calculated using the exponential equation which accounts for PMV data, as in ISO 7730 [9], showed substantial differences (See Table 1) in the latter for the AC room only. A slightly higher percentage of participants were dissatisfied in the RP room (due to cold) than in the AC room, although the proportion was small in both cases.

Table 2 shows a summary of differences (offsets) found in terms of TS votes for the three timestamps, also taking into account the move from one room to another between timestamps 2 and 3. The changes in TS dropped in both rooms after approximately half an hour of exposure, meaning that short-term acclimatization is accompanied by an initial overshooting for hot responses which is later adjusted by the respondent at timestamp 2. Such changes are more evident and significant in the AC room. In the RP room, with a larger effect size (higher Pearson’s r) and a comparatively lower significance ($p = 0.06$), changes in TS from timestamp 1 to 2 are less pronounced and responses are more strongly correlated. When changing rooms, offsets and effect sizes (Pearson’s r-value) show opposite trends for both possible moves, i.e., from AC to RP versus from RP to AC. Statistical significance ($p < 0.05$) is reached for the move from RP to AC with a significant rise in TS.

4 Discussion

The experiments described here highlight the difficulty of obtaining accurate values for T_{MRT} when air movement is variable and non-negligible. This problem is typically encountered outdoors but appears to be a problem in some indoor situations, too. Thus, in the AC room, the use of the globe thermometer to obtain the mean radiant temperature and PMV data proved to be insufficiently accurate when the AC equipment was in operation. This is because the change in air velocity near the globe thermometer, even at speeds as low as 0.2 m/s, leads to almost instantaneous differences in the globe temperature reading, while the temperature of the wall surfaces, and hence the true value of T_{MRT}, change much more slowly. This raises questions about the use of globe temperature readings to assess or control dynamic conditions such as mechanically air-conditioned environments, where thermal comfort is mainly achieved through convective heat exchange. While ISO 7726 states that "It should be noted that the smaller the diameter of the globe, the greater the effect of the air temperature and air velocity, thus causing a reduction in the accuracy of the measurement of the mean radiant temperature" [19], though this is not a formal requirement of the standard. However, this restriction implies that the measurement is best performed in quasi-steady state conditions, as the response time of the standard copper black globe may be quite long. Recent research on thermal comfort has highlighted the importance of dynamic (drifting) conditions and locally varying temperatures not only to achieve comfort but also to create healthy conditions [22]. This suggests, in turn, that adequate means must be found for monitoring and controlling conditions in dynamic environments.

In our study, air temperature in the AC room, although controlled by a thermostat, fluctuated during the experiment within the limits of the controller's 'dead zone'. Because globe temperature measurements may have a relatively long time constant—up to several minutes—the estimation of the mean radiant temperature can be seriously impaired when conditions are dynamic. In this case, the globe thermometer registered values higher than the average of the instantaneous influences of convection and radiation, therefore overestimating the calculated mean radiant temperature (T_{MRT}) in the AC room.

Dynamic conditions are fairly common in AC environments, especially the split systems installed in small offices and at homes. This is because the control scheme is still used in many all-air systems (i.e. cycling on and off in response to variations from the set-point). These variations can have an important impact on thermal perception, even if the PMV is the same in both rooms, 'on average'.

The slightly inferior performance of the AC room resulted from the reduced effect of air conditioning on the room's surface temperatures, as the AC unit was only operated during a given session, beginning 30 min before the room was occupied (pre-cooling). Measurements of the surface temperature in both rooms indicated that structural cooling and thermal stabilization are obtained in the RP room by radiant cooling, whereas in the AC room, thermal control is achieved only within the short period of the session through rapid changes in the air temperature.

Finally, the study wishes to contribute to knowledge gaps in terms of occupant thermal perception in radiant against all-air systems. The study conducted by [11] in 60 offices in the U.S. and Canada had the drawback that the offices surveyed were not exactly equivalent in terms of volume, function, location, outdoor microclimate, and exposure because evaluations did not take place simultaneously and at one single location. In their study, radiant systems included TABS, embedded surface systems, and ceiling panels, all treated as radiant systems. This study is controlled and thus avoids these limitations—but is much smaller in scope.

In arid regions of the Global South, passive solutions based on evaporative cooling are promising, using either direct or indirect cooling systems. Because differences between dry-bulb and wet-bulb temperatures (the wet-bulb temperature depression) in such areas are large, the cooling output is high. A previous study conducted in Brazil showed that in dry locations an indirect evaporative cooling, roof-pond-based system can reduce thermal discomfort nearly all year round [23]. An ongoing project by one of the authors is currently evaluating the performance of a roof-pond system coupled with radiant cooling panels to enhance cooling. An interesting feature of this novel cooling system is the fact that the cooling unit is detached from the building's structure and utilizes a closed water loop to feed the ceiling-mounted radiant cooling panels. Therefore, its implementation in existing buildings is facilitated and can benefit retrofitting schemes in social housing in Global South countries [24].

5 Conclusions

Because roof ponds in hot climates can supply water that is only a little cooler than the air temperature, rooms cooled by roof ponds typically exhibit only minor differences in radiant temperature compared to rooms cooled by conventional air conditioning systems. Yet, as this study shows, occupants can perceive even small differences in their environment, which coincides with several studies on radiant cooling cited in the introductory section of the chapter. This should encourage researchers who seek to implement passive cooling systems that rely on indoor radiant cooling (sometimes with added thermal mass in the indoor environment) in arid regions of the Global South. Such designs offer, in addition to economic advantages, improved thermal stabilization. Although this study evaluated the potential of an experimental roof pond cooled by evaporation to promote indoor thermal comfort, the results may also be applicable to commercial radiant cooling systems supplied with mechanically chilled water.

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References

1. Li R, Yoshidomi T, Ooka R, Olesen BW (2015) Field evaluation of performance of radiant heating/cooling ceiling panel system. Energy Build 86:58–65. https://doi.org/10.1016/j.enbuild.2014.09.070
2. ASHRAE (2012) Panel heating and cooling. In: ASHRAE handbook HVAC system and equipment Atlanta 2012, Atlanta, USA
3. Babiak J, Olesen B, Petras D (2009) Low temperature heating and high temperature cooling: embedded water based surface heating and cooling systems, 2nd edn. Helsinki, Finland
4. Mustakallio P, Bolashikov Z, Rezgals L, Lipczynska A, Melikov A, Kosonen R (2017) Thermal environment in a simulated double office room with convective and radiant cooling systems. Build Environ 123:88–100. https://doi.org/10.1016/j.buildenv.2017.06.029
5. Kim MK, Liu J, Cao SJ (2018) Energy analysis of a hybrid radiant cooling system under hot and humid climates: a case study at Shanghai in China. Build Environ 137:208–214. https://doi.org/10.1016/j.buildenv.2018.04.006
6. Liu J, Kim MK, Srebric J (2022) Numerical analysis of cooling potential and indoor thermal comfort with a novel hybrid radiant cooling system in hot and humid climates. Indoor Built Environ 31:929–943. https://doi.org/10.1177/1420326X211040853
7. Karmann C, Schiavon S, Bauman F (2017) Thermal comfort in buildings using radiant vs. all-air systems: a critical literature review. Build Environ 111:123–131. https://doi.org/10.1016/j.buildenv.2016.10.020
8. Schellen L, Loomans MG, de Wit MH, Olesen BW, van Marken Lichtenbelt WD (2013) Effects of different cooling principles on thermal sensation and physiological responses. Energy Build 62:116–125. https://doi.org/10.1016/j.enbuild.2013.01.007
9. ISO (2005) ISO 7730:2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva, Switzerland
10. Imanari T, Omori T, Bogaki K (1999) Thermal comfort and energy consumption of the radiant ceiling panel system. Energy Build 30:167–175. https://doi.org/10.1016/S0378-7788(98)00084-X
11. Karmann C, Schiavon S, Graham LT, Raftery P, Bauman F (2017) Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings. Build Environ 126:431–441. https://doi.org/10.1016/j.buildenv.2017.10.024
12. Dawe M (2019) Field evaluation of occupant satisfaction and energy performance in eight LEED-certified buildings using radiant systems. Master's thesis, University of California, Berkeley. https://escholarship.org/uc/item/6d95z6sw
13. Erell E, Yannas S, Molina J (2006) Roof cooling techniques. In: Compagnon R, Haefeli P, Weber W (eds) The 23rd conference on passive and low energy architecture, Geneva, Switzerland, pp 571–575
14. Krüger EL, Fernandes LC, Mutsafi-Haller W, Erell E (2018) Comparing occupant thermal perception of air conditioning and ceiling-mounted radiant cooling panels coupled to a roof pond. In: 10th international windsor conference 2018: rethinking comfort, NCEUB 2018, Windsor, UK, pp 139–149
15. Fernandes LC, Krüger EL, Erell E (2020) Thermal perception in a room with radiant cooling panels coupled to a roof pond. In: PLEA 2020 a Coruña: planning post carbon cities
16. Bitan A, Rubin S (1991) Climatic atlas of Israel for physical planning and design. Tech. rep., Israel Meteorological Service and Ministry of Energy and Infrastructure
17. Erell E, Etzion Y, Brunold S, Rommel M, Wittwer V (1992) A passive cooling laboratory building for hot-arid zones. In: Proceedings of the 3rd international conference - energy and building in Mediterranean area, Thessaloniki, Greece, pp 117–124
18. Erell E, Etzion Y (1999) Analysis and experimental verification of an improved cooling radiator. Renew Energy 16:700–703. https://doi.org/10.1016/S0960-1481(98)00255-9
19. ISO (1998) ISO 7726:1998. Ergonomics of the thermal environment - Instruments for measuring physical quantities, Geneva, Switzerland

20. ISO (1995) ISO 10551:1995. Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. Geneva, Switzerland
21. World Health Organization (1995) WHO Technical Report Series; 854. Physical status: the use and interpretation of anthropometry. Tech. rep., Geneva, Switzerland. https://apps.who.int/iris/handle/10665/37003
22. van Marken Lichtenbelt W, Hanssen M, Pallubinsky H, Kingma B, Schellen L (2017) Healthy excursions outside the thermal comfort zone. Build Res Inf 45:819–827. https://doi.org/10.1080/09613218.2017.1307647
23. González-Cruz E, Krüger EL (2015) Evaluating the potential of an indirect evaporative passive cooling system for Brazilian dwellings. Build Environ 87:265–273. https://doi.org/10.1016/j.buildenv.2015.01.020
24. González-Cruz EM, Krüger EL (2022) Experimental study on a low energy radiant-capacitive heating and cooling system. Energy Build 255:111674. https://doi.org/10.1016/j.enbuild.2021.111674

Occupant Satisfaction with Certified Green Office Buildings in Chile

Maureen Trebilcock-Kelly, Francisco Castro, Paulina Wegertseder-Martínez, Jaime Soto-Muñoz, and Raúl Ramírez-Vielma

Abstract Contemporary office buildings have primarily adopted environmental sustainability criteria through the guidelines and requirements of domestic or international green building rating systems. These systems incorporate criteria aimed at reducing resource consumption and the building's impact on the environment into their design, as well as criteria to improve indoor environmental quality (IEQ). However, doubts remain about the ability of green rating systems to guarantee occupant satisfaction with the building and its indoor environment in contrast with their counterparts. This research is based on a field study comparing occupant satisfaction in certified green office buildings with conventional buildings in Chile, from a sample of 176 occupants of green buildings and 175 occupants of buildings (N = 351). The study included a survey of occupants and the monitoring of thermal conditions in workspaces. The results showed that there are no significant differences in satisfaction and comfort between green buildings and their conventional counterparts. The occupants of conventional buildings showed trends of higher overall satisfaction for the winter and summer months, as well as for winter and summer temperatures. The other criteria, such as air in winter and summer, showed fairly similar results in both building types.

M. Trebilcock-Kelly (✉) · F. Castro · P. Wegertseder-Martínez
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mtrebilc@ubiobio.cl

P. Wegertseder-Martínez
e-mail: pwegertseder@ubiobio.cl

J. Soto-Muñoz
Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: jaimesoto@ubiobio.cl

R. Ramírez-Vielma
Department of Psychology, Universidad de Concepción, Concepción, Chile
e-mail: rauramir@udec.cl

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1 Introduction

The main objective of green building rating systems is to reduce the environmental impact of buildings through energy performance optimization and resource use efficiency criteria, among others. Issues related to occupant well-being play an important role in these systems, generally as a dimension known as indoor environment quality or IEQ [1] which complements criteria related to energy and environmental impact [2]. In recent years, many countries around the world have developed their own green building assessment systems or methods, responding to the specific needs of their cultural and climatological context [3]. In 2014, Chile developed CES (Sustainable Building Certification in Spanish), which is applicable for both new and existing buildings. Despite the diversity among different systems, several authors note that all benefit occupants in physical, social, and/or psychological ways [4], which could have implications on health and well-being in the medium or long term. However, occupant well-being and comfort may be in conflict with building performance. For example, the energy efficiency of a building is positively affected by a compact building envelope and reduced ventilation rates, but for occupant well-being, the ventilation rate must be higher to dissipate particulate matter. In this conflict, sometimes efficiency is prioritized over occupant wellbeing [5].

For this reason, some authors have examined the ability of these methods to predict occupant satisfaction. Of note are [6] and [7] studies, which conclude that the LEED method does not affect occupant satisfaction with the building or with their workspace, in addition to finding that the positive influence of LEED certification on occupant satisfaction decreases over time. More recent research indicates that there is no complete and consistent conclusion regarding whether occupants are indeed more satisfied with their indoor environment in certified green buildings in contrast to conventional buildings [8–12]. Previous studies by Elnaklah et al. [13] grouped findings regarding the differential impact that certified sustainable buildings have on occupant satisfaction compared to conventional buildings or national benchmarks for indoor environmental quality. Studies suggesting higher occupant satisfaction in certified sustainable buildings for both thermal comfort and indoor air quality (IAQ) accounted for 56.25% of the universe [1, 14], while those showing lower satisfaction with certified sustainable buildings when compared to conventional buildings accounted for 31.25% [6, 14], and 12.5% found no difference between the two [15].

Some authors argue that the diversity of occupant characteristics conflicts with how certification systems are designed to target an average standard user, without considering habits, personal factors, or multivariate behaviors. For example, Almeida et al. [16] observed that people tend to feel a moral obligation towards specific behavior in a green building, such as energy saving, which, therefore, has a positive impact in these terms, but an unknown effect on satisfaction. Context is an important factor in these studies. A review made by Khoshbakht et al. [10] found that research in the UK and US showed negligible differences in occupant satisfaction between sustainable buildings and their conventional counterparts regarding indoor environmental quality, while studies in China and South Korea discovered significantly higher satisfaction in sustainable buildings. The authors argue that the two contexts, western and eastern, result in different characteristics in the quality of design and maintenance of office buildings in general, which influences the baseline of occupant comfort and satisfaction. This suggests that occupant satisfaction in certified sustainable buildings is not universal, as there are local factors that influence this problem and merit further investigation at the contextual level [9].

In Latin America, 2066 buildings had been LEED certified by 2021. Similarly, in Chile, the LEED certification system has had a great impact, with more than 233 buildings certified. Additionally, 55 buildings are certified under the national CES system. Little research has been made on occupant satisfaction in sustainable buildings located in Latin American contexts. More specifically, the Chilean context has two characteristics that make this study particularly interesting: on one hand, the significant number of certified green buildings considering the size of the country, and on the other, the absence of mandatory regulations on energy and indoor environmental quality for office buildings. The latter would suggest that there may be a significant gap between conventional and green buildings. In any case, considerable progress has been made in Latin America regarding the creation of standards and regulations to promote green buildings in the coming years [17]. The objective of this article is to compare the satisfaction of occupants of LEED and CES certified sustainable office buildings with occupants of conventional office buildings located in Chilean cities, taking into consideration dimensions of thermal environment and air quality, in order to expand world knowledge on the subject.

2 Methodology

The methodology was based on fieldwork consisting of a survey of 351 occupants of 9 office buildings, together with measurements of the indoor thermal environment. 176 occupants of 3 certified green buildings and 175 occupants of 6 conventional buildings were studied in the cities of Concepción and Santiago. The survey was conducted in spring 2017 to reveal the occupants' perception of comfort in both winter and summer. A hard copy of the questionnaire was delivered to the occupants early in the morning and collected at the end of working hours in the early evening. It comprised closed-ended questions organized into sections on comfort and satisfaction in the workspace, ability to control the indoor environment, and prioritization of IEQ dimensions. Comfort and satisfaction for winter and summer were evaluated on a scale from 1 to 7 (See Fig. 1). In addition, the thermal environment (operative temperature and relative humidity) of the same offices was monitored on winter, summer, and spring days, using DELTA OHM HD 32.3 equipment, which was placed near the participants.

1. Comfort in the workspace									
How would you describe the typical conditions of your usual work area in winter and summer?									
Temperature	Uncomfortable	1	2	3	4	5	6	7	Comfortable
	Too hot	1	2	3	4	5	6	7	Too cold
	Constant	1	2	3	4	5	6	7	Varies during the day
Air	Still	1	2	3	4	5	6	7	Draughty
	Dry	1	2	3	4	5	6	7	Humid
	Fresh	1	2	3	4	5	6	7	Stuffy
	Odorless	1	2	3	4	5	6	7	Smelly
General conditions	Unsatisfactory	1	2	3	4	5	6	7	Satisfactory
2. Interaction with the indoor environment									
In general, how satisfied are you with your ability to control the indoor environment in your office?									
	Very unsatisfied	1	2	3	4	5	6	7	Very satisfied

3. Comfort and productivity						
Do you consider that the influence of the following parameters on its productivity is						
	Very High	High	Average	Low	Very Low	None
Temperature						
Noise						
Air quality						
Glare						
Lighting levels						

Fig. 1 Questionnaire design

The buildings were selected using comparability criteria in terms of geographic location and year of construction. The buildings are located in the two largest Chilean cities, Concepción (3 buildings) and Santiago (6 buildings), and are distributed equally, green buildings and conventional buildings, in each city. Table 1 shows the year of construction, window-to-wall ratio, and climate control mode for the case studies. Regarding climate control mode (Mode): Heating only (HT) corresponds to those buildings that only have a heating system, but are naturally ventilated by opening windows in summer; Mixed Mode (MM) corresponds to those cases that have an air-conditioning system but also operable windows, which enables natural ventilation through the opening of windows during mild periods; and Heated Ventilated and Air-Conditioned buildings (HVAC) correspond to all those sealed and air-conditioned buildings with no operable windows. As can be seen, all certified green buildings have HVAC systems, while conventional buildings varied between HT, MM, and HVAC. This also relates to window opening options, since green buildings are all sealed, with no option to open windows, unlike conventional buildings where most allow window opening.

Of the 9 case studies, two are LEED certified and one has both LEED and CES certifications. Table 2 shows the LEED credits for the following case studies: Case F, Core and Shell (v2009); Case K, Commercial Interiors (v2009); and Case O, Core and Shell (v2009). Case K is also nationally CES certified as “Outstanding Certification”, with a score of 56 out of 59. Thus, Case K could be considered the greenest building in terms of certification, since it holds a double certification, Gold level in LEED, and “Outstanding” in CES. This case also has the highest number

Table 1 Characteristics of the case studies

Group	Case study code	N part.	Year	Built area (m^2)	City	WWR (%)	Mode	Operable windows
Conventional buildings	A	25	2016	4395	Concepción	70	HT	Yes
	H	29	2009	3100	Concepción	50	HT	Yes
	J	24	2009	12000	Santiago	70	MM	Yes
	L	33	2015	5947	Santiago	70	MM	Yes
	M	36	2016	15931	Santiago	40	HVAC	Some
	Q	28	2006	59000	Santiago	>80	HVAC	No
	Subtotal	175						
Green buildings	F	42	2013	8702	Concepción	70	HVAC	No
	K	38	2016	20150	Santiago	>80	HVAC	No
	O	96	2016	18630	Santiago	40	HVAC	No
	Subtotal	176						
Total		351						

N part: Number of participants; WWR: Window-to-Wall Ratio; HT: Heating only; MM: Mixed Mode; HVAC: Heated, Ventilated, and Air-Conditioned building

Table 2 LEED credits obtained by cases F, K, and O

LEED credits	Case F	Case K	Case O
Subtotal Sustainable Sites	20/28	21/21	22/28
Subtotal Water Efficiency	6/10	11/11	8/10
Subtotal Energy and Atmosphere	11/37	13/37	11/37
Subtotal Materials and Resources	2/13	3/14	4/13
Subtotal Indoor Environmental Quality	3/12	8/17	4/12
Subtotal Innovation	5/6	4/6	6/6
Subtotal Regional Priority	4/6	4/6	4/5
Total	51/110	64/110	59/110
Certification	Silver	Gold	Silver

Table 3 Operative temperature and relative humidity of the case studies

Group	Case study code	Winter		Spring		Summer	
		RH (%)	OT (°C)	RH (%)	OT (°C)	RH (%)	OT (°C)
Conventional buildings	A	60.2	20.3	47.6	21.1	57.0	21.5
	H	44.6	22.5	49.8	22.6	56.4	23.4
	J	41.9	21.7	41.9	21.9	49.0	23.9
	L	34.9	23.4	33.4	23.1	47.2	23.7
	M	43.4	21.0	34.4	22.8	44.3	23.3
	Q	41.8	21.7	38.0	22.5	48.2	23.3
	Average	44.5	21.8	40.9	22.3	50.4	23.2
Green buildings	F	46.2	22.8	48.3	23.1	51.7	23.5
	K	39.7	22.1	34.0	23.3	40.0	24.4
	O	39.8	22.8	47.7	22.9	48.9	24.1
	Average	41.9	22.6	43.3	23.1	46.9	24.0

RH: Relative Humidity; OT: Operative Temperature

of credits of the 3 cases in the IEQ category, which should be reflected in occupant satisfaction (Table 2).

3 Results and Discussion

This study has analyzed a set of data extracted from the comfort survey, comparing the results according to the type of certification that the buildings have, either green (LEED or CES) or conventional (without certification). The results are divided by the climatic seasons. Table 3 shows operating temperature and relative humidity, where green buildings are 0.8K higher in temperature than conventional buildings across all seasons.

Table 4 Characterization of occupants, office type, and building type

		Occupants		
		Conventional building	Green building	Total
Sex	Male	93 (53%)	93 (53%)	186 (53%)
	Female	82 (47%)	83 (47%)	165 (47%)
Age	18 to 25	14 (8%)	6 (3%)	20 (6%)
	26 to 35	73 (42%)	82 (47%)	155 (44%)
	36 to 45	35 (20%)	56 (32%)	91 (26%)
	46 to 55	37 (21%)	18 (10%)	55 (16%)
	56 to 65	15 (9%)	11 (6%)	26 (7%)
	Over 65	1 (1%)	3 (2%)	4 (1%)
Office type	Open plan	134 (77%)	167 (95%)	301 (86%)
	Enclosed, shared space	35 (20%)	2 (1%)	37 (11%)
	Enclosed, private space	6 (3%)	7 (4%)	13 (4%)

The characterization data by building type for the 351 occupants of the 9 buildings are displayed in Table 4. The male/female ratio is equal in both groups of buildings, as well as the number of occupants under 45 years of age, although the age distribution differs slightly between the two groups. Also, the most predominant age group is in the range of 26–35 years, averaging 44% between both groups of buildings. The greatest difference is in office type: green buildings are 95% open plan offices, compared to 77% in conventional buildings.

3.1 *Responses to the Survey*

The average results for each question for the green and conventional buildings groups are graphed in Figs. 2 and 3.

The results show that occupants' perceptions in both winter and summer are very similar in both groups of buildings. Conventional buildings are better evaluated in terms of thermal comfort than green buildings in both winter and summer, with a greater difference in winter.

However, green buildings are better evaluated in terms of temperature in both winter and summer, as demonstrated by the fact that the average occupant response remains around 4, between too hot and too cold, while in conventional buildings this figure moves slightly towards too cold in winter and too hot in summer. The biggest gap is in air quality, where green buildings are better evaluated in both winter and summer in terms of odors and freshness. Concerning overall satisfaction, conventional buildings are rated slightly higher than green buildings.

Figure 4 shows the boxplot analysis of all 351 occupants' responses for satisfaction under general conditions in winter and summer. It can be seen that, on average,

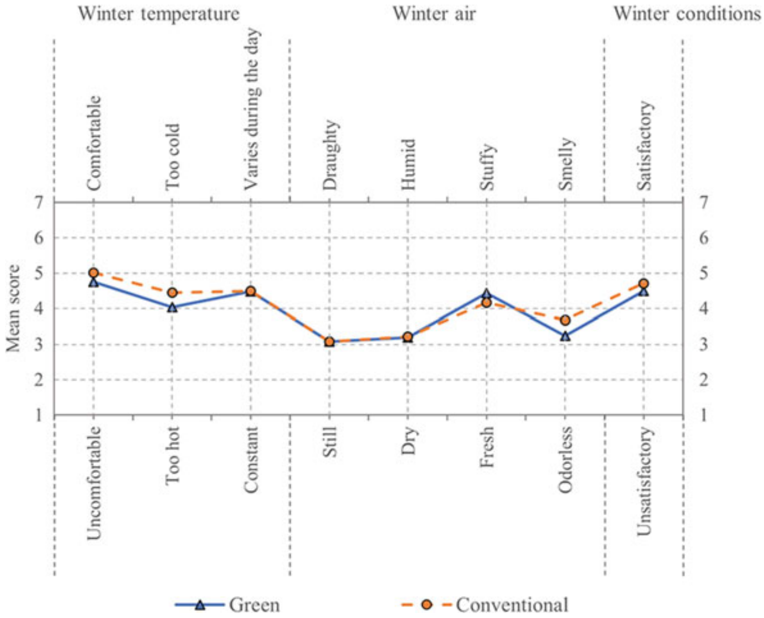

Fig. 2 Occupants' responses comparing green versus conventional buildings in winter

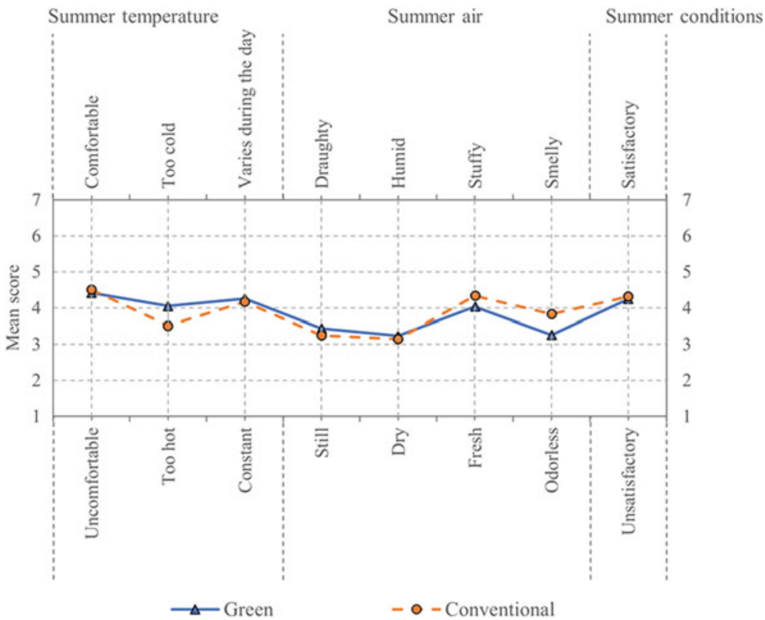

Fig. 3 Occupants' responses comparing green versus conventional buildings in summer

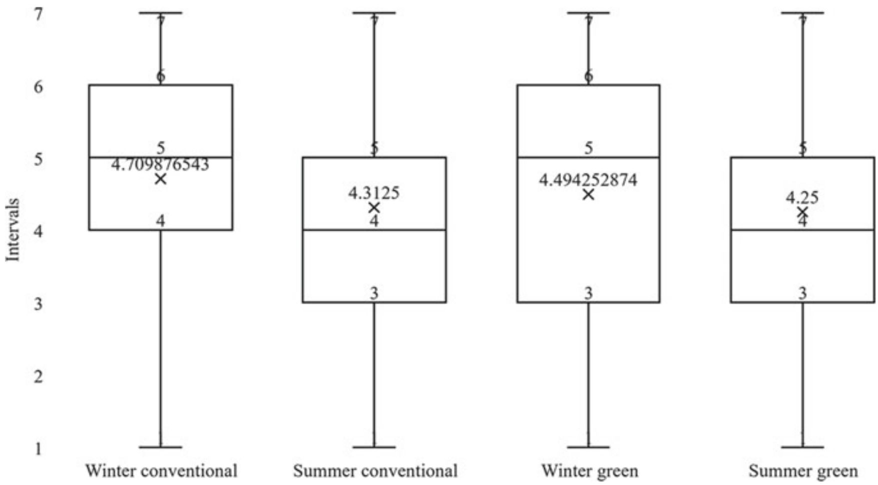

Fig. 4 Boxplot of satisfaction with general conditions in winter and summer for green and conventional buildings

conventional buildings present higher occupant satisfaction than green buildings in both seasons. In summer, satisfaction is lower and has less variation than in winter for both building groups. This can also be verified by comparing the averages of each building type, which demonstrate greater satisfaction for the winter months, especially in the case of conventional buildings.

Occupant satisfaction with general conditions in winter and summer, along with winter and summer temperatures for each case study are shown in Fig. 5. The analysis demonstrates that the maximum and minimum limits of the standard deviation are 4.94 and 4.05 respectively, the overall average of all responses is 4.50, and the standard deviation is 0.44. Case J (conventional) was the best-evaluated building, with an average response of 5.5 in winter and 5.4 in summer.

On the contrary, cases A, H, and F have the lowest average satisfaction of the study, 4.1 and 3.9 respectively, which is interesting considering that case F is certified LEED Silver. As can be seen, most of the cases are within the standard deviation limits except for case J, which has both winter and summer averages above the maximum limits, thus making it the best-evaluated case study for this question on general conditions. In an overview of all cases, most of the responses would seem to indicate that the general conditions are more unsatisfactory for the summer months.

Occupants' perception of how much each indoor environmental factor affects productivity is shown in Fig. 6. It can be observed that, in general, green building occupants perceive factors such as temperature, noise, and air quality, while lighting levels affect their productivity more than conventional building occupants.

There is a more marked difference in the noise factor, which highly and very highly affects the productivity of green building occupants. This may be related to the fact that green buildings have predominantly open plan layouts, where intrusive noise

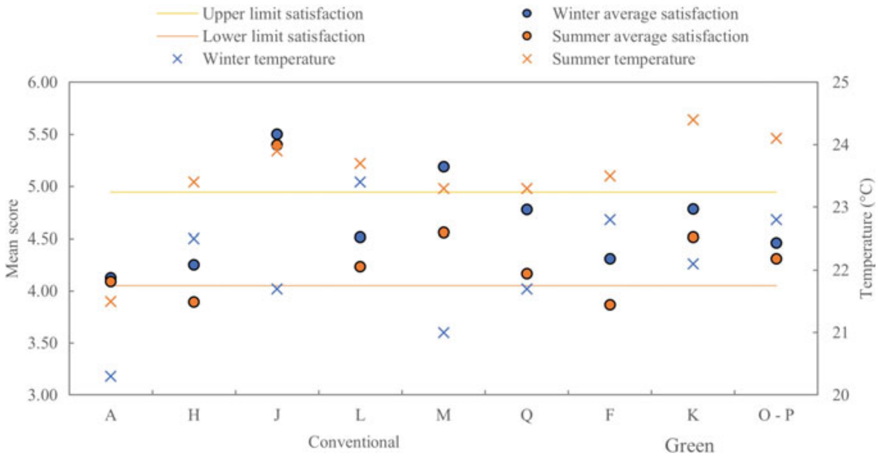

Fig. 5 Satisfaction and average temperatures for each case study

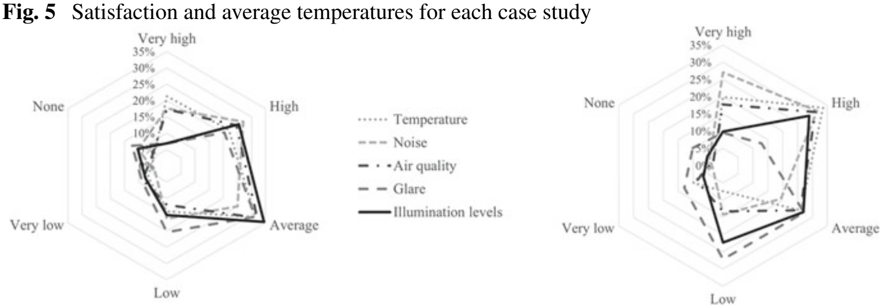

Fig. 6 Indoor environmental factors that affect productivity. Left: conventional buildings. Right: green buildings

can be greater. Glare is the only factor that affects the productivity of conventional occupants more.

Table 5 shows that the occupants of conventional buildings are more satisfied with their opportunity to control the indoor environment. The green buildings that are part of this study do not have operable windows, unlike conventional buildings that generally possess some operable windows, thereby allowing for natural ventilation. This could explain the greater satisfaction with indoor environmental control, which is in line with other studies that conclude that personal control of certain aspects of the environment can result in greater comfort and satisfaction, and sometimes better energy performance [11]. Bluyssen et al. [18] infer that limiting the use of personal controls has a negative impact and causes more symptoms associated with Sick Building Syndrome, and conversely, providing proximity to a window with an outdoor view will favor the occupant's mood and thus their mental health [19]. The variable of window opening may have a significant influence on the results, as it seems important to have control over window openings for the perception of satisfaction and additional control of the user inside the building.

Table 5 Satisfaction with the opportunity to control the indoor environment

Building type	Very dissatisfied						Very satisfied	Average
	1	2	3	4	5	6	7	
Conventional	4%	9%	12%	27%	18%	22%	8%	4.45
Green	17%	12%	19%	26%	12%	12%	4%	3.54

4 Conclusions

This research is based on a field study comparing the satisfaction of occupants of certified office buildings with conventional buildings in Chile, based on a sample of 176 occupants from 3 certified green buildings and 175 occupants from 6 conventional buildings (N = 351).

The main conclusions of this study are that from the data set analyzed of 351 survey responses from 9 office buildings, it can be concluded that there are no significant differences in satisfaction and comfort between green buildings and their conventional counterparts. The occupants of conventional buildings showed trends of higher overall satisfaction for the winter and summer months, as well as for winter and summer temperatures. The other criteria, such as air in winter and summer, showed fairly similar results in both building types.

Green buildings predominantly have an open plan layout and non-operable windows, which could explain why occupants express more sensitivity to noise and less satisfaction with the opportunities to control the indoor environment than occupants of conventional buildings. The best-evaluated building was a conventional building located in Santiago, built in 2009, making it the oldest building in the group. The building has a mixed mode operation system and allows for natural ventilation through the opening of windows.

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References

1. Thatcher A, Milner K (2012) The impact of a ‘green’ building on employees’ physical and psychological wellbeing. Work 41:3816–3823. https://doi.org/10.3233/WOR-2012-0683-3816
2. Loftness V, Hakkinen B, Adan O, Nevalainen A (2007) Elements that contribute to healthy building design. Environ Health Perspect 115:965–970. https://doi.org/10.1289/ehp.8988
3. Cole RJ, Valdebenito MJ (2013) The importation of building environmental certification systems: international usages of BREEAM and LEED. Build Res Inf 41:662–676. https://doi.org/10.1080/09613218.2013.802115
4. McArthur J, Powell C (2020) Health and wellness in commercial buildings: systematic review of sustainable building rating systems and alignment with contemporary research. Build Environ 171:106635. https://doi.org/10.1016/j.buildenv.2019.106635

5. Koponen IK, Asmi A, Keronen P, Puhto K, Kulmala M (2001) Indoor air measurement campaign in Helsinki, Finland 1999 – the effect of outdoor air pollution on indoor air. Atmos Environ 35:1465–1477. https://doi.org/10.1016/S1352-2310(00)00338-1
6. Altomonte S, Schiavon S (2013) Occupant satisfaction in LEED and non-LEED certified buildings. Build Environ 68:66–76. https://doi.org/10.1016/j.buildenv.2013.06.008
7. Schiavon S, Altomonte S (2014) Influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings. Build Environ 77:148–159. https://doi.org/10.1016/j.buildenv.2014.03.028
8. Geng Y, Ji W, Wang Z, Lin B, Zhu Y (2019) A review of operating performance in green buildings: energy use, indoor environmental quality and occupant satisfaction. Energy Build 183:500–514. https://doi.org/10.1016/j.enbuild.2018.11.017
9. Lee J, Wargocki P, Chan Y, Chen L, Tham K (2019) Indoor environmental quality, occupant satisfaction, and acute building-related health symptoms in green mark-certified compared with non-certified office buildings. Indoor Air 29:112–129. https://doi.org/10.1111/ina.12515
10. Khoshbakht M, Gou Z, Lu Y, Xie X, Zhang J (2018) Are green buildings more satisfactory? a review of global evidence. Habitat Int 74:57–65. https://doi.org/10.1016/j.habitatint.2018.02.005
11. Altomonte S, Schiavon S, Kent MG, Brager G (2019) Indoor environmental quality and occupant satisfaction in green-certified buildings. Build Res Inf 47:255–274. https://doi.org/10.1080/09613218.2018.1383715
12. Steinemann A, Wargocki P, Rismanchi B (2017) Ten questions concerning green buildings and indoor air quality. Build Environ 112:351–358. https://doi.org/10.1016/j.buildenv.2016.11.010
13. Elnaklah R, Fosas D, Natarajan S (2020) Indoor environment quality and work performance in "green" office buildings in the Middle East. Build Simul 13:1043–1062. https://doi.org/10.1007/s12273-020-0695-1
14. Gou Z, Prasad D, Lau SSY (2013) Are green buildings more satisfactory and comfortable? Habitat Int 39:156–161. https://doi.org/10.1016/j.habitatint.2012.12.007
15. Leaman A, Bordass B (2007) Are users more tolerant of "green" buildings? Build Res Inf 35:662–673. https://doi.org/10.1080/09613210701529518
16. Almeida LM, Tam VWY, Le KN (2020) Quantification of the energy use due to occupant behaviour collected in surveys: a case study of a green and non-green building. J Build Perform Simul 13(6):777–803. https://doi.org/10.1080/19401493.2020.1825529
17. Zepeda-Gil C, Natarajan S (2020) A review of "green building" regulations, laws, and standards in Latin America. Buildings 10:188. https://doi.org/10.3390/buildings10100188
18. Bluyssen PM, Roda C, Mandin C, Fossati S, Carrer P, de Kluizenaar Y, Mihucz VG, de Oliveira Fernandes E, Bartzis J (2016) Self-reported health and comfort in 'modern' office buildings: first results from the European OFFICAIR study. Indoor Air 26:298–317. https://doi.org/10.1111/ina.12196
19. Ko WH, Schiavon S, Zhang H, Graham LT, Brager G, Mauss I, Lin YW (2020) The impact of a view from a window on thermal comfort, emotion, and cognitive performance. Build Environ 175:106779. https://doi.org/10.1016/j.buildenv.2020.106779

Design Strategies and Tools

Layout Design to Remove Barriers to Comfort, Energy Efficiency, and Solar Systems in Housing

Silvia de Schiller

Abstract This chapter analyzes the role of layout patterns and morphological characteristics of land sub-division in social housing to reduce energy demand while promoting comfort, energy efficiency, and the implementation of solar energy. In this context, the project was focused on design factors and scales in different climates and latitudes of Argentina, from 22° to 55 °S. Based on experiences evaluating social housing programmes at a national level and projects by eight provincial housing institutes in different bioclimatic zones, the target was to achieve a reduction of conventional energy, implementing bioclimatic design strategies, energy-efficient measures, and solar systems. Requirements on a layout scale were essential to achieve solar access in façades and solar systems while providing solar protection to avoid overheating and the use of air conditioning. Design alternatives were implemented for wind protection to improve outdoor spaces in cold climates, and breeze and ventilation in humid subtropical areas. Density, solar access, façade orientation, plot size, and vegetation were evaluated, comparing benefits on both planning and building scales. These have successfully contributed to the development of national housing standards which remove barriers and achieve better housing conditions with less energy demand, a result that is relevant for other regions of the Global South.

Keywords Social housing · Bioclimatic strategies · Energy efficiency · Solar energy

S. de Schiller (✉)
Research Centre Habitat and Energy, Faculty of Architecture, Design and Urbanism, University of Buenos Aires, Buenos Aires, Argentina
e-mail: sdeschiller@gmail.com

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1 Introduction

The integration of layout pattern design for energy efficiency measures and renewable solar systems offers significant economic, social, and environmental benefits, fostering sustainable development, reducing impacts and energy demand while promoting comfort and a better quality of life, according to de Schiller [1].

This chapter aims to show the relevance of a key factor to removing barriers in widely differing environmental conditions in Argentina, shown by de Schiller and Evans [2], potentially useful in the Global South context, according to the IRAM 11603 [3] (See Fig. 1).

To achieve these benefits, the challenge was to promote the implementation of both strategies together within the design resources in the production and use of the built environment, as presented by de Schiller [4]. This required ensuring adequate transfer to policy and legislation to provide support for project development on urban and building scales, with the relevant contribution of professional skills and institutional legal frameworks in the different climatic zones of the country, with possible extensions to other countries of the region, as Jenks [5] points out. Active and solid participation in the social context, from both institutions and future inhabitants,

Locations

N°	Representative locations	Bioclimatic Zone
1	Formosa, Formosa	Ib
2	Tafí Viejo, San Miguel de Tucumán	IIb
3	Salta Capital, Salta	IIIa
4	San Martin, Mendoza	IIIa / IVa
5	San Nicolas, Buenos Aires	IIIb
6	Rawson, Chubut	IVc
7	Zapala, Neuquén	VI
8	Ushuaia, Tierra del Fuego	VI South

Zones: IRAM Standard11.603:2012

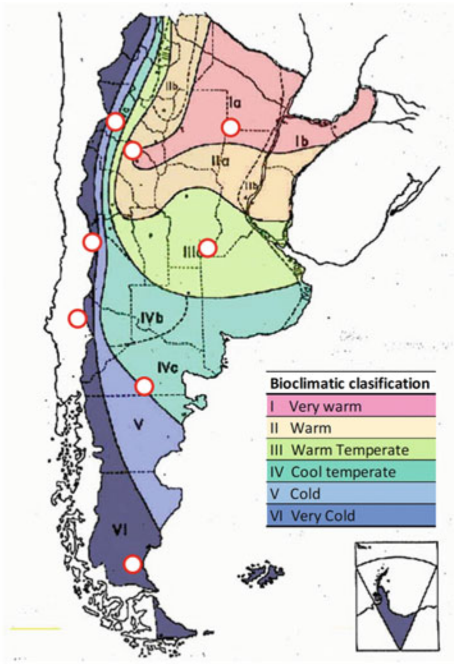

Fig. 1 Location of the eight study projects used to analyze energy efficiency measures to improve thermal comfort, representative of the wide climatic variation and bioclimatic zones found in Argentina, IRAM 11603 [3]

is also required, allowing cooperative actions to achieve positive user control of renewable and passive systems.

In this context, the study presents design strategies for both layout and unit design, with energy reduction measures and the integration of solar energy systems in the development of housing programmes.

Research by de Schiller and Evans [6] shows that these objectives are possible for the implementation of social housing projects at the national level, considering local conditions, and social, environmental, and economic requirements. For this purpose, specific energy-efficient measures at a layout scale are analyzed in the design process of social housing projects. The research is based on the experiences of assessing Provincial Housing Institutes programmes in eight different localities, representative of the broad climatic variation found in Argentina, and relevant for similar conditions in the Global South.

These include major variations from hot and humid sub-tropical climates in the NE, hot and dry climates with large temperature swings in the NW, cold climates at high altitudes with strong solar radiation in the Puna, temperate climates with both high and low-temperature swings at intermediate latitudes, cold and windy climates, extremely low-temperature mountain climates in high latitudes, and cold desert climates in southern Patagonia, as pointed out by Evans and de Schiller [6]. In this framework, examples from the Federal Housing Plan are presented, analyzing the performance achieved with the Minimum Quality Standards of the Secretary of Housing [7], to evaluate results that aim at achieving a 30% reduction of conventional energy use by implementing supplementary measures on the layout scale, considering the efficiency levels required by the programme.

2 Criteria to Implement Sustainable Building Measures

To promote an adequate and effective integration in projects at the house design scale, these measures incorporate the following criteria:

- Improving the thermal performance of the building envelope, with suitable thermal insulation in walls, windows, and roofs, as well as grouping to minimize areas exposed to outdoor air to reduce energy demand with the contribution of efficiency measures, adopting the improved levels established in the IRAM National Standard [8].
- Implementing bioclimatic design strategies in housing units to ensure both solar access in winter and shading in summer. These strategies should be carefully integrated, but not compete with one another, with effective protection from cold and strong winds in cold climates, or to catch breezes in hot climates. This will achieve a better balance between energy demand and supply to promote comfort by improving the environmental performance for users. The IRAM Standard 11603 [3] and other publications from Evans and de Schiller [9] indicate appropriate regional strategies.

- Integrating renewable energy installations on a housing design scale to increase renewable energy supply, and reduce conventional energy use and operating costs in favor of health and well-being. Recent government publications by the Secretary of Housing provide design recommendations [7].

At the layout scale, a series of measures were considered to achieve the project objective: a 30% effective reduction of conventional energy demand and the related environmental impacts in the context of sustainable development for social and economic benefit [4].

3 Design Requirements for Housing Layouts

To complement these measures at the housing design scale, the following requirements were proposed on a layout scale, as they will condition the design of housing projects, in widely varying bioclimatic conditions in different zones of the country.

The following measures played a key role, interacting on both an urban and unit scale: solar access on facades, optimized location and inclination of solar collectors, and potential benefits provided by outdoor spaces on both unit and grouping scales, combined with a local breeze for natural ventilation while ensuring sun and wind protection. According to de Schiller [10], all these measures, implemented at the design decision scale, will also effectively contribute to energy conservation with suitable building envelopes.

As complementary interaction between scales is not always considered in institutional policies for housing project development and production, the professional response also needs technical support to implement integrated criteria. Therefore, this study identifies a vacant niche that needs to be covered to anticipate environmental impacts and avoid conflicting bioclimatic strategies incorporated in the design of housing units without an effective resolution on the layout scale, influencing the environmental and energy performance of housing units.

To clarify the layout design's environmental requirements a research method was developed, applied and structured with specific issues, including solar access on facades and outdoor spaces, while promoting the effective installation of renewable energy systems [11].

4 Research Methodology

The method used in this study focused on solar access, shading, wind protection, and natural ventilation. It considered climatic conditions as the base issues, followed by a selection of key factors, to contribute to removing barriers on the layout scale. This process led to a discussion of conflicting requirements pointing to the relevant results obtained when research is implemented in new legislation for the production of housing projects at a national level with local practical innovation.

4.1 Solar Access and Shading

Energy-efficient and comfortable housing projects require solar radiation incidence in passive systems, by adopting favorable façade orientation and window dimensions in living spaces. To achieve this objective, attention should be paid to the location, latitude, and topography at an urban design scale, along with density, building height, and grouping, while defining compatible house design with form and orientation in individual plots. This helps to define envelope performance and the characteristics of openings by variations between locations. These criteria are essential to achieve winter solar access in cold climates while ensuring summer solar protection in hot and humid climates. The IRAM Standard [3] recommends orientations to achieve the required levels of solar radiation.

Although favorable solar access in both private and communal outdoor areas does not directly affect conventional energy demand, it contributes to improving comfort levels in outdoor and intermediate spaces, as well as the indirect impact on indoor spaces. It also encourages vegetation growth to improve the local microclimate.

At the same time, solar collectors for domestic water heating, considering their limited storage capacity, require effective sun access all year round. According to the Energy Secretary [12], in summer, they can generate more useful energy than needed for hot water supply, while, in winter, solar energy may be insufficient to satisfy demand.

To achieve both, the solar collectors' slope is critical to optimize annual performance while considering the potential impact of partial shading which can significantly affect the effective final energy efficiency result.

Additionally, according to the recommendations of the Energy Secretary [13], grid-connected photovoltaic installations require a similar orientation, but a lower inclination for solar access to optimize total energy generation over the year to obtain the maximum economic benefit for the user.

Special care is needed to avoid partial shading projected by cables, posts, water tanks, and other obstacles from nearby surroundings or housing units.

The impact of possible future extensions of adjacent houses to the north should also be considered to avoid unwanted shading.

In this context, it is relevant to note that solar access and solar protection in building design depends on local climate conditions, such as in hot climates at both humid or dry lower latitudes, and cold and temperate climates at higher latitudes in the south, as the following analysis using IRAM Standards 11603 [3] shows.

- In *hot climates*, sun access design must consider the need for shading with solar protection in summer months, particularly by optimizing north-facing orientations, and allowing access to winter sun compatible with solar protection elements such as overhangs and pergolas with vegetation, while unfavorable west-facing orientations can receive limited sun in winter but suffer excessive summer solar radiation.

- In *cold and temperate climates*, heat conservation requires significant control of surface areas exposed to outdoor conditions, where the form factor, the relation between the external surface and building volume, depends on the volume and grouping of the housing units. The IRAM Standard 11604 [14] shows the importance of the total surface area of walls and roofs in contact with the outdoor environment on the volumetric heat loss coefficient.

4.2 Wind Protection and Natural Ventilation

The impact of wind increases heat losses in winter, an aspect that is critical in cold and temperate climates as a result of two basic mechanisms that promote heat transfer from the external surface of walls and roofs to the outdoor air and the increased heat losses due to higher ventilation rates, as Evans and de Schiller [9] explain. This is due to cold air infiltration through doors, windows, and ventilation vents, a relevant factor in the cold and windy climates of Patagonia and the high Andes region. In this context, design decisions on housing layout play an important role by reducing wind exposure considering density, outdoor space proportions, and distances between buildings.

As de Schiller [15] points out, this can be achieved with favorable width–height relationships, as well as the form and orientation of both housing units and grouping. It should be noted that, in general, a lack of professional knowledge on wind design strongly affects project development. Appropriate tools can be used to overcome this deficiency such as computational fluid dynamics studies or wind tunnel tests during the design process.

On the other hand, in the hot and humid climates of the NE Region of Argentina, improved air movement achieved through cross-ventilation can reduce or even eliminate the demand for artificial conditioning by mechanical means, with the corresponding reduction of costs and environmental and health impacts. This cross-ventilation strategy requires suitable spaces between buildings considering their form and height, windows on opposite sides of the housing units, and interior design to facilitate free indoor air movement. In calm situations, without effective natural air movement, ceiling fans offer comfort with very low energy demand, but this will require a suitable floor-to-ceiling height, which can affect building heights and the eventual length of wind shadows on the layout scale.

4.3 Key Factors on the Layout Scale

Energy savings achieved through insulation and bioclimatic design must be compared with the embodied energy of building materials and construction system components.

At the same time, planning decisions on layout and density affect the demand for urban infrastructure to supply water, electricity, gas, etc., as well as the economy regarding road and transport networks. Thus, these factors generate the following impacts:

Embodied energy. While building materials and manufacturing processes require conventional energy and generate greenhouse gas emissions (GHG), the design and grouping of housing units can help to reduce the volume of materials used. The possibility of sharing party walls is a relevant factor when estimating the environmental and energy performance of the building envelope. However, in seismic zones, double-party walls are required to separate adjoining structures.

Urban infrastructure. The cost of urban infrastructure, with sewer, water, electricity, and gas distribution networks depends on the urban design and density of the housing complex.

Building plots. The lot size substantially affects the ability to implement bioclimatic design strategies on a housing unit scale. In turn, the design of the urban fabric is an important factor that influences the definition of the infrastructure for each unit, in extension and distribution.

Transport. The design of housing projects with increased population density also promotes access to public transport and community facilities, improving both the economy and accessibility, a relevant factor in the design of new settlements in peripheral urban areas.

These factors are linked and strongly affect the design approach to promote sustainable housing, complementing the sun and wind requirements analyzed in the previous section.

The response to all these factors during the initial housing programme and layout planning stage is essential to contribute to an effective design proposal. These will then guide planners and designers, considering project consolidation and further construction, to prevent energy inefficiency and poor comfort levels, avoiding or reducing dependence on artificial conditioning over the housing life cycle.

5 Discussion of Conflicting Requirements

In this context, it is relevant to consider conflicts between requirements to clarify the process of analyzing specific conditions together with the potential contradictions between them, for example:

- Different requirements for the implementation of measures to optimize solar gains in colder seasons or sun protection in warmer months.
- Conflicting requirements between suitable orientations to achieve adequate cross-ventilation or wind protection, and those needed for solar gains in winter and sun protection in summer.
- Higher densities are required to optimize the compactness of the built fabric for wind protection and heat conservation while lower densities improve solar access for the housing units and outdoor spaces.

Other factors that may limit the implementation of the requirements established in the project include the plot size and the orientation of adjacent urban subdivisions within the urban fabric of the city where the new housing complex will be built.

It should be noted that the experimental housing groups studied in the analysis of the R&D project include the development of different alternative designs following the programmed conditions to compare with increasing levels of energy efficiency considered in the study. These housing units, which had to be sited on plots with four different orientations, have a typical land subdivision and a plot size of 10 m wide. Within these conditions, designs were developed for four different cases to be compared and evaluated using the following alternatives:

- Existing conventional housing, designed by the local provincial housing authority, was used as a "reference" case.
- This was compared to units with the same design incorporating improved thermal insulation of the building envelope.
- The next level applied bioclimatic strategies in an improved passive design to achieve the benefits of layout and grouping of housing units.
- The final level included solar systems for water heating and photovoltaic modules for power generation integrated into the improved passive design.

However, it should be noted that the inclusion and integration of these variants in a single project of 16 houses with different designs limited the possibilities of achieving optimal groupings at an urban scale. The different house designs in adjacent plots reduce the benefits of grouping, as the conflicts in the following comparative examples show.

5.1 House Orientation Versus Grouping & Layout

In plots with north and south access, the design of the housing unit achieves good sunlight on the facades of the front or rear, respectively, while also allowing grouping

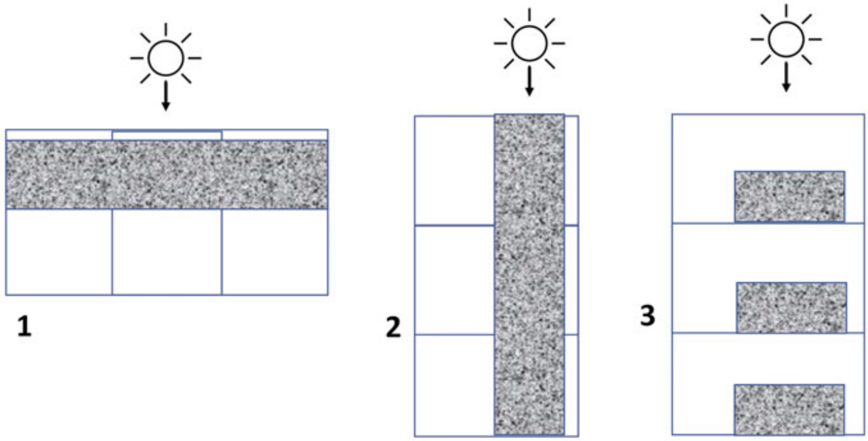

Fig. 2 Orientation and grouping for solar access: 1. Row housing on east–west street; 2. Row housing on north–south street with poor solar access; 3. Separated housing on north–south street with better solar access but increased heat loss

houses with shared party walls, reducing the wall surface in contact with the outside air, thus leading to greater energy efficiency.

On the other hand, in plots with east or west access, house design with favorable solar gains requires north-facing facades to face the lateral party wall. This situation can be compromised by the addition of an upper story in the adjacent unit to the north. So, the building design, to optimize solar gains, also requires separate units without the possibility of shared party walls, increasing energy losses in winter due to a larger surface exposed to wind and outside air (See Fig. 2).

In this case, it is relevant to note that the distance between units is limited by these orientations due to the 10 m standard plot width, reducing the possibility of achieving adequate solar access in mid and high latitudes.

To implement effective cross-ventilation, the main rooms should be orientated towards the prevailing winds with an acceptable variation of 45° in the horizontal plane, preferably avoiding ventilation through two bedrooms, due to the loss of privacy and lower wind speed. With a 10 m standard plot width, good cross-ventilation is achieved in units with two bedrooms on the ground floor, although three-bedroom units require wider plots. As an alternative, a two-story house allows improved exposure to both the breeze and sun with a larger façade surface, but increased height may need more distance between units.

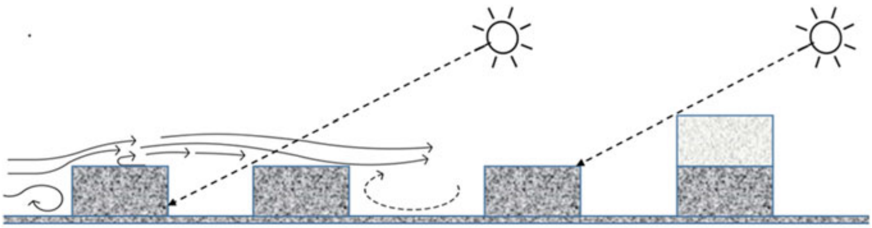

Fig. 3 Spacing for solar access, wind protection, or breeze for cross-ventilation, with an additional story extension producing winter shade

5.2 Layout Density Versus Sun and Wind Protection

Strong Patagonian winds increase energy demand for heating and decrease comfort conditions in outdoor spaces. In this case, cold winds require reduced distances between buildings and a layout to achieve the mutual protection of the units. At the same time, to receive adequate sunlight, more space is needed between built volumes, due to the low angular height of the sun in these higher latitudes from 40 to 55° South (See Fig. 3).

By implementing an environmentally conscious design, it is then possible to achieve favorable access to the winter sun from the north and protection from the strong prevailing winds from the west and southwest, typical of the Patagonian region of the country.

5.3 Layout Density Versus Solar Access

On 10 m wide plots with east or west access, only 4 m remain between the passive solar system and the party wall of the adjacent house, 2.80–3 m high, to the north. According to de Schiller [16], this proportion of outdoor space strongly limits access to the sun for windows or passive solar systems at latitudes above 30°. If the neighboring houses build a second-floor extension at a later stage, the projected shadows reduce further the favorable contribution of winter solar radiation (See Fig. 4).

5.4 Initial Housing Design Versus Subsequent Extensions

According to the Argentine Social Housing Policy and regulations, the initial design of two-bedroom housing units should allow for a future third-bedroom extension. It should be noted that the implementation of effective cross-ventilation and direct winter sun access can be received in all the main rooms of two-bedroom single-story units with conventional 10 m frontage plots.

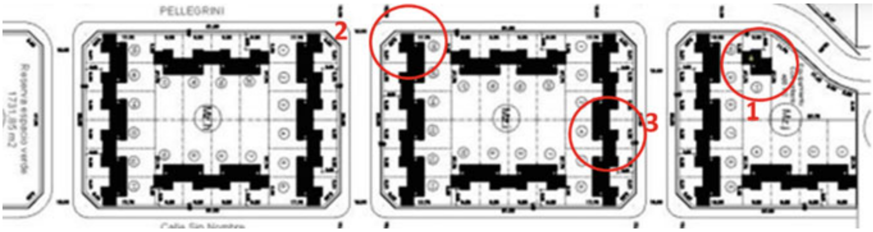

Fig. 4 Housing layout and energy demand for heating, central region Bioclimatic Zone III: 1. Free-standing house; 2. End of terrace House, 5.5% saving; 3. Mid-terrace house, 10.9% saving

However, with a later extension, the third bedroom receives no winter sun in temperate and cool climates, and cross-ventilation could be limited or difficult in hot humid climates. Therefore, better conditions can be achieved on a wider plot of 12.5 m frontage depending on the site available, even though this increases the cost of land, access roads, and urban infrastructure extensions.

Alternatively, two-story houses can be designed, even though the higher units cast longer shadows and reduce air movement on an urban scale. In this framework, the conditions related to land tenure, property law, and land use regulations, typical in Latin-American countries, have to be considered, as a relevant factor that determines the possible future modification and extension of each dwelling. However, weak building control exercised by municipal authorities is another situation that produces informal additions to housing units, exercised without building permits or compliance with local building codes.

6 Achieving Benefits on a Layout Scale

The following relevant benefits can be achieved by using appropriate project design measures, considering orientation and energy performance [11]:

Planned orientation. In existing homes with improved thermal insulation, as in the case of the Zapala housing project, Neuquén Province, 40°S, varying the orientation from NE to SE increased energy demand by approximately 5%, with the same construction cost. However, with an improved passive design, the variation in energy demand was minimal in homes with four different orientations since all the windows and passive solar systems had favorable NE and NW orientations.

Energy performance. A study of the energy demand in the four housing design categories indicates the magnitude of potential reductions. These estimates consider the total conventional energy demand for hot water, heating, cooking, and other uses. Energy inputs include the contribution of conventional energy, the metabolic heat of occupants, direct solar radiation through windows, and indirect radiation provided by passive solar systems. The values depend on variations of the plot subdivisions, the layout design, and the proposals for house plans, as well as the contribution of the construction, and characteristics of materials and the building system. They also vary according to weather conditions, the supply of solar radiation, and latitude, with possible adjustments for location and height above sea level. For example, in very cold climates at high latitudes with limited solar radiation, housing clusters, and compact shapes can offer greater benefits than increasing the north-facing surface area, while in cold and temperate climates at low latitudes, capturing favorable solar resources offers greater benefits than compact forms.

Another factor to consider when evaluating energy benefits in design decisions and setting up the layout is the great variation in the total demand for housing in different bioclimatic regions. The energy demand for heating and hot water in cold climates is more than double that in temperate climates, while solar energy capture can be halved. Thus, the priorities for urban design measures vary considerably in different regions. The performance of solar collectors and photovoltaic panels also varies according to their orientation to the sun.

It should be noted that units are often located parallel or perpendicular to the street frontage, which also affects the performance of passive solar systems as the Energy Secretary [12] warns. As an example, the results of efficiency losses are shown for different solar systems according to orientation in the Buenos Aires Province, 34°S:

- *Photovoltaics:* a PV module in Buenos Aires loses only 2% of its annual generation with a change from the optimal north orientation to 30° to the E or W of N, 5% with a 60° variation, and 9% with east or west orientation.
- *Thermal solar collectors:* the useful energy for heating water decreases from the optimum facing north, decreasing 2.5% as it swings 30° east or west. With a swing of 60° from the north, the decrease is 7%, and at 90° reaches 15%.
- *Passive solar systems:* the reduction in useful solar energy is approximately 22% with a NE or NO orientation, compared to the optimal to the north, although the result may depend on other factors that affect shadow projections. With east and west orientations, the contributions of solar systems are minimal. It should be noted that solar systems can contribute up to 30% of heating energy demand in favorable designs in this temperate climate.
- *Grouping:* houses with a shared party wall reduce heat losses by approximately 1.5–2%, while a terrace house with two party walls in contact with adjacent units reduces losses by 2.5 to 3%.

A favorable urban design with suitable orientations of the units, adding all these factors together, can provide an additional 5.5% saving of conventional energy, with improved comfort at little or no cost, compared to a typical design layout with no consideration of sun and/or wind orientations, based on an average reduction for projects in different climate zones, Table 1.

Table 1 Reduction in conventional energy with efficient building and solar gain

Measures to improve comfort		Without better grouping (%)	With better grouping (%)	Saving (%)
Housing design	Improved wall insulation	6.1	7.5	
	Improved roof insulation	7.8	7.8	
	Reduce thermal bridges	1.5	1.7	
	Improved windows	7.9	7.9	
	Control of ventilation losses	5.1	5.7	
	Insulation of floors	0.7	1.0	
	Reduction in conventional energy demand for heating	29.1	31.5	2.4
Improved solar gains	Better orientation less shading	4.1	6.0	
	Avoidance of winter shading	2.5	3.5	
	Replacement of conventional with solar energy	6.6	9.5	2.9*

* Site orientation, layout, and density reduce optimum solar gains, de Schiller [4]

7 Results of Implementing the Research

The results, although they achieve modest reductions in the conventional energy demand, obtained key environmental benefits at very low cost, and the contributions enhance measures on other design scales, both in architectural design and construction. This saving, estimated at 31%, contributes to a total average conventional energy saving, through improved thermal envelopes and construction details and the application of bioclimatic design strategies on an urban layout and unit scale, together with rational design integration and feasible implementation of both thermal and PV modules solar collectors.

These particular issues integrated into a general overview of the relevance that energy demand must be considered at the project design stage, but as mentioned previously, these solar installations, with higher costs, can then be incorporated after construction, in subsequent improvements and/or extensions, only if the basic conditions for solar access were considered from the very beginning of the layout design process.

The energy and economic benefits are greatest in colder high-latitude or high-altitude locations, while the social value of improved comfort and use of outdoor space are additional advantages in all locations. Design decisions on an urban layout scale have a significant impact on energy demand, complementing measures on architectural and construction scales. In this regard, it should be emphasized that measures such as thermal roof insulation or improved window quality can be incorporated over time but initial design decisions on subdivisions, plot size, access, and orientation, are fixed and cannot be modified once the houses are built.

In this way, the influence of orientation and plot size generates long-term impacts, which last beyond the lifetime of the buildings. Additionally, subsequent extensions, typical of many housing projects, often added to meet the requirements of growing families, increase the useful space but may decrease environmental quality, generating greater dependence on conventional energy supply.

At the same time, densification offers economic benefits in the provision of transport, efficient land use, and access to urban infrastructure, as de Schiller [16] mentions, although it can limit the flexibility and reduce the environmental quality of housing, as explained by the Secretary of Housing [7].

As a result of the studies undertaken, improved thermal standards for social housing were implemented by the National Housing Authority, and the Ministry of Internal Affairs, such as better external envelope performance and solar water installations in all regions of the country, effectively contributing to removing barriers in social housing projects in the context of sustainable development, and promoting innovative legislation for social housing projects, as Evans and de Schiller [17] show.

8 Conclusions

Estimates of potential energy-saving measures on a housing planning scale achieve the modest but significant long-term advantages with a favorable cost–benefit ratio.

The combination of decisions on a project scale with complementary measures at the architectural and construction scale enhances energy efficiency while achieving significant reductions in conventional energy demand and resulting greenhouse gas emissions.

It should be noted that design decisions and energy-conscious measures on a layout scale also offer the benefits of improved comfort in indoor and outdoor spaces.

In multiple ways, removing barriers in the application of bioclimatic design strategies at the scale of housing groups and general layout design decisions in a different and complementary view, integrated with energy efficiency measures and the implementation of solar renewable energy, contribute to the goal of achieving more sustainable social housing development in the Global South.

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References

1. de Schiller S (2020) Desafís de la eficiencia energética. In: de Schiller S (ed) Sustentabilidad, Eficiencia Energética y Renovables en Vivienda Social, Ediciones CIHE, Secretaría de Investigaciones, FADU-UBA. Buenos Aires, Argentina
2. de Schiller S, Evans JM (2019) Vivienda sustentable y eficiencia energética: el desafío del diseño en la ciudad contemporánea. In: XXIII Congresso y XXXVIII Encontro Arquisur 'A producao da Cidade Contemporánea no Cone Sul: desafíos e perspectivas da Arquitetura e do Urbanismo', Belo Horizonte, Brazil
3. IRAM (2012) Norma IRAM 11.603, Aislamiento térmico de edificios. Clasificación Bioambiental de la República Argentina. Instituto Argentino de Normalización y Certificación, Buenos Aires, Argentina
4. de Schiller S (2014) Diseño bioclimático, eficiencia energética y energía solar para la reducción de energía convencional en vivienda social. In: ASADES-ISES, Oberá, Misiones, AVERMA, INENCO, UNSa, Salta, Argentina
5. Jenks M (2000) Sustainable urban form in developing countries? In: Jenks M, Burgess R (eds) Compact cities: sustainable urban forms for developing countries. Spon Press, London, UK, pp 1–6
6. de Schiller S, Evans JM (2000) Urban climate and compact cities in developing countries. In: Jenks M, Burgess R (eds) Compact cities: sustainable urban forms for developing countries. Spon Press, London, UK, pp 117–124
7. Secretaría de Vivienda (2019) Estíndares Mánimos de Calidad para Viviendas de Interés Social, Marco para la promoción de viviendas inclusivas, asequibles y sostenibles. Secretaría de Energía, Ministerio de Hacienda, Presidencia de la Nación, Buenos Aires, Argentina
8. IRAM (1996) IRAM 11605:1996, Acondicionamiento térmico de edificios. Condiciones de habitabilidad en edificios. Valores míximos de transmitancia térmica en cerramientos opacos. Instituto Argentino de Normalización y Certificación, Buenos Aires, Argentina
9. Evans JM, de Schiller S (1991) Diseño Bioambiental y Arquitectura Solar, 2nd edn. EUDEBA Editorial de la Universidad de Buenos Aires, Buenos Aires, Argentina
10. de Schiller S (2019) Eficiencia energética edilicia, ASADES 2017, San Juan. In: Casabianca GA (ed) Caminos alternativos hacia una matriz energética más sustentable, PIUBAES, Programa Interdisciplinario de la Universidad de Buenos Aires en Energías Sustentables, EUDEBA Editorial de la Universidad de Buenos Aires. Buenos Aires, Argentina
11. de Schiller S (2017) Energía e impacto ambiental en ciudades. In: Casabianca GA (ed) La UBA y la Energía: Desafíos energéticos en la Argentina?: PIUBAES, 1st edn. EUDEBA Editorial de la Universidad de Buenos Aires, Buenos Aires, Argentina, pp 33–38
12. Secretaría de Energía (2019) Guía Rápida para la Implementación Provincial de la Ley Nacional de Generación Distribuida Renovable. Secretaría de Energía, Ministerio de Hacienda, Presidencia de la Nación, Buenos Aires, Argentina
13. Secretaría de Energía (2019) Ley 27424, Régimen de fomento a la generación distribuida de energía renovable integrada a la red eléctrica pública. Secretaría de Energía, Senado de la Nación, Buenos Aires, Argentina
14. IRAM (2001) Norma IRAM 11604:2001, Aislamiento térmico de edificios. Verificación de sus condiciones higrotérmicas. Ahorro de energía en calefacción. Coeficiente volumétrico

G de pérdidas de calor. Cálculo y valores límites. Instituto Argentino de Normalización y Certificación, Buenos Aires, Argentina
15. de Schiller S (2005) Aporte bioclimático a la sustentabilidad de espacios urbanos. In: VII Encontró Nacional e VI Encuentro Latinoamericano de Confort en Ambiente Construido, ENCAC-ELACAC, Asociación Nacional de Tecnología del Ambiente Construido (ANTEC), Maceió, Brazil
16. de Schiller S (2001) Sustentabilidad y transformación del tejido urbano en la cuadrícula latinoamericana. In: Falú A, Carmona M (eds) Globalización, forma urbana y gobernabilidad. TUD-UNC, Delft-Córdoba
17. Evans JM, de Schiller S (2017) The role of passive low energy design in energy labelling of housing. In: Proceedings passive & low energy architecture, PLEA 'Design to Thrive', Edinburgh, Scotland

Adaptive Passive Measures for Tropical Climates—A Case Study for Mauritius

Mahendra Gooroochurn

Abstract Tropical climates, typically marked by high relative humidity, require bespoke considerations to improve energy efficiency and thermal comfort in built spaces. With ever more adverse weather patterns caused by climate change, evidenced by temperature extremes, and rising peak electrical power demand caused by greater reliance on air-conditioning systems, the carbon footprint of buildings is expected to increase progressively unless passive measures based on bioclimatic design considerations are integrated into new constructions and retrofitted in the existing building stock. This chapter reviews the passive measures tested in tropical climates to rate their efficacy, and identify barriers that have prevented their widespread adoption. As building systems and contexts become increasingly complex, and with the prevalence of micro-climates, bioclimatic design tools coupled with adaptive passive measures are needed to effectively define and regulate the interaction of the building envelope with the environment it is situated in. The warm coastal region and the colder central plateau of Mauritius are taken as a case study to present the necessary customization and modulation of passive measures. Furthermore, this chapter looks ahead to the application of IoT and machine learning algorithms for predictive control of building elements.

Keywords Tropical climate · Passive design · Adaptive control · Machine learning · Predictive control

M. Gooroochurn (✉)
Mechanical and Production Engineering Department, Faculty of Engineering, University of Mauritius, 80837 Reduit, Moka, Mauritius
e-mail: m.gooroochurn@uom.ac.mu

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1 Introduction

The rapid rate of urbanization has placed unprecedented pressure on utilities, where a direct and unsustainable coupling has been observed between carbon emissions and an increase in built-up areas. This has been accompanied by an increase in natural disasters including flooding, heat waves, drought, and climate extremes linked to climate change. Climate change is today considered as one of the most pressing challenges facing humanity, with a consensus being sought at the COP26 conference on climate targets to stay within the elusive goal of keeping global temperature rises under 1.5 °C. The built environment, as a mitigation measure, is a central theme in discussions to achieve this goal, given the significant resources associated with the construction, operation, and demolition of buildings [1].

However, adaptation measures will be just as important to deal with the consequences of climate change. The carbon emissions associated with the built environment are related to the energy used in running active building systems such as lighting, air-conditioning equipment, and mechanical ventilation seeking to provide a suitable indoor environment for occupants. The increased use of HVAC systems, the consequence of harsher weather patterns, has been a concern around the world, while a lack of development strategies has also been linked to the increased cooling requirements [2]. The increased installation of air-conditioning equipment recently in Mauritius in response to harsher summers, and the associated increase in peak electricity demand, are clear evidence of an unsustainable correlation between carbon and building footprints.

The fundamental need to consider bioclimatic design when incorporating passive elements in building design is well documented and heavily emphasized in green building design literature. Moreover, the close correlation of indoor environmental quality and energy use with the prevailing dynamic ambient conditions means that the ability to modulate the influence of passive elements on the interaction with the building envelope can reap further rewards. The objective of this chapter is to first present the main research findings reported in the literature on bioclimatic design principles for passive building design, with a focus on tropical climates, followed by the efficacy of passive and hybrid systems investigated in Mauritius, including the automation of passive measures. The results obtained are set in the context of Mauritius' climate zones to show the appeal of implementing IoT and machine learning techniques to modulate the influence of passive systems on the building envelope, and thereafter the indoor environment, as opposed to keeping them as static elements. Finally, research is provided on the development of customized AI algorithms for different building typologies, proposing a 3 × 3 building simulation model.

The chapter is structured as follows: Section 2 describes the tropical climate of Mauritius followed by a review of passive design research findings in Sect. 3. Section 4 focuses on bioclimatic design to discuss the potential of using passive measures for the different climate zones in Mauritius based on past experimental and simulation studies, including investigations on the automation of passive measures.

Section 5 concludes the chapter and provides guidelines for applying IoT technology and AI algorithms to regulate the influence of passive measures.

2 Tropical Context of Mauritius

Mauritius has a complex climate distribution, that has not been segregated into climate zones for building performance assessment. The presence of micro-climates further complicates establishing distinct climate zones, although such a delineation will be key to establishing reference (or notional) building parameters. This is seen as a key step in the performance assessment of future buildings, e.g., the Part L regulations in the UK and the ASHRAE 90.1 performance rating method, where baseline energy (or carbon) performance is required to make benchmark comparisons. In general, Mauritius has a high level of humidity across the island and has a high-altitude central plateau with a warm climate regime in summer (October–March) and a cold one in winter (April–September). This would warrant cooling in summer and heating in winter, although fixed heating systems are not common and people in these regions resort to small portable air-based heating systems when needed.

On the other hand, the focus has been on installing fixed air-conditioning systems across the whole island, especially in commercial buildings, although recent years have witnessed an increase in HVAC installations in the residential sector too, mainly the result of harsher summers under the effects of climate change. The situation throughout the lowlands and coastal regions has been different, with a greater need for cooling, although winter temperatures generally provide suitable conditions for thermal comfort without the need for active cooling. However, a marked change has been observed over recent years, again attributed to climate change, where record low temperatures have been observed in conventionally warm areas, e.g., at Pamplemousses in the north of the island.

The tropical climate does not experience significant seasonal and diurnal variations like other climate types, with peak summer temperatures of around 35 °C and winter temperatures as low as 12 °C being common in Mauritius, although recently a record low temperature of 8 °C was reported during the winter of 2021. The diurnal temperature variation involves fluctuations of around 10 °C, which provide good scope for night flushing in summer periods. Unfortunately, this period coincides with the mosquito breeding period, limiting the ability to harness the cooler external air, while a lack of pressure gradient indoors can also limit airflow through these spaces.

The solar position does not change dramatically across seasons, with the sun rising around the Northeast–East and setting in the Northwest–West orientations at the winter solstice, and rising around the Southeast–East and setting around the Southwest–West orientations at the summer solstice as far as the azimuth component of the solar angle is concerned, with a maximum elevation of 90° at the summer solstice and a minimum elevation of around 45° at the winter solstice. Knowledge of the solar position can result in interesting passive design as illustrated in Fig. 1 for overhang design, and the use of deciduous plants as shown in Fig. 2.

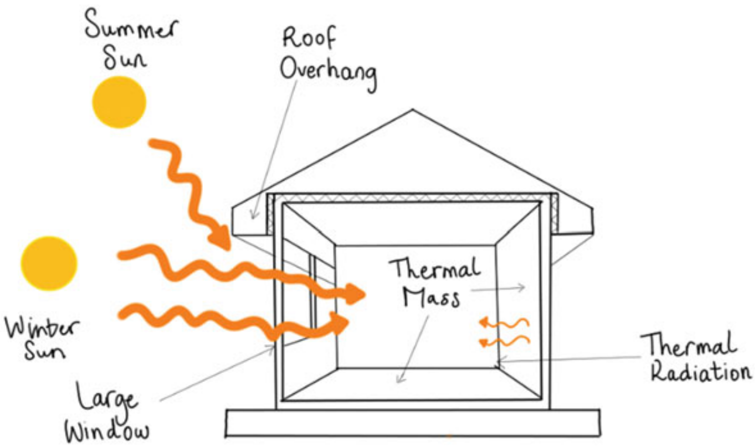

Fig. 1 Summer and winter sun positions [3]

Fig. 2 Use of trees to provide flexible shading on building facades

The increased dependence on active cooling is a clear indication of the overarching need to limit heat gains across Mauritius' climate zones, but adaptive passive measures may be a better avenue for certain areas. Furthermore, reduced costs for renewable energy systems such as solar PV (priced at \$10.50 per kW for ground-mounted and \$17.50 per kW for roof-mounted in the cost model proposed by [4]) and solar thermal systems (with a price range based on current market rates, starting from around \$500 for a 150 L non-pressurized system to around \$1300 for a 300 L pressurized system) over the past decade, coupled with the good solar yield in tropical climates (mean annual average insolation that varies from 1237 $\mathrm{kW\,h/m^2}$ to 1901 $\mathrm{kW\,h/m^2}$ over Mauritius [5]), means their integration into the built environment will allow further improving the energy performance with a favorable return on investment. Nevertheless, achieving maximum energy efficiency using passive design measures should remain the priority before considering any renewable energy system, as depicted in the workflow for a holistic, integrated building design process recommended by green building frameworks such as LEED[1] and BREEAM.[2] With

[1] https://www.usgbc.org/leed.

[2] https://www.breeam.com/.

the advent of renewable energy sources at affordable prices and increasing efficiency of conversion, their integration into the energy mix of buildings can be seen as an effective move to green for the built environment, but renewable energy should be considered when the energy efficiency has been optimized with due consideration of passive design and building energy systems control.

Moreover, since erecting buildings necessarily leads to disruptions in the site's natural characteristics, not considering solar positions and regenerating natural systems by integrating vegetation into the built environment can lead to serious disruptions in indoor and outdoor spaces, as witnessed in the planned Hanoi capital city [6] and Putrajaya in Malaysia [7–9].

3 Bioclimatic Design and Passive Measures

Bioclimatic design pertains to the due consideration in the building design process of the prevailing climate at the project site, and passive measures relate to the incorporation of building elements as part of the building envelope itself so that the building can regulate the air, heat, and light transfer between the indoor and outdoor environments. The importance of bioclimatic design has led to active research into tools and methods that consider the climate and thus influence building design [10, 11]. Glazing is one of these tools, and it is a crucial element of a building thanks to its functional (access to views, daylight, and air movement) and aesthetic attributes, but at the same time, it allows direct solar radiation to penetrate indoor spaces, generally, with high thermal parameters (thermal conductance, U-value and, solar heat gain coefficient, SHGC). The extent to which this key element can be integrated, as characterized by the Window-to-Wall (WWR) ratio, has been attracting the interest of several researchers [12, 13].

The design of shading devices for windows needs to consider the range of solar elevation angles that will be encountered along that particular orientation throughout the year, and whether there is a strict need to keep out direct solar radiation throughout the year or not. Weather variations over seasons or days in a given season can be tackled simply by installing flexible shading devices such as awnings, louvers, and shutters (See Fig. 3), although this places the responsibility on the user to appropriately control the systems, and there lies the appeal of having simple mechatronic systems to control the deployment of these passive measures and optimize the harnessing of natural resources by monitoring relevant external climate parameters and indoor conditions.

The other heat sources/sinks in a building occur through the roof and wall, which can have both heat transfer characteristics (conductive and radiative) and thermal mass. Although thermal mass has been considered an effective passive measure, the occupancy profile is also an important consideration. For example, having the building envelope absorb heat during the day and emit it back to indoor spaces in the evening may not be desirable for a residential-type occupancy. The roof, the most exposed part of a building, can be the prevailing source of heat gains in a

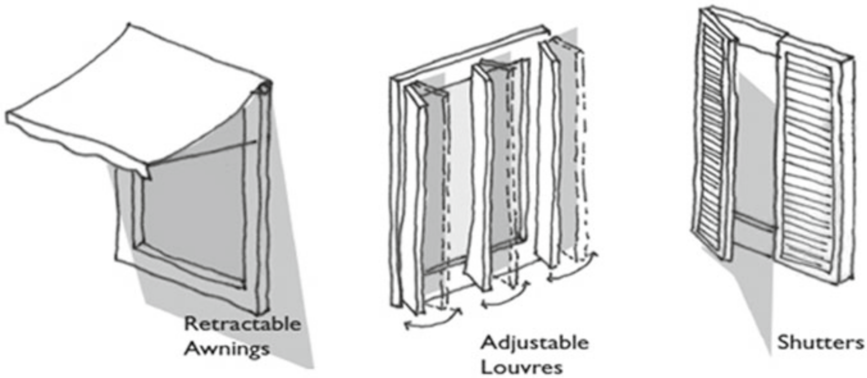

Fig. 3 External shading devices for low-elevation sun [14]

building, and several approaches have been considered to passively regulate heat transfer, including cool roofs and green roofs. Al-Obaidi et al. [15] concluded that the solar reflectivity of the roof surface is the most important component of the Solar Reflective Index (SRI) when assessing the performance of a cool roof, whereas Yew et al. [16] showed the possibility of using a ventilated cavity to dissipate heat through convection and natural wind pressure. Zhang et al. [17] confirmed the effectiveness of cool roofs and, at the same time, the significance of heat gains through the roof by reporting on a payback period of only 1.4 months.

Another effective and highly sustainable measure for the built environment is the green roof, which has the benefit of modifying the roof construction itself and hence is not simply a shading element. Through its various layers (typically protection, drainage, filter, and substrate layers), a green roof attempts to replicate the soil characteristics in only a few centimeters of the substrate.

Nevertheless, both cool and green roofs are fixed passive measures, which can work very effectively in summer conditions but may work against providing a comfortable indoor space during winter periods, especially for colder areas where no heating system is installed. Indeed, installing green roofs in the central plateau region in Mauritius may lead to colder indoor temperatures, warranting the installation of elaborate heating systems. However, other passive measures can be considered to complement the loss of heat gains, such as allowing beneficial direct solar radiation to penetrate the spaces through glazed areas.

The thermal comfort and energy efficiency of indoor spaces can be enhanced by promoting air movement across the building as much as possible, especially when the ambient conditions are suitable for achieving human comfort. Human comfort can be assessed using the parameters of the ASHRAE 55 standard [18], although research into bespoke thermal comfort models is needed to adapt solutions to the local context and avoid overdesign as highlighted by Attia et al. [19] when developing bioclimatic design strategies for Madagascar. For example, enforcing a 60% maximum allowable humidity level in Mauritius will mean there are no hours during the year which can be classified as comfortable and that active cooling and dehumidification need to be prescribed when the reality is that humidity levels above 60% can be admitted for thermal comfort.

In a nutshell, the research reported in the literature strongly supports the integration of passive design principles into the sustainable design of spaces as well as for retrofitting existing buildings. The prime focus for passive design should be providing shading from unwanted solar radiation to prevent overheating and promoting cross-ventilation to flush the spaces as regularly as possible with fresh air. The regulation of heat transfer through glazed surfaces necessarily comes as a trade-off for daylight penetration, but as illustrated with the automated solutions later in this chapter, it becomes possible to limit this compromise to just periods when there is a risk of overheating.

4 Exemplar Passive Designs Tested in Mauritius

This section reviews selected passive measures tested in Mauritius, in view to illustrate in Sect. 4.4 how they can be automated to provide the desired flexibility in their operation.

4.1 Analysing the Efficacy of Passive Measures for Mauritius

A comprehensive research study was carried out by Gooroochurn et al. [20] to assess the efficacy of passive design measures for the tropical climate and concrete construction culture of Mauritius using simulation models and experimentation. The following passive measures were considered, with a focus on shading provided to the building elements:

- External shading devices for high-angle and low-angle sun.
- Internal shading using curtains.
- Pitched roof.
- Roof shading.

The emphasis of this research work has been on shading, as priority was given to stopping solar radiation from causing excessive heat gains as opposed to subsequently remediating the effect of a high solar gain. The research was based on a new simulation model (Fig. 4) that is not a specific building layout in itself as this approach would require a large number of simulation models to be used. The simple three-by-three array of spaces was conceived to allow analyzing heat transfer through outdoor building elements connected to a given indoor space, to understand the heat flow dynamics in that space, hence the influence of passive measures on the thermal phenomena involved. In this way, despite the spaces being connected, each space was

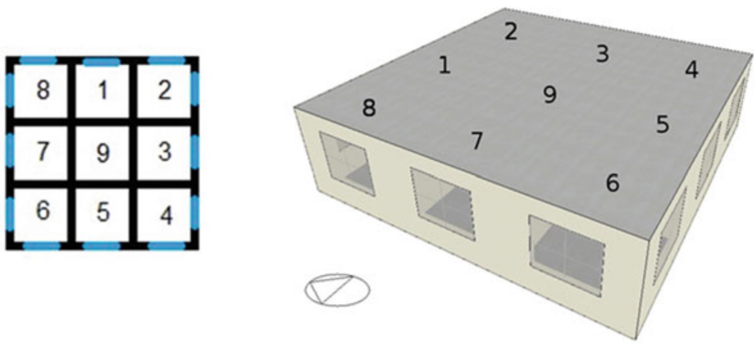

Fig. 4 3×3 space layout used to assess passive measures and controls [20]

handled separately. The philosophy behind this approach was again dealing with the source of any heat gain or loss at its root as opposed to dealing with the subsequent effect.

Even though the simulation model does not represent an actual building layout, it allowed producing sub-space scenarios that will be encountered in a real layout, and hence provides a simple, yet powerful methodology to study the complex building physics involved in deciding the prevailing temperature (air, operative, and radiative) and heat gain/loss in the indoor spaces. The simulation model was made using the Designbuilder® software and consists of rooms one to eight with external walls and room nine with no external walls.

The odd-numbered spaces have only one external façade with a corresponding glazed surface, and the even-numbered spaces have two, and the outside walls are mutually perpendicular to each other, with their respective glazed areas. When this hypothetical layout is rotated through 360° in suitable increments (10° was used in the study), each rotation yields configurations of spaces that will be found in practice in real building layouts, and hence the results of the corresponding parametric analysis can be applied. The research findings also presented four sets of indoor air temperature measurements recorded during summertime in a two-story house on the first and second floors, with northeast and southwest orientations, to compare the trend obtained with the simulation results.

4.1.1 Simulation and Experimental Results

The rooms with corner configurations (even-numbered rooms) were particularly difficult to deal with, as direct solar radiation from the glazed surfaces, at different times during the day, led to heat agglomeration, significant peak heat gains (up to five times more), and radiative heat from interior walls and roof surfaces. When used in conjunction, roof and glazing shading were found to work effectively in achieving significantly reduced heat gains, whereas dealing with one element only led to increased heat gains in the other due to the thermal balance that needs to exist based on laws of thermodynamics. Even if the walls were found to yield relatively lower heat gains, the radiative effect of the heated surfaces caused by the high thermal mass of the concrete constructions was an important phenomenon to factor in. An exterior high reflective wall finish was found to be an effective way to limit the heat accumulated on the skin and the subsequent radiative heat.

The use of simple curtains as an internal shading device was found to be a low-cost solution for existing buildings and for low-cost housing, where external shading cannot be considered, although external shading yielded better heat regulation results. Since the roof is of prime concern for Mauritius, the benefit of constructing single and double-pitched roofs, instead of flat roofs was investigated. The reduction in the peak cooling load was found to be marginal and deemed not significant enough to warrant a change in construction practices from the flat roof which is common in Mauritius, given the significant cost this would entail and the limitation in not allowing further vertical extension. The use of highly reflective coating and green roofs was deemed more favorable [21].

The experimental measurements clearly showed the significant influence of flat roofs as a source of heat gain. This was done by comparing the temperature on the first and second floors and the equally significant high heat gains in the northeast orientation through the glazed openings as compared to the southwest orientation, which does not see the sun, which supported the simulation results.

4.2 *Ventilated Façades*

The use of single-sided hollow blocks (See Fig. 5 left) leads to trapped air pockets (See Fig. 6), which further increases the radiative effect and increases the amount of time needed for wall surfaces to cool down to the ambient temperature at night. To circumvent this problem, Gooroochurn et al. [22] tested a space-saving ventilated

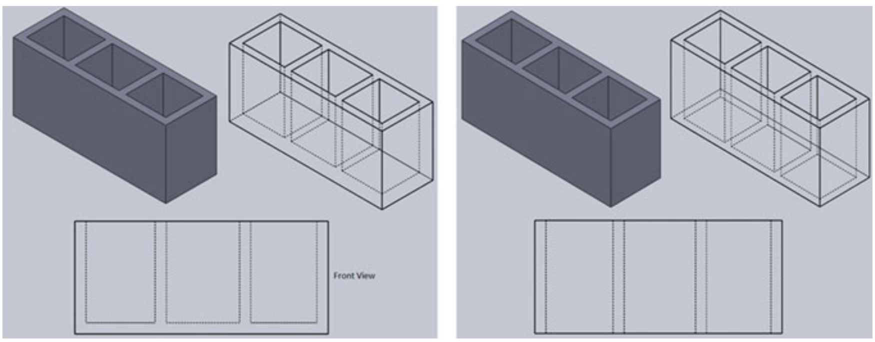

Fig. 5 Normal single-sided hollow block (left) and light double-sided hollow block (right)

Fig. 6 Heat trapped in cavities with normal blocks

Fig. 7 Heat control with ventilated cavity

façade using double-sided hollow cavity concrete blocks (See Fig. 5 right), already available on the market, making slots on the outside wall to allow the connected air cavities to be flushed passively when heated air rises through the buoyancy effect (see Fig. 7).

The experimental results of indoor surface temperatures measured in the different directions for a reference building (with normal, single-sided blocks) and an adjacent building built with light, double-sided hollow blocks, show reduced indoor surface temperatures across all orientations, with as much as a 6 °C drop observed in the west direction. As explained below, this system is also amenable to controlling the buoyancy effect during day and night-time flushing, so that the system can be readily adapted to indoor and outdoor conditions and for the desired indoor environment.

4.3 Solar Chimney

Despite the reported benefits of solar chimneys in the literature for promoting cross-ventilation in buildings, especially during periods of low wind regimes, the local construction industry resisted their conventional integration into buildings as a black concrete tower erected at roof level for esthetic and structural reasons, and due to lack of scientific findings on their performance in the local context. To provide a simpler, cheaper, and more acceptable design, which can be constructed using local workmanship available in the aluminum industry, Gooroochurn et al. [23] proposed a solar chimney made of glass panes and an aluminum structure (Fig. 8).

The proposed system can be installed either fixed to facades or roof mounted, as in both cases, the buoyancy force generated can be used to cause pressure gradients in indoor spaces and lead to forced ventilation. The installation of a solar chimney on the roof is beneficial in being exposed to the sun throughout the day, hence promoting airflow for longer periods, whereas the façade mounted one will only be exposed during certain periods of the day, depending on its orientation. Given the solar path in Mauritius, having solar chimneys in the northeast and northwest orientations will permit greater exposure during the day. However, roof-mounted systems impose greater structural implications on the building and may lead to water ingress problems during heavy rainfall periods, which needs special attention. The installation of several façade mounted systems at strategic orientations (for example one in the northeast and one in the northwest) can also be considered to achieve airflow for longer periods of time.

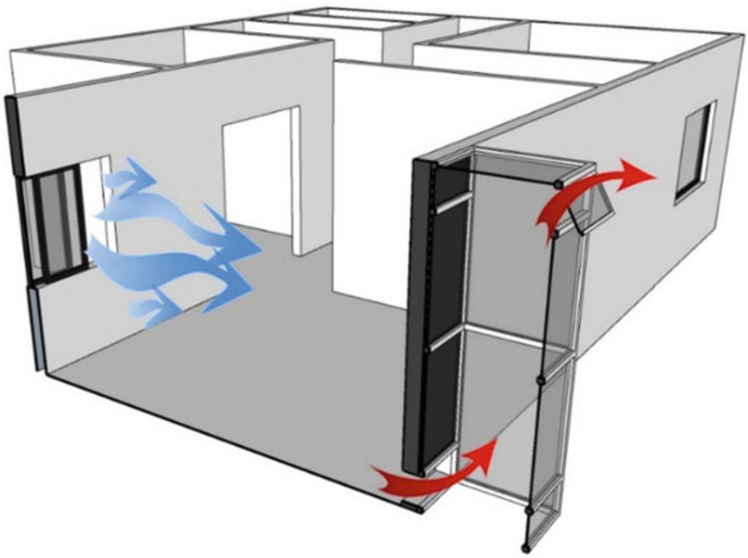

Fig. 8 Glass-based, wall-mounted solar chimney prototype [3]

4.4 Automation of Passive Measures

A whole range of control strategies has been applied in the modulation of building systems, reviewed by Alkhatib et al. [24]. The implementation of intelligent controls requires a knowledge base for decision-making and hence a priori information about the process. As discussed earlier, passive design in itself offers a static response to environmental stimuli and can lead to limitations regarding the highly dynamic nature of weather patterns at the project site.

However, access to hardware and software modules needed to implement required mechanisms may not be easily accessible in tropical countries, as pointed out by Byon and Jeong [25]. Hence, developing and integrating low-cost mechanisms to automate passive measures for air, light, and heat control represents a nice opportunity for businesses, both existing ones, and start-ups. The three-by-three simulation model described earlier was configured to be able to simulate performance with no automated passive measures implemented and one with these implemented. In the Designbuilder® model considered, electrochromic glazing control was configured to model the shading of glazed openings, and the cooling degree day metric, with a base temperature of 25 °C was used to compare the results, showing a 12.6% reduction. Meanwhile, fully shading the windows yielded a 15.6% reduction. This shows that implementing an automated system to control glazed opening shading allowed balancing the trade-off between heat gains and daylight penetration. In practice, the window shading mechanism can take the form of a curtain control or blind control. The proposed three-by-three simulation model offers the added possibility of generating intensive datasets for climate data and targeted output parameters such as operative and radiative temperatures and heat gains through the different building elements.

5 Discussion and Conclusion

The built environment has rightly received great interest in the sustainability agenda of the world's nations, and has an important human dimension apart from the infrastructural considerations, given that we spend so much time indoors and the prevailing indoor environmental quality affects our health, mental state, and performance. Harnessing natural resources at a site level is a key circular economy principle, in line with bioclimatic building design, that needs close attention. At the same time, measures need to be taken to prevent these site elements from deteriorating indoor conditions, and this is where passive design plays the crucial role of modulating the transfer of air, heat, and light between indoor and outdoor environments.

Therefore, as elaborately presented in this chapter, passive design is a key skill and knowledge that needs to be imparted to designers of building projects. In its absence, it will be difficult to ascertain the environment-friendliness of building projects. The focus of the passive measures considered has been shading to tackle the causes of heat transfer instead of the effects. Once the fundamental level of passive design has been satisfied, further opportunities to promote better indoor conditions with a reduced carbon footprint can be sought by automating these passive measures, and studies have shown the benefit of implementing smart controls for air, heat, and light interactions between the building and its immediate surroundings. This has been demonstrated through a non-exhaustive list of passive measures such as automated curtains, external shading, ventilated walls, and solar chimney systems.

Looking ahead, the use of IoT sensors and actuators to collect real-time data on ambient and indoor conditions, and accordingly regulate the performance of passive measures can be implemented as a predictive control strategy [26], where AI algorithms can be applied for the decision-making. However, AI algorithms need extensive datasets to train the learning engine, which is difficult to develop for each building typology, although the dynamic tuning of the learning engine performance can be achieved during operation through reinforcement learning. The initial training dataset for the specific configuration of a given building layout can be generated from simulation models, for example, the three-by-three array model presented earlier can be used for this purpose. In conclusion, an optimized framework for achieving energy efficiency and thermal comfort can be achieved, by combining passive measures conceived through bioclimatic design considerations for the specific site, controllable to be able to influence the interaction between the building envelope and the ambient environment, and at a higher level, being able to predict the anticipated indoor conditions using AI techniques. This design configuration will offer the needed resiliency against weather vagaries while making maximum use of natural resources available at the project site.

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References

1. Gooroochurn M, Cadersa A, Pattoo P (2021) Circular design in the construction industry in Mauritius with a case study for demolition waste management. J Inst Eng Mauritius March 2021:73–84
2. Giridharan R, Emmanuel R (2018) The impact of urban compactness, comfort strategies and energy consumption on tropical urban heat island intensity: a review. Sustain Cities Soc 40:677–687. https://doi.org/10.1016/j.scs.2018.01.024
3. Gooroochurn M (2022) Circular homes - an energy-water-materials nexus for community climate engagement and action at grassroots level in the built environment. Results Eng 15:100548. https://doi.org/10.1016/J.RINENG.2022.100548
4. Timmons D, Dhunny A, Elahee K, Havumaki B, Howells M, Khoodaruth A, Lema-Driscoll A, Lollchund M, Ramgolam Y, Rughooputh S, Surroop D (2019) Cost minimization for fully renewable electriaddress systems: a Mauritius case study. Energy Policy 133:110895. https://doi.org/10.1016/j.enpol.2019.110895
5. Ramgolam YK (2018) Modelling and evaluation of photovoltaic system through holistic resource assessment. PhD thesis, Faculty of Engineering, University of Mauritius

6. Qaid A, Lamit HB, Ossen DR, Shahminan RNR (2016) Urban heat island and thermal comfort conditions at micro-climate scale in a tropical planned address. Energy Build 133:577–595. https://doi.org/10.1016/j.enbuild.2016.10.006
7. Moser S (2010) Putrajaya: Malaysia's new federal administrative capital. Cities 27:285–297. https://doi.org/10.1016/j.cities.2009.11.002
8. Qaid A, Ossen DR (2015) Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions. Int J Biometeorol 59:657–677. https://doi.org/10.1007/s00484-014-0878-5
9. Ahmed AQ, Ossen DR, Jamei E, Manaf NA, Said I, Ahmad MH (2015) Urban surface temperature behaviour and heat island effect in a tropical planned address. Theor Appl Climatol 119:493–514. https://doi.org/10.1007/s00704-014-1122-2
10. Tsitoura M, Michailidou M, Tsoutsos T (2017) A bioclimatic outdoor design tool in urban open space design. Energy Build 153:368–381. https://doi.org/10.1016/j.enbuild.2017.07.079
11. Stavrakakis G, Tzanaki E, Genetzaki V, Anagnostakis G, Galetakis G, Grigorakis E (2012) A computational methodology for effective bioclimatic-design applications in the urban environment. Sustain Cities Soc 4:41–57. https://doi.org/10.1016/j.scs.2012.05.002
12. Alwetaishi M (2019) Impact of glazing to wall ratio in various climatic regions: a case study. J King Saud Univ - Eng Sci 31:6–18. https://doi.org/10.1016/j.jksues.2017.03.001
13. Su X, Zhang X (2010) Environmental performance optimization of window-wall ratio for different window type in hot summer and cold winter zone in china based on life cycle assessment. Energy Build 42:198–202. https://doi.org/10.1016/j.enbuild.2009.08.015
14. Gooroochurn M, Giridharan R (2021) Enhancing energy performance and comfort of built environment in tropical climates. In: Urban microclimate modelling for comfort and energy studies, Springer, Cham, pp 137–161. https://doi.org/10.1007/978-3-030-65421-4_7
15. Al-Obaidi KM, Ismail M, Rahman AMA (2014) Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: a literature review. Front Architect Res 3:283–297. https://doi.org/10.1016/j.foar.2014.06.002
16. Yew MC, Yew MK, Saw LH, Ng TC, Chen KP, Rajkumar D, Beh JH (2018) Experimental analysis on the active and passive cool roof systems for industrial buildings in Malaysia. J Build Eng 19:134–141. https://doi.org/10.1016/j.jobe.2018.05.001
17. Zhang Z, Tong S, Yu H (2016) Life cycle analysis of cool roof in tropical areas. Procedia Eng 169:392–399. https://doi.org/10.1016/j.proeng.2016.10.048
18. ASHRAE (2013) ANSI/ASHRAE standard 55: thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Enginieers, Atlanta, USA
19. Attia S, Lacombe T, Rakotondramiarana HT, Garde F, Roshan G (2019) Analysis tool for bioclimatic design strategies in hot humid climates. Sustain Cities Soc 45:8–24. https://doi.org/10.1016/j.scs.2018.11.025
20. Gooroochurn M, Coret JY, Brown N, Venkannah S, Wright AJ (2021) Assessing the efficacy of passive measures for the tropical context of Mauritius through parametric simulations and in-situ measurement. In: CIBSE 2021 technical symposium, London, UK, pp 13–14
21. Gooroochurn M, Chooneea M, Bhoodoo D (2021) Development of a sustainability matrix for plant selection & analysis of the use of landscaping to promote energy efficiency and thermal comfort in the built environment. In: 2nd international conference on recent advances in fluid and thermal sciences, iCRAFT2020. BITS, Pilani Campus Dubai, UAE, pp 19–21
22. Gooroochurn M, Shamachurn H, Surnam BYR, Cadersa A (2020) Experimental and simulation analysis of the performance of a low cost and space preserving ventilated façade for hot and humid climates. In: The fourth international conference on efficient building design (ASHRAE), Beirut, Lebanon
23. Gooroochurn M, Lollchund R, Rughooputh S, Shamachurn H, Rughooputh R (2021) Assessing the efficacy of solar chimneys in Mauritius through dynamic simulations and in-situ measurements. Tech. rep., Mauritius Research and Innovation Council Technical Report
24. Alkhatib H, Lemarchand P, Norton B, O'Sullivan D (2021) Deployment and control of adaptive building facades for energy generation, thermal insulation, ventilation and daylighting: a review. Appl Therm Eng 185:116331. https://doi.org/10.1016/j.applthermaleng.2020.116331

25. Byon YS, Jeong JW (2020) Annual energy harvesting performance of a phase change material-integrated thermoelectric power generation block in building walls. Energy Build 228:110470. https://doi.org/10.1016/j.enbuild.2020.110470
26. Gooroochurn M, Mallet D, Jahmeerbacus I, Shamachurn H, Hassen SZS (2021) A framework for AI-Based building controls to adapt passive measures for optimum thermal comfort and energy efficiency in tropical climates. In: FTC 2021-future technologies conference 2021, Vancouver, Canada, pp 526–539. https://doi.org/10.1007/978-3-030-89880-9_39, https://link.springer.com/10.1007/978-3-030-89880-9_39

Exploring the Potential of Adaptive Behavior as a Tool Intended for Comfort and Saving Energy

Hanan Al-Khatri

Abstract Thermal adaptation processes involve all the actions taken by people to acclimatize themselves to their thermal surroundings. Based on the adaptive principle of thermal comfort, it is possible to view these processes as a tool that architects and engineers can use to satisfy indoor thermal comfort demands. Nevertheless, doubts arise in doing this because of the complexity of quantifying the adaptive behavior impact on energy savings. The need to understand when, where, and how to use each adaptive action requires artificial intelligence because its techniques can intelligently control adaptive measures to satisfy the competing demands of achieving indoor thermal comfort and saving energy. The narrative review in this chapter indicated the potential role of adaptive actions in removing the barrier of satisfying thermal comfort demands in public buildings with minimum energy consumption. The expanded application of artificial intelligence in thermal comfort research is promising in quantifying adaptive behavior's role as an intended design tool to achieve indoor thermal comfort. Fuzzy logic and neural networks are the most useful among the different artificial intelligence techniques. Research is required to explore the role of other adaptive actions besides operating windows that captured several researchers' interest.

Keywords Adaptive behavior · Thermal comfort · Thermal adaptation · Artificial intelligence

H. Al-Khatri (✉)
Department of Civil & Architectural Engineering, College of Engineering, Sultan Qaboos University, Muscat, Sultanate of Oman
e-mail: khatri@squ.edu.om

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1 Introduction

Reflecting a broad interest, several fields of scientific research provide definitions of thermal comfort including psychology, physiology, physics, and sociology among others. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) defines thermal comfort as 'that condition of mind which expresses satisfaction with the thermal environment.' [1, p. 4]. This definition considers the psychological aspect of thermal comfort [2]. Likewise, thermal comfort is defined as 'the sensation of well-being of an individual in a specific environment' [3, p. 32] and as 'a state in which there is no driving impulses to correct the environment by behavior' [4, p. 2.4].

Physiology considers that thermal comfort is achieved when the thermal receptors, distributed in the skin, and the hypothalamus produce the minimum reaction to the surrounding temperature or its change [5]. Physics defines thermal comfort as an equilibrium condition where thermal balance is achieved between the human body and the surrounding environment taking into consideration that both sweat rate and skin temperature are kept in the comfort range [2].

It is worth mentioning that thermal comfort and thermal neutrality are widely used interchangeably despite the distinction made between them by some studies. This is witnessed in ASHRAE's thermal sensation scale, where the central categories (slightly cool, neutral, slightly warm) are considered to represent thermal comfort [6]. This is in line with the thermal comfort definition set by Fanger as 'a condition where people prefer neither warmer nor cooler' [7]. It is noteworthy that the Chartered Institution of Building Services Engineers (CIBSE) defines thermal neutrality as 'that situation in which people describe themselves as neither cool nor warm' [8, p 1.7].

It is possible to consider thermal comfort as a regional field of research. This is mainly because of the influence that the climatic, cultural, and social background factors have on the thermal comfort of different groups of people as emphasized by many studies [9–14]. For instance, indoor thermal comfort was achieved during the 1970s in Iraq and Britain at 32 °C and 17 °C, respectively [15]. Iraq is an Arabic country located in a hot desert climate according to the Koppen-Geiger climate classification, whereas Britain is located in a temperate oceanic climate. Based on this, it is crucial to consider this regionalism when studying thermal comfort, which is taken into consideration in this chapter that focuses on thermal adaptation in the region between the Tropic of Cancer and the Tropic of Capricorn.

This chapter is a modest contribution to the efforts of removing barriers to thermal comfort in the Tropics region. Considering the climatic conditions of this region, it may not be possible to satisfy indoor thermal comfort demands, especially in public buildings, without consuming large amounts of energy. Indeed, several recent studies have highlighted the rapid escalation in energy consumption for cooling and heating purposes. This barrier is formed by the collective contribution of several challenging factors. As demonstrated in Fig. 1, examining these factors points to the influence of climate change, energy poverty, buildings' architectural features, the subjective nature of thermal comfort, restrictions on adaptive behavior, and lack

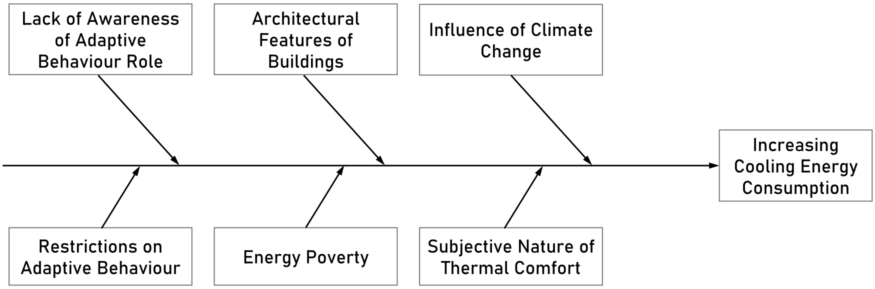

Fig. 1 Contributing factors to the barrier to achieving thermal comfort in public spaces without consuming large amounts of energy

of awareness of adaptive behavior's role in achieving thermal comfort. The efforts required to remove the factors that contribute to this barrier are not equal. For instance, relaxing the restrictions on adaptive behavior or improving the buildings' response to their climates is not on the same scale as counteracting the influence of climate change or eliminating energy poverty. This chapter attempts to balance the need to satisfy thermal comfort demands with reasonable energy consumption in buildings by exploring the possibility of integrating adaptive behavior as a tool intended to achieve thermal comfort in buildings. This integration is promising as witnessed in the emerging personal comfort models [16–18].

2 Thermal Adaptation

Thermal adaptation is closely related to thermal comfort, and it includes all behaviors people perform to thermally adapt to the surrounding environment aiming at achieving thermal comfort or, at least, reducing thermal discomfort [19–21]. The processes of thermal adaptation vary in their effectiveness, economic consequences, ease [22], environmental consequences, and availability. They are categorized into psychological, physiological, and physical processes as presented in Fig. 2.

Psychological adaptation such as exposure time, expectation, and naturalness has a considerable influence on thermal comfort. In general, these mechanisms affect thermal tolerance and behavioral actions and, therefore, thermal acceptance, perception, and adaptation. For instance, exposure time has a considerable effect on determining the acceptance of thermally uncomfortable environments [23]. People exhibit higher tolerance if they spend less time in such environments.

The thermal expectation is based on people's thermal experiences, and it affects their thermal acceptance of the surroundings as well as some behavioral adaptation actions like changing postures, changing clothing, or drinking hot or cold beverages. It has a negative effect on tolerating air temperature fluctuations in air-conditioned buildings where it is generally high compared with naturally ventilated buildings [21].

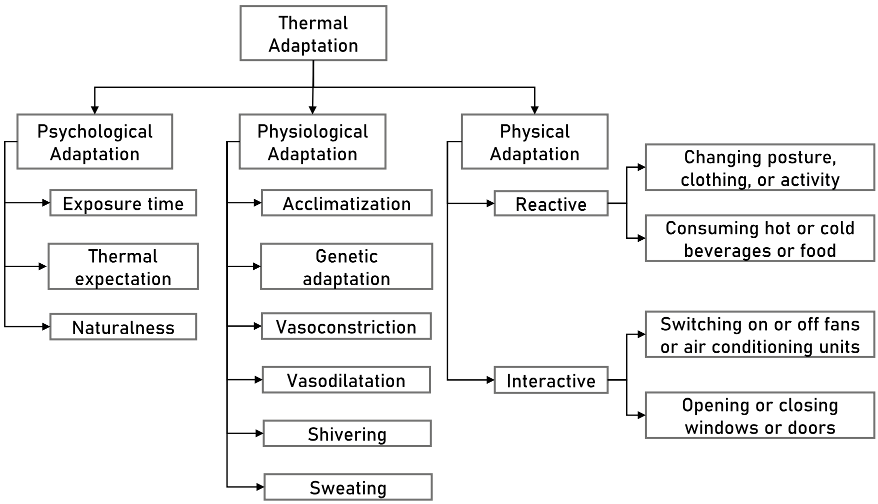

Fig. 2 Thermal adaptation processes

Exploring the influence of thermal history on expectation revealed the complexity and difficulty associated with lowering thermal expectation compared with adaptation to a new ambiance [24]. Indeed, the thermal experiences of cool environments narrow the comfort range, which is negatively reflected in people's thermal adaptability [25].

In contrast, naturalness, which is the indoors' natural appearance achieved mainly by internal plants and landscape views, is positively reflected in adaptability as it broadens acceptability ranges [20]. Aesthetically beautiful environments provoke higher levels of satisfaction, and they result in lowering thermal sensation votes under hot summer conditions [26]. A direct statistical correlation connects the increase in the sense of place and its beauty, including naturalness, on the one hand, and the increase in thermal adaptation, and therefore, thermal comfort, on the other [27].

Physiological adaptation is time-dependent. It can occur in a few days or weeks or several years. The acclimatization process is an example of a shorter term adaptation, whereas the genetic adaptation is an example of a longer term adaptation [20, 21, 28]. Acclimatization is achieved when the body's sensitivity toward certain thermal conditions, that represent thermal stress, is reduced. The reduction in sensitivity can be achieved by being frequently subjected to thermal stress. Other forms of physiological adaptation can occur in even shorter periods like vasoconstriction, vasodilatation, shivering, and sweating. Both vasoconstriction and vasodilatation are related to blood circulation in the skin's surface vessels. The former occurs under cold conditions, where the vessels contract in an attempt to reduce the heat loss from the skin. On the contrary, vasodilatation involves expanding the vessels to increase heat loss from the skin under hot conditions [19, 29].

Known also as behavioral adaptation, physical adaptation is affected by climatic, social, cultural, and economic factors as well as the architectural features of the buildings [22, 30]. It involves behaviors like consuming hot or cold beverages or food, changing posture, clothing, or activity, switching on or off fans or air conditioning systems, and opening or closing windows, doors, or curtains [11, 20, 31]. These behaviors can be classified into two groups, namely reactive and interactive behaviors. The first involves changing the person's thermal state and the other involves changing the surrounding environment [20].

2.1 Thermal Adaptation and Thermal Comfort

Thermal adaptation is closely related to thermal comfort. This relationship is clearly expressed in the adaptive principle of thermal comfort, which states that 'if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' [16, p. 8]. This implies that relaxing the possible restrictions of thermal adaptive actions can help occupants in achieving thermal comfort. From an energy perspective, thermal comfort can be restored by active actions like switching on an air conditioning unit, or by passive actions like opening a window. The latter consumes no operative energy.

It is ultimately crucial to enable the buildings' users to restore indoor thermal comfort by passive means. This is a duty of architects and engineers as well as a matter of environmental awareness among the buildings' users. The justification for this is witnessed in the scenarios that predict increasing cooling energy in buildings due to the influence of climate change [32]. As a matter of design, there is a need to quantify the role of each adaptive action in achieving thermal comfort levels. The difficulty associated with this task forms a real barrier to achieving indoor thermal comfort. Adding to this difficulty is the regional nature of thermal comfort that is influenced by climatic, cultural, and social background factors [9, 33–37]. Hence, any attempts to overcome this barrier should be regional.

It should be remembered that relying on any adaptive action has a certain limit after which this action is no longer useful for restoring thermal comfort. Such a situation is called adaptive saturation. It should also be remembered that restrictions on adaptive actions are present in buildings owing to different reasons including the buildings' architectural features, operational reasons, outdoor context, and cultural preferences. In this regard, the question of the extent to which it is possible to depend on adaptive behavior to achieve indoor thermal comfort is important and relevant. Researchers should strive to provide reliable answers despite the difficulty associated with these attempts.

3 Adaptive Behavior as a Comfort Tool

A major and basic function of any building, regardless of its type, is to achieve thermal comfort for its users. To do this, designers and engineers depend on different passive and active tools like passively optimizing the building envelope and integrating heating, ventilation, and air conditioning (HVAC) systems. Regarding the adaptive principle of thermal comfort, the adaptive behavior of the building's users can be thought of as another tool that contributes to achieving thermal comfort. However, this tool has a special nature that distinguishes it from other tools, which may partially illustrate the explicit avoidance of depending on it as an 'intended' method to achieve thermal comfort for the buildings' occupants. This is justifiable because relying on adaptive actions in their simple forms like opening a window, for instance, does not guarantee satisfying the demands of indoor thermal comfort. On the contrary, these adaptive actions may exaggerate thermal discomfort if performed incorrectly. Hence, there is a substantial need to understand when, where, and how to depend on each adaptive action to have a positive impact represented in passively achieving thermal comfort or by consuming a small amount of energy. The difficulty of these questions arises from the complexity of the factors that affect adaptation behavior.

4 Methodology

A narrative literature review was performed motivated by the question of quantifying the role of adaptive behavior in achieving indoor comfort and saving energy. To search for answers to this question, different approaches for reviewing the published literature are available including realist synthesis, meta-analysis review, systematic review, and narrative or non-systematic review. The latter was applied because of its broad scope that matches the nature of the question. Scopus, Science Direct, Abstracts in New Technology and Engineering, and Civil Engineering Abstract databases were consulted using a keyword search of thermal adaptation, thermal comfort, thermal acceptability, thermal sensation, thermal preference, comfort temperature, neutral temperature, school, classroom, or student. A special focus on educational buildings led the search at the beginning because it is interesting to investigate the effect of adaptive behavior on thermal comfort in educational buildings that are characterized by a general restriction on such behaviors. Later, the application of artificial intelligence in thermal comfort was explored using artificial intelligence and thermal comfort as search keywords. It is worth mentioning that the manual selection of articles mentioned in the articles returned from the search was applied, as is the case in most narrative reviews. Considering that thermal comfort studies are generally classified into rational and empirical studies [11, 38], rational studies were excluded as well as empirical studies that do not report the adaptive behavior of users. Studies reported from geographical regions outside the tropics were excluded. A selected number of the papers from the search extending over 12 years were reviewed focusing on the reported thermal comfort votes, the available opportunities of adaptive behavior, and the impact of allowing adaptive behavior on the users' thermal comfort conditions.

5 Discussion

Looking for answers in the published literature from the Tropics region reveals that the relationship between adaptive behavior and thermal comfort has captured the attention of researchers. For instance, the influence of occupants' behavior on consumed energy to achieve indoor thermal comfort in high-rise residential buildings in Hong Kong was investigated by questionnaires and interviews. Occupants from different floors relied on different adaptive actions to achieve indoor thermal comfort in summer. A difference of more than 25% in the consumed energy between these occupants was attributed to differences in their energy-related behaviors like opening windows or operating air conditioning units. It is worth mentioning that the increase observed in consumed energy for those occupants on the twentieth and lower floors was statistically significant [39].

In general, classrooms exhibit high restrictions on adaptive behaviors, especially during lessons. In such situations, students mostly depend on a passive adaptive action, namely altering their clothing level, to satisfy their thermal comfort demands. A study carried out in naturally ventilated elementary and high schools in Taiwan revealed that the students were able to restore their thermal comfort in November, December, and January when the indoor operative temperatures fluctuated between 21 and 29 °C by adjusting just their clothing level [12]. In another study conducted in mixed-mode ventilation schools in Taiwan, the students' actions related to windows, fans, and air conditioners were monitored. The students depended mainly on just opening windows to improve their thermal conditions. This action was used under a range of indoor operative temperatures up to around 25 °C. When the temperature increased to 29 °C, the students combined opening windows with operating fans. Further increases in operative temperature were controlled by these two mechanisms up to 30.3 °C when the students switched to operating fans and air conditioning [40].

Moreover, the occupants' interactions with buildings as well as the influence of these interactions on their productivity were investigated in a study conducted in an office building in Brazil. The individual evaluations of different aspects of the indoor environment for some occupants resulted in certain actions that triggered discomfort for other occupants. Accordingly, the researchers highlighted the importance of understanding the role of subjective evaluations in determining the conditions of the indoor environment. The necessity of this understanding evolves from the fact that the occupants' productivity is influenced by their interactions with the indoor environment [41].

Despite the interest in thermal adaptation and its role in achieving indoor thermal comfort, there is a scope for future research that focuses on quantifying this role to identify adaptive behavior as an 'intended' tool to achieve indoor thermal comfort. In this regard, the expanded application of artificial intelligence in the built environment is promising.

6 Artificial Intelligence and Thermal Adaptation

Artificial intelligence has the potential to assist architects and engineers in their duty of integrating adaptive behavior in buildings as a tool intended to passively achieve thermal comfort or with minimal energy consumption. Indeed, using artificial intelligence applications in buildings increased indoor thermal comfort satisfaction rates to around 90% and the savings in energy consumed to maintain comfort to more than 50% [42]. Artificial intelligence resembles human thinking in that it makes decisions based on collected data. This ability to make decisions based on gathered information is closely related to the mechanism where adaptive behavior is determined by occupants. The advantage of integrating artificial intelligence lies in the high potential to avoid the faulty operation of adaptive behavior.

Buildings should be smart to take full advantage of artificial intelligence capabilities that aim at enhancing the buildings' thermal and energy performance [43]. For a building, being smart implies success in reaching a balance between the competing demands of thermal comfort on the one hand and energy savings on the other [44]. This is performed by integrating features that enable the regulation of passive adaptive actions by artificial intelligence.

Among the different artificial intelligence techniques, fuzzy logic (FL) and neural network (NN) stand out in terms of their useful applications in thermal comfort. The former can execute decisions that improve the internal thermal environment using the buildings' control techniques based on the user's sensation and preference. The latter is sensitive to a training process where decisions are made in complex contexts with non-linear relations between the variables [43, 45]. Applying these techniques has been witnessed in buildings. For instance, a fuzzy control system was developed to monitor and thermally adapt the indoor environment to satisfy the users' demands based on their actions. The system reads the users' actions via a separate computer vision system that translates the actions into their metabolic rate equivalents, which, in turn, are used to feed the predicted mean vote index. Based on the index, the fuzzy control system adjusts indoor conditions to suit the users [46]. Integrating the Bayesian theorem, a Bayesian neural network (BNN) algorithm was developed to predict occupants' thermal preferences. The training process of the model used the ASHRAE global thermal comfort database II. Testing the model accuracy using different inputs and outputs revealed that the highest accuracy was achieved using occupants' subjective measures as an input and window opening or closing as an output. Besides, the accuracy of the proposed algorithm is higher compared with the predicted mean vote or the adaptive model predictions. It is expected that applying this model and similar ones leads to enhancing buildings' thermal performance [47]. The recurrent neural network (RNN) was also used to propose a model to control windows' opening and closing in a naturally ventilated office building in China. The model was based on reinforced learning and was trained using real measurements conducted previously in that office. Comparing the indoor conditions of the office before and after allowing the proposed model to control the windows revealed an enhancement of more than 90% in air quality and thermal comfort [48].

7 Summary

Thermal adaptive behavior has the potential to be a design tool intended to achieve indoor thermal comfort. However, its role in satisfying thermal demands and reducing energy consumption for cooling purposes requires quantification. The complexity that the relationship between comfort and adaptive behavior entails can be resolved by the interference of artificial intelligence. However, even though integrating artificial intelligence has improved the accuracy of the thermal sensation and preferences predictions and, ultimately, has led to enhancing indoor environment conditions, further research is still required. For example, more adaptive actions that influence indoor thermal comfort are still waiting to be investigated and controlled by artificial intelligence techniques. Additionally, the application of artificial intelligence should not be limited to thermal comfort; rather, it should be used to control building measures that influence all aspects of indoor comfort. Furthermore, it can be extended to provide outdoor comfort. However, it should be noted that comfort regionalism should be considered in all these attempts.

References

1. ASHRAE (2010) ANSI/ASHRAE standard 55–2010 thermal environmental conditions for human occupancy. American society of heating, refrigerating and air-conditioning engineers, Atlanta, USA
2. Höppe P (2002) Different aspects of assessing indoor and outdoor thermal comfort. Energy Build 34:661–665. https://doi.org/10.1016/S0378-7788(02)00017-8
3. Koch-Nielsen H (2007) Stay cool: a design guide for the built environment in hot climates. Earthscan, London
4. Hensen JLM (1991) On the thermal interaction of building structure and heating and ventilating system. PhD thesis, Eindhoven University of Technology, Eindhoven. https://doi.org/10.6100/IR353263
5. Mayer E (1993) Objective criteria for thermal comfort. Build Environ 28:399–403. https://doi.org/10.1016/0360-1323(93)90016-V
6. Givoni B (1998) Climate considerations in building and urban design. Wiley, Danvers
7. Feriadi H, Wong NH (2004) Thermal comfort for naturally ventilated houses in Indonesia. Energy Build 36:614–626. https://doi.org/10.1016/j.enbuild.2004.01.011
8. CIBSE (1999) Environmental design - CIBSE guide A. The Chartered Institution of Building Services Engineers, London, UK
9. Al-Khatri H, Alwetaishi M, Gadi MB (2020) Exploring thermal comfort experience and adaptive opportunities of female and male high school students. J Build Eng 31:101365. https://doi.org/10.1016/j.jobe.2020.101365
10. Zomorodian ZS, Tahsildoost M, Hafezi M (2016) Thermal comfort in educational buildings: a review article. Renew Sustain Energy Rev 59:895–906. https://doi.org/10.1016/j.rser.2016.01.033
11. Singh MK, Mahapatra S, Atreya S (2011) Adaptive thermal comfort model for different climatic zones of North-East India. Appl Energy 88:2420–2428. https://doi.org/10.1016/j.apenergy.2011.01.019
12. Hwang RL, Lin TP, Chen CP, Kuo NJ (2009) Investigating the adaptive model of thermal comfort for naturally ventilated school buildings in Taiwan. Int J Biometeorol 53:189–200. https://doi.org/10.1007/s00484-008-0203-2

13. Pitts A (2006) The language and semantics of thermal comfort. In: 4th windsor conference: comfort and energy use in buildings - getting them right. NCEUB network for comfort and energy use in buildings, Windsor, UK
14. Chappells H, Shove E (2005) Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. Build Res Inf 33:32–40. https://doi.org/10.1080/0961321042000322762
15. Humphreys MA (1976) Field studies of thermal comfort compared and applied. J Inst Heat Vent Eng 44:5–27
16. Kim J, Zhou Y, Schiavon S, Raftery P, Brager G (2018) Personal comfort models: predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. Build Environ 129:96–106. https://doi.org/10.1016/j.buildenv.2017.12.011
17. Boerstra A (2010) Personal control in future thermal comfort standards? In: Conference on adapting to change: new thinking on comfort, WINDSOR 2010, Windsor, UK
18. Kim J, Schiavon S, Brager G (2018) Personal comfort models - a new paradigm in thermal comfort for occupant-centric environmental control. Build Environ 132:114–124. https://doi.org/10.1016/j.buildenv.2018.01.023
19. Nicol F, Humphreys M, Roaf S (2012) Adaptive thermal comfort: principles and practice, 1st edn. Routledge, London. https://doi.org/10.4324/9780203123010
20. Nikolopoulou M, Steemers K (2003) Thermal comfort and psychological adaptation as a guide for designing urban spaces. Energy Build 35:95–101. https://doi.org/10.1016/S0378-7788(02)00084-1
21. Brager GS, de Dear RJ (1998) Thermal adaptation in the built environment: a literature review. Energy Build 27:83–96. https://doi.org/10.1016/S0378-7788(97)00053-4
22. Mishra AK, Ramgopal M (2013) Field studies on human thermal comfort - an overview. Build Environ 64:94–106. https://doi.org/10.1016/j.buildenv.2013.02.015
23. Zhou X, Liu Y, Luo M, Zhang L, Zhang Q, Zhang X (2019) Thermal comfort under radiant asymmetries of floor cooling system in 2 h and 8 h exposure durations. Energy Build 188–189:98–110. https://doi.org/10.1016/j.enbuild.2019.02.009
24. Luo M, de Dear R, Ji W, Bin C, Lin B, Ouyang Q, Zhu Y (2016) The dynamics of thermal comfort expectations: the problem, challenge and implications. Build Environ 95:322–329. https://doi.org/10.1016/j.buildenv.2015.07.015
25. Ning H, Wang Z, Ji Y (2016) Thermal history and adaptation: does a long-term indoor thermal exposure impact human thermal adaptability? Appl Energy 183:22–30. https://doi.org/10.1016/j.apenergy.2016.08.157
26. Lau KKL, Choi CY (2021) The influence of perceived aesthetic and acoustic quality on outdoor thermal comfort in urban environment. Build Environ 206:108333. https://doi.org/10.1016/j.buildenv.2021.108333
27. Zabetian E, Kheyroddin R (2019) Comparative evaluation of relationship between psychological adaptations in order to reach thermal comfort and sense of place in urban spaces. Urban Climate 29:100483. https://doi.org/10.1016/j.uclim.2019.100483
28. Epstein Y, Moran DS (2019) Extremes of temperature and hydration. In: Keystone JS, Kozarsky PE, Connor BA (eds) Travel medicine, 4th edn. Elsevier, pp 407–415. https://doi.org/10.1016/B978-0-323-54696-6.00044-6
29. BS En ISO (2001) BS EN ISO 11399: Ergonomics of the thermal environment - Principles and application of relevant international standards. CEN European Committee for Standardization, Brussels
30. Peeters L, de Dear R, Hensen J, D'haeseleer W (2009) Thermal comfort in residential buildings: comfort values and scales for building energy simulation. Appl Energy 86:772–780. https://doi.org/10.1016/j.apenergy.2008.07.011
31. de Dear R, Brager G (1998) Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 104:1–18
32. Chakraborty D, Alam A, Chaudhuri S, Başağaoğlu H, Sulbaran T, Langar S (2021) Scenario-based prediction of climate change impacts on building cooling energy consumption with explainable artificial intelligence. Appl Energy 291:116807. https://doi.org/10.1016/j.apenergy.2021.116807

33. Humphreys M, Nicol F, Roaf S (2015) Adaptive thermal comfort: foundations and analysis, 1st edn. Routledge, London. https://doi.org/10.4324/9781315765815
34. Al-Khatri H, Gadi MB (2019) Investigating the behaviour of ASHRAE, Bedford, and Nicol thermal scales when translated into the Arabic language. Build Environ 151:348–355
35. Parsons K (2014) Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort, and performance, 3rd edn. CRC Press, Boca Raton
36. Messing K, Stellman JM (2006) Sex, gender and women's occupational health: the importance of considering mechanism. Environ Res 101:149–162. https://doi.org/10.1016/j.envres.2005.03.015
37. Indraganti M, Rao KD (2010) Effect of age, gender, economic group and tenure on thermal comfort: a field study in residential buildings in hot and dry climate with seasonal variations. Energy Build 42:273–281. https://doi.org/10.1016/j.enbuild.2009.09.003
38. Djongyang N, Tchinda R, Njomo D (2010) Thermal comfort: a review paper. Renew Sustain Energy Rev 14:2626–2640. https://doi.org/10.1016/j.rser.2010.07.040
39. Du J, Yu C, Pan W (2020) Multiple influencing factors analysis of household energy consumption in high-rise residential buildings: evidence from Hong Kong. Build Simul 13:753–769. https://doi.org/10.1007/s12273-020-0630-5
40. Chen CP, Hwang RL, Shih WM (2014) Effect of fee-for-service air-conditioning management in balancing thermal comfort and energy usage. Int J Biometeorol 58:1941–1950. https://doi.org/10.1007/s00484-014-0796-6
41. Bavaresco MV, Ghisi E, D'Oca S, Pisello AL (2021) Triggering occupant behaviour for energy sustainability: exploring subjective and comfort-related drivers in Brazilian offices. Energy Res Soc Sci 74:101959. https://doi.org/10.1016/j.erss.2021.101959
42. Fard ZQ, Zomorodian ZS, Korsavi SS (2022) Application of machine learning in thermal comfort studies: a review of methods, performance and challenges. Energy Build 256:111771. https://doi.org/10.1016/j.enbuild.2021.111771
43. Mehmood MU, Chun D, Zeeshan Han H, Jeon G, Chen K (2019) A review of the applications of artificial intelligence and big data to buildings for energy-efficiency and a comfortable indoor living environment. Energy Build 202:109383. https://doi.org/10.1016/j.enbuild.2019.109383
44. Mofidi F, Akbari H (2020) Intelligent buildings: an overview. Energy Build 223:110192. https://doi.org/10.1016/j.enbuild.2020.110192
45. Karyono K, Abdullah BM, Cotgrave AJ, Bras A (2020) The adaptive thermal comfort review from the 1920s, the present, and the future. Dev Built Environ 4:100032. https://doi.org/10.1016/j.dibe.2020.100032
46. Al-Faris M, Chiverton J, Ndzi D, Ahmed AI (2021) Vision based dynamic thermal comfort control using fuzzy logic and deep learning. Appl Sci 11:4626. https://doi.org/10.3390/app11104626
47. Ma N, Chen L, Hu J, Perdikaris P, Braham WW (2021) Adaptive behavior and different thermal experiences of real people: a bayesian neural network approach to thermal preference prediction and classification. Build Environ 198:107875. https://doi.org/10.1016/j.buildenv.2021.107875
48. Han M, May R, Zhang X, Wang X, Pan S, Da Y, Jin Y (2020) A novel reinforcement learning method for improving occupant comfort via window opening and closing. Sustain Cities Soc 61:102247. https://doi.org/10.1016/j.scs.2020.102247

Thermal Adaptation in Non-Extreme Climates to Potentially Reduce Energy Consumption

Arturo Raúl Maristany and Gabriela Magali Arrieta

Abstract In architectural design, there are specific construction considerations for each climate type and it is the extreme situations that have clearer design strategies to make efficient buildings require the lowest possible energy consumption for air conditioning. The so-called intermediate or non-extreme climates are very common in the southern hemisphere, where design strategies for buildings are not as standardized and depend on the behavior of users and their ability to adapt. Adaptive models consider the outdoor conditions for calculating the comfort temperature but, in these climates, aspects such as the operability of the adaptive façade and the users' evaluation must also be considered to obtain a comfort temperature that matches the climate, taking advantage of users' adaptability. This chapter presents information from research carried out in homes in non-extreme climates of the Southern Hemisphere, where the users' assessment of comfort plays an essential role. It shows that the comfort temperature in these climates is no longer a linear standard but varies depending on both outdoor conditions and the users' capacity to adapt.

Keywords Thermal adaptation · Comfort · Non-extreme climates · Residential

1 Introduction

Comfort is "that condition of mind that expresses satisfaction with the thermal environment" [1]. The thermal need is "the final thermal environment that a person actualizes by employing enough control approaches" [2]. Considering that people

A. R. Maristany (✉)
Center for Acoustic and Lighting Research (CIAL), Universidad Nacional de Córdoba, Faculty of Architecture, Urbanism and Design, Córdoba, Argentina
e-mail: amaristany@unc.edu.ar

G. M. Arrieta
National Council for Scientific and Technical Research (CONICET), Buenos Aires, Argentina
e-mail: g.arrieta@mi.unc.edu.ar

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Table 1 Thermal environment parameters

Meteorological parameters	Physiological parameters	Parameters of architectural space	Circumstantial parameters
Air temperature	Gender	Materials	Type of activity
Relative humidity	Physical complexion	Textures and colors	Metabolic intake
Wind speed	Metabolism	Vegetation	Clothing
Solar radiation		Air conditioning	Acclimatization
Infrared radiation		Ventilation or winds	Dwell time

Source [7]

spend up to 90% of their time indoors [3, 4], it is important to study the thermal comfort of users and their perception of air quality in buildings, as these positively or negatively influence the satisfaction, performance, and health of the occupants [5, 6].

The comfort range is characterized by considering multiple parameters (the main ones are synthesized in Table 1), where the analysis and associated indicators have a high level of subjectivity.

Indoor environments must be habitable, comfortable, safe, and productive, with low energy costs, and their design must meet sustainability requirements [8]. Recently, thermal comfort models based on field studies have achieved better performance than traditional methods, based on theory or prediction (e.g., the predicted mean vote model) [9]. And, as Williamson and Daniel [10] mention, the use of an appropriate adaptive comfort model to assess building performance certainly has the potential to help design buildings that respond to the needs of occupants. Over the past two decades, the world has experienced a sharp increase in energy consumption in developing countries, and the trend is expected to continue in the near future [11].

The so-called adaptive approach requires the thermal adaptation of buildings and people, and this can contribute to saving a significant amount of energy [12]. It seems more likely that the strong correlation typical of indoor and outdoor temperatures in highly permeable building designs mean that the outdoor temperature is a reasonable indicator of indoor temperature fluctuations. As a result, conventional adaptive models based on outdoor temperature may have high levels of ability to predict comfortable indoor temperatures, but only in climate-sensitive buildings that track the natural cycles outdoors [13].

Jara [14] reports that the sensation described by individuals surveyed in naturally ventilated buildings approaches the measurement in the PMV (Fanger's Predictive Mean Vote index, based on a scale of seven levels of thermal sensation, which predicts the subjective vote of a large group of people about their thermal environment). Clear evidence was also found that people adapt more strongly to indoor temperatures, regardless of conditioning strategy (i.e., natural ventilation, air conditioning, or mixed mode) [13].

Very cold or very hot extreme climates require standardized and rigorous design strategies to meet indoor livability levels. But temperate, or so-called intermediate climates, does not have clearly defined strategies. These climates, very frequently found in the Southern Hemisphere, also allow developing countries to respond to the housing deficit with affordable buildings that take little account of comfort conditions. This contributes to users resorting to mechanical means of conditioning and the high energy consumption mentioned above. This translates into a broad ability to define flexible relative guidelines, aimed at achieving efficient dwellings that collaborate toward thermal conditioning through the adaptability of their envelopes and that avoid dependence on artificial conditioning mechanisms [15]. That is why this chapter addresses residential thermal adaptation in non-extreme climates and its potential for energy savings.

2 Thermal Comfort in Non-Extreme Climates

According to Marincic et al. [16], the current demand for housing in developing countries has led to the construction of affordable houses with designs that are unsuitable for the climatic conditions of the region, making them uncomfortable, in addition to consuming a lot of energy. Knowing the specific thermal comfort conditions for each climate and population type favors the design of more habitable buildings that respond to the particular needs of their users. When outdoor weather conditions are not extreme, in a developing country context with an interest in solving housing demand, there are no flexible, standardized strategies, and housing solutions emerge that pay little attention to the variable conditions of indoor comfort. In this context, the role of adaptive reference standards is fundamental. In this type of standard, the preference ranges and adaptation of individuals to a thermal environment depend on the relationship of outdoor and indoor temperatures with comfort temperatures, and on the user's previous thermal experience that influences their thermal perception and ability to adapt.

Building rating systems in Latin America emerged in 2003. Some focus on rating performance holistically, considering aspects concerning water, energy, materials and waste, and urban insertion. On the other hand, others focus only on evaluating the energy performance of the building, analyzing aspects of thermal comfort and energy efficiency. However, they are not mandatory for construction in all countries [17]. From 2019 to 2021, a study of indoor thermal comfort was carried out in residential sectors of the city of Córdoba, Argentina. The comfort ranges regulated by the linear IRAM standards, used as a reference in this country, were compared with the adaptive standards. It was noted that the two standards, ASHRAE 55 [1] and UNE-EN 15251 [18], which are presented as adaptive with respect to the outdoor temperature, differ in their ways of considering it, which makes their relationship with daily thermal variations very different (See Table 2).

It is evident that the criterion defined by EN-15251 follows a variation trend that enables more accurate comfort margins to be defined than those of ASHRAE 55 and with a dynamic adjustment to outdoor temperature conditions. These comfort ranges can be covered with resources and design strategies of the architectural envelope,

Table 2 Comfort temperature reference levels (T_{co}) in ventilated buildings according to ASHRAE 55 [1] and EN-15251 [18]

Hygrothermal comfort		
Standard	Parameter	Reference levels
ASHRAE 55	PPD-PMV	$T_{co} = 0.31T_{ref} + 17.8$ (°C)
		T_{ref} = prevalent outdoor air temperature 7 to 30 days before the day in question
EN-15251	PPD	$T_{co} = 0.33T_{rm7} + 18.8$ (°C)
		T_{rm7} = weighted average of the daily outdoor temperature of the previous seven days

T_{co}: Comfort temperature

using ventilation or other similar resources. In the same way, using these mechanisms, it would be impossible to achieve the comfort standards recommended by the criteria currently accepted in the standards.

Figure 1 compares the comfort ranges defined by the reference standard used for construction in Argentina, IRAM 11659-1 and IRAM 11605, and the T_{co} proposed by the adaptive models considered above, depending on the outdoor temperature. IRAM proposes three levels of comfort (A recommended, B medium, and C Minimum). Although the proposed values of thermal comfort are for artificially conditioned buildings, they are the only normative reference framework available in Argentina, and they are also used to evaluate thermal comfort in naturally conditioned buildings.

It is observed that the comfort ranges established by IRAM do not correlate with the ranges corresponding to the adaptive comfort models. IRAM's recommended winter comfort level A roughly fits adaptive comfort levels, mainly for low outdoor temperatures, while the summer comfort level A is below adaptive comfort ranges. On the other hand, although different comfort ranges are established for winter and summer, there is no adaptation based on the outdoor temperature for intermediate seasonal situations.

In the Southern Hemisphere, the least comfortable periods are summer, which begins on December 21 and ends on March 21, and winter, which begins on June 21 and ends on September 21. Figures 2 and 3 compare the average daily temperatures for 2019 with the comfort levels for both periods and those defined by IRAM and the T_{co} proposed by the adaptive models.

In summer, the comfort temperatures calculated according to EN-UNE 15251 are very close to the comfort level C, minimum, proposed by IRAM, while level B, medium, approximates the mean value proposed by ASHRAE. It is important to highlight the great temperature difference that there is between comfort level A, recommended by IRAM, and the T_{co} calculated according to EN-UNE 15251, reaching an average value of 3°C of difference in summer. In winter, the outdoor temperatures are quite different from those calculated by both the regulations and the adaptive standards. IRAM level A approaches the values established by ASHRAE, but with

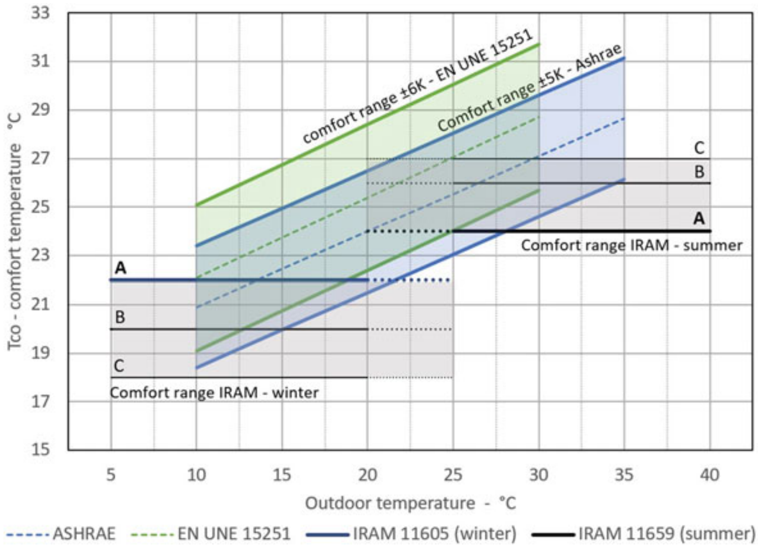

Fig. 1 Comfort ranges according to IRAM compared to T_{co}, according to the two adaptive comfort models for Cordoba

an average 10°C difference with the T_{med} per day. In this period, IRAM comfort level C is the only one that tries to approach the real temperatures, anticipating any possible difficulty in achieving comfort in this period through passive means.

The temperature and humidity conditions in the living spaces of the homes studied were surveyed. At the same time, users were surveyed, within the environments being monitored, about their thermal assessment. The survey consisted of seven multiple-choice questions, assessing the thermal environment on a 7-point scale (−3 very cold, −2 cold, −1 a little cold, 0 neither cold nor hot, 1 a little hot, 2 hot, 3 very hot), future preference, and acceptability. Taking the temperature and assessment data, and through the so-called thermal sensation interval means method (MIST, in Spanish) [19], an indoor temperature range was obtained where most users reported feeling comfort. The standards mentioned were then compared with the assessment of the residential users. In summer (Fig. 2), the comfort range obtained for 68% of the people is between 23.6 and 29.8°C, with a T_{co} assessed at 26.6°C, which is much less demanding than all the authors studied and is consistent with the outdoor seasonal temperatures and their variations [20].

In winter (See Fig. 3), as expected, the comfort range obtained from the survey assessments for 68% of the people was between 16.8 and 22°C, with a T_{co} at 19.4°C, which was again less demanding than current standards [15]. It is less demanding not only for the assessment of warmer comfortable temperatures in summer and cooler in winter but also for the breadth of the comfort range, which matches the characteristic outdoor condition of these climates.

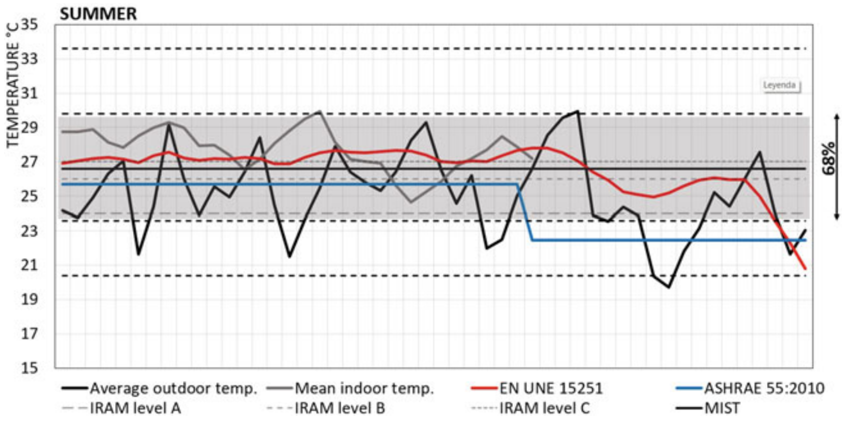

Fig. 2 Mean indoor temperatures, Comfort temperature according to ASHRAE 55 and EN-UNE 15251, Comfort range, and T_{co} according to assessment for summer (MIST)

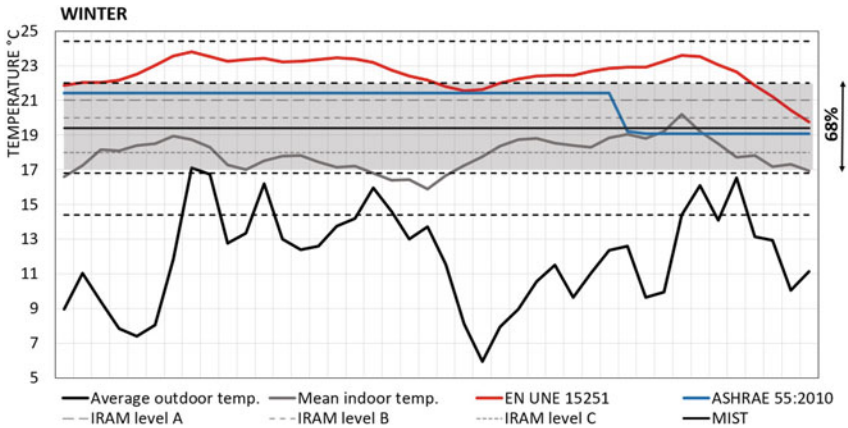

Fig. 3 Mean indoor temperatures, Comfort temperature according to ASHRAE 55 and EN-UNE 15251, Comfort range, and T_{co} according to assessment for winter (MIST)

The residential building sector represents 44% of local electricity consumption, with the user being responsible for this consumption, particularly on using systems that consume large quantities of energy, such as individual air conditioning systems [21]. Energy education for development refers to building a system of knowledge, procedures, skills, behaviors, attitudes, and values regarding the proper use of forms of energy, its generation, and management. This implies that it must be oriented toward knowledge training that includes the technological, financial, and social advances that make the inhabitant an active part of the energy models [22].

3 User Perceptions, Comfort Temperature, and Tolerance Ranges

The MIST method [19, 23] mentioned above was applied in studies on residential comfort carried out in Córdoba, Argentina [15, 20]. In the study on the residential comfort ranges assessed by people in winter and summer, the indoor temperatures monitored are associated with user evaluation on a 7-point scale, from very cold to very hot (See Fig. 4). At each level of thermal sensation, the average and its trend line (orange) are calculated, which allows the neutral temperature (T_n) to be determined. Then the standard deviation of each level of thermal sensation is calculated and 1 standard deviation is added and subtracted from the average (gray and yellow) to obtain the comfort range of 68% compliance, also called the reduced range. Then, by adding and subtracting 2 standard deviations (in blue and green), the comfort range is calculated for 95% conformity or the extended range.

In summer, an asymmetrical climate behavior occurs, because, due to extreme heat conditions, no cold sensations are observed. In this period, temperatures are concentrated within a narrower range and the comfort range assessed is broader, showing people's ability to adapt to that type of weather (See Fig. 4). During winter, the temperatures monitored are spread over a wider range, and the assessments range from very hot to very cold, demonstrating the great thermal amplitude in that period (See Fig. 5).

In a similar study by [19] in the desert climate of Baja California, Mexico, variation in thermal comfort temperature was observed between one level of activity and another. This was due to the difference in the levels of shelter, periodicity of activity, and the thermal and psychological adaptation of the subjects. The variability in symmetry and asymmetry of the trend lines in the three levels of activity was due to the diversity of levels of acclimatization and reactive and interactive behaviors of

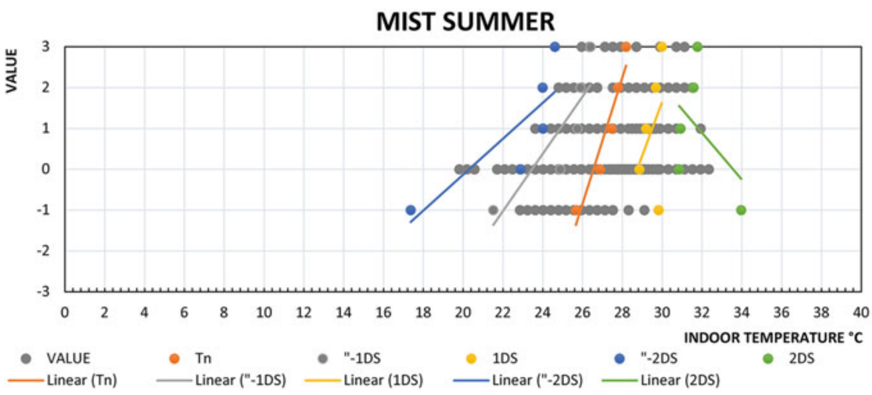

Fig. 4 Comfort range assessed by users in homes studied during the summer period (MIST)

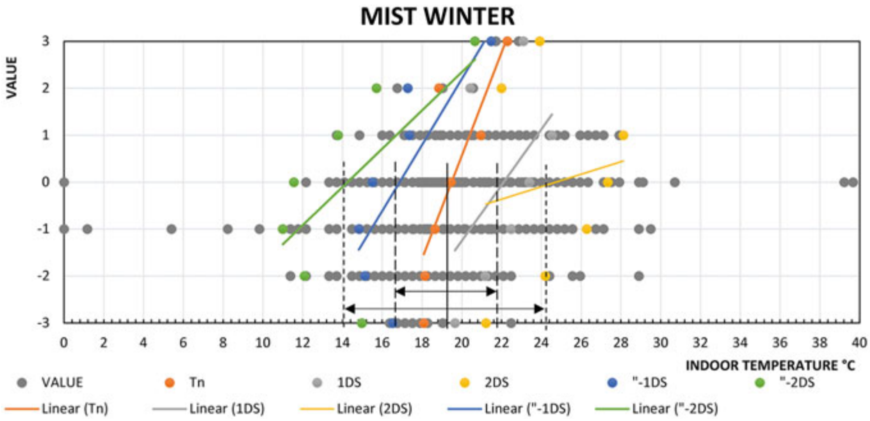

Fig. 5 Comfort range assessed by users in homes studied during the winter period (MIST)

the subjects. The greatest variation in thermal sensation occurs in moderate activity, due to the different activities and ranges of their global metabolism.

The study by García Gomez et al. [24] in Mérida, Yucatán, Mexico, concludes that the assessment of the thermal environment shows a greater acceptance and tolerance by inhabitants of self-built housing than by those who inhabit social housing. This indicates that there is not only acclimatization to the environment but also its acceptance. A better thermal adaptation of users of self-built housing was observed compared to people living in social housing. This is due to the experience and expectation of the thermal environment in the self-built home, where subjects know that they are not likely to have access to electromechanical means of ventilation or cooling, due to their economic situation.

This demonstrates their adaptability and degree of acceptance of the thermal conditions of their homes, which is above what is established as limits in international standards. The thermal preferences of people also differed according to the climatic conditions of the place and especially the indoor conditions in which they live.

Bravo Morales and González Cruz [25] found that field studies on thermal comfort, based on the adaptive principle, are generally oriented toward the development of local comfort standards for the design and construction of buildings by climates and cultures, for different air conditioning conditions (cooling or mechanical heating or natural ventilation) and type of construction. The results of some field studies conducted in the city of Maracaibo, Venezuela, confirm the premise of the adaptive model, that the levels of adaptation depend on the experiences and thermal expectations of individuals, and the thesis that the conditions where people express neutrality are the result of the average indoor conditions of their homes.

The adaptability of people and their assessment of comfort varies according to the type of climate as well as to the biological, physiological, and psychological aspects currently included in the adaptive models. Comparing the study by García Gomez et al. [24] in summer in Mexico with that of this article in the summer of

Table 3 Temperature and comfort ranges according to a study by García Gomez et al. [24] compared to the results of the MIST study in Córdoba

Location	Climate	Type of housing	Thermal comfort temperature (°C)	Minimum thermal comfort limit (°C)	Maximum thermal comfort limit (°C)
Yucatán	Warm humid	Social housing	32.3	27.9	35.1
Mexico		Self-built housing	34.5	28.3	36.1
Córdoba, Argentina	Temperate warm	Homes monitored in Córdoba (2019–2021)	26.6	23.6	29.8

Córdoba, Argentina, (See Table 3), shows the considerable difference between the comfort temperature assessed for each case, being several degrees higher in Mexico, because it is a warm–humid climate, while Córdoba has a temperate–warm climate. This confirms the importance of the local climate, outdoor conditions, and personal expectations in the feeling of thermal well-being.

4 Comfort Temperature is No Longer a Linear Standard

As García Gomez et al. [24] mention, climatic contexts and sociocultural development of the different environments undoubtedly condition user expectations. This also has implications for energy use, access to the electricity grid, and technology, among other aspects. The studies mentioned describe different situations within the Southern Hemisphere, different contexts, and types of climates. But in all of them, it can be noted that the users' perception varies depending on certain personal, social, and cultural parameters, which are related to habituation or expectation. Namely, the comfort temperature ceases to be a linear or static standard that can be calculated only from standardized formulas and becomes a variable condition, depending on daily and seasonal climatic conditions, as well as on the adaptability of the users, their tolerance, and expectations.

The internationally established standards consider climate parameters more generally, and adaptive models also certainly consider daily and seasonal thermal variation, but they do not include the user. It is the latter who, starting from these factors, can significantly vary the temperature that buildings must reach indoors to efficiently fulfill their function.

Energy consumption in ever more densely populated cities is steadily increasing. Built spaces account for about 40% of the global energy consumed and contribute more than 30% of total CO_2 emissions. A large proportion of this energy is used for the thermal comfort of these buildings [11]. Users demand safe, clean, and well-air-conditioned places, but for this reason, it is essential to integrate theoretical concepts with the perceptions of inhabitants, to thus be able to achieve an optimal balance between thermal well-being, social standards, energy consumption, and sustainable development.

In intermediate climates or those with non-extreme thermal conditions of heat or cold, it is common for buildings to be operable when naturally ventilated, which implies an almost constant connection of the indoor thermal environment with the outdoor. The adaptive standards mentioned in this chapter, ASHRAE 55 and EN-UNE 15251, consider outdoor thermal variations for calculating the comfort temperature. But the results of the MIST method mentioned show that user assessment, conditioned by psychological, biological, physiological, sociocultural, and economic aspects that have implications in the perception of comfort temperature, demonstrate that thermal well-being in residential spaces is a much broader and more complex condition than the mere external thermal variation. It is the users' assessment that determines the final energy consumption, and which should be targeted when defining the residential indoor thermal comfort range.

References

1. ASHRAE (2004) ANSI/ASHRAE standard 55: Thermal environmental conditions for human occupancy
2. He Y, Li N, Lu J, Li N, Deng Q, Tan C, Yan J (2021) Meeting thermal needs of occupants in shared space with an adjustable thermostat and local heating in winter: An experimental study. Energy Build 236:110776. https://doi.org/10.1016/j.enbuild.2021.110776
3. Brasche S, Bischof W (2005) Daily time spent indoors in German homes-Baseline data for the assessment of indoor exposure of German occupants. Int J Hyg Environ Health 208:247–253. https://doi.org/10.1016/j.ijheh.2005.03.003
4. Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Exposure Sci Environ Epidemiol 11:231–252. https://doi.org/10.1038/sj.jea.7500165
5. Che WW, Tso CY, Sun L, Ip DY, Lee H, Chao CY, Lau AK (2019) Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system. Energy Build 201:202–215. https://doi.org/10.1016/j.enbuild.2019.06.029
6. Kim J, Hong T, Kong M, Jeong K (2020) Building occupants' psycho-physiological response to indoor climate and co_2 concentration changes in office buildings. Build Environ 169:106596. https://doi.org/10.1016/j.buildenv.2019.106596
7. Bojórquez G (2010) Confort térmico en exteriores: actividades en espacios recreativos. PhD thesis, Universidad de Colima, Colima, Mexico
8. Bellia L, d'Ambrosio Alfano FR, Fragliasso F, Palella BI, Riccio G (2021) On the interaction between lighting and thermal comfort: An integrated approach to IEQ. Energy Build 231:110570. https://doi.org/10.1016/j.enbuild.2020.110570
9. Gao N, Shao W, Rahaman MS, Zhai J, David K, Salim FD (2021) Transfer learning for thermal comfort prediction in multiple cities. Build Environ 195:107725. https://doi.org/10.1016/j.buildenv.2021.107725

10. Williamson T, Daniel L (2020) A new adaptive thermal comfort model for homes in temperate climates of Australia. Energy Build 210:109728. https://doi.org/10.1016/j.enbuild.2019.109728
11. Yang L, Yan H, Lam JC (2014) Thermal comfort and building energy consumption implications-A review. Appl Energy 115:164–173. https://doi.org/10.1016/j.apenergy.2013.10.062
12. Rijal HB (2021) Thermal adaptation of buildings and people for energy saving in extreme cold climate of Nepal. Energy Build 230:110551. https://doi.org/10.1016/j.enbuild.2020.110551
13. Parkinson T, de Dear R, Brager G (2020) Nudging the adaptive thermal comfort model. Energy Build 206:109559. https://doi.org/10.1016/j.enbuild.2019.109559
14. Jara P (2015) Confort térmico, su importancia para el diseño arquitectónico y la calidad ambiental del espacio interior. Utopia Teoria Praxis 7:106–121
15. Arrieta G, Maristany A (2019) Revisión de los rangos de confort invernal de viviendas en Córdoba, como condición para el acondicionamiento natural. Avances en Energías Renovables y Medio Ambiente 23:103–113, http://sedici.unlp.edu.ar/handle/10915/109526
16. Marincic I, Ochoa JM, del Río JA (2012) Confort térmico adaptativo dependiente de la temperatura y la humedad. ACE: Architecture. City Environ 7:27–46. https://doi.org/10.5821/ace.v7i20.2572
17. Reus Netto G (2017) Sistemas de calificación edilicia en Latinoamérica. Propuesta de zonificación regional a partir de la necesidad de grados día de refrigeración y calefacción aplicada a edificios de vivienda en Latinoamérica. Master's thesis, Universidad Nacional de La Plata. https://doi.org/10.35537/10915/62912
18. AENOR (2008) UNE-EN 15251:2008. Parámetros del ambiente interior a considerar para el diseño y la evaluación de la eficiencia energética de edificios incluyendo la calidad del aire interior, condiciones térmicas, iluminación y ruido
19. Bojórquez G, Gómez-Azpeitia LG, García-Cueto R, Luna A, Romero R (2010) Confort higrotérmico para actividades en espacios exteriores: periodo cálido, en clima cálido seco extremo. In: International Conference Virtual City and Territory. 6to. Cogreso Internacional Ciudad y Territorio Virtual, Mexicali, 5, 6 y 7 Octubre 2010, Universidad Autónoma de Baja California. https://doi.org/10.5821/ctv.7639
20. Arrieta G, Maristany A (2020) Rangos de confort estival de viviendas en Córdoba como referencia para el acondicionamiento natural. Avances en Energías Renovables y Medio Ambiente 24:7–18. http://sedici.unlp.edu.ar/handle/10915/109526
21. Alonso Frank A, Kuchen E (2018) Nivel de eficiencia del usuario (neu) vs. consumo eléctrico en 14 edificios residenciales en altura en San Juan, Argentina. Revista Hábitat Sustentable 8:68–79. https://doi.org/10.22320/07190700.2018.08.01.06
22. Gallego Torres AP, Castro Montaña JE (2014) Sobre el rol innovador de la educación energética para la investigación en ingeniería. Ingeniería 19:147–163. http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0121-750X2014000200009
23. Gómez-Azpeitia LG, Bojórquez G, Ruiz P, Romero R, Ochoa J, Pérez M, Reséndiz O, LLamas A (2009) Comfort temperatures inside low-cost housing: Case: Six warm climate cities in Mexico. In: PLEA2009–26th conference on passive and low energy architecture, vol 26, pp 498–503
24. García Gomez C, Bojórquez Morales G, Ruiz Torres P (2011) Sensación térmica percibida en vivienda económica y auto-producida, en periodo cálido, para clima cálido húmedo. Ambiente Construído 11:099–111. https://doi.org/10.1590/S1678-86212011000400008
25. Bravo Morales GC, González Cruz EM (2003) Confort térmico en el trópico húedo: experiencias de campo en viviendas naturalmente ventiladas. Ambiente Construído 3:47–55. https://seer.ufrgs.br/index.php/ambienteconstruido/article/view/3450

A Pathway to Comfort by Natural Conditioning: Selecting Bioclimatic Design Resources

John Martin Evans

Abstract Passive building design and construction modifies outdoor environmental conditions, improving comfort and reducing dependence on artificial conditioning and conventional energy. This chapter presents an analysis of bioclimatic design resources and selection methods developed over the last 50 years and presents a new approach based on the response to typical external conditions with special emphasis on the control of temperature swings and modification of indoor average temperatures. This is based on the dynamic variations of periodic heat flow using bioclimatic design resources such as thermal inertia that affects the indoor conditions over the daily cycle. The method aims at promoting appropriate combinations and levels of bioclimatic strategies, to guide the designer at the initial design stage before definitive decisions. The graphic tool allows the designer to use climate data and comfort limits to select and visualize alternative design resources, promoting participation in the development of bioclimatic approaches to near-zero energy buildings.

Keywords Natural conditioning · Climate · Bioclimatic design · Thermal comfort · Passive strategies

1 Introduction

The latest report of the Intergovernmental Panel on Climate Change [1] emphasizes the need to reduce greenhouse gas emissions and avoid potentially catastrophic environmental impacts. This is especially important in the building sector due to the long-term impacts and conventional energy demand of permanent structures [2, 3]. Much of the

J. M. Evans (✉)
Research Centre Habitat and Energy, Faculty of Architecture, Design and Urbanism, University of Buenos Aires, Buenos Aires, Argentina
e-mail: evansjmartin@gmail.com

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region below the Tropic of Cancer has also suffered from a severe housing deficit in quantity and quality with a demand for more and better solutions [2].

However, many designers and builders do not have the knowledge and tools to respond to this new challenge with appropriate sustainable solutions. This chapter therefore emphasizes the need to identify suitable bioclimatic strategies at an early design stage, presenting a new approach to select passive solutions that reduce or avoid dependence on air conditioning and heating with the inevitable impacts, promote near-zero energy-building solutions, and overcome the barriers to environmental comfort.

This new approach allows the identification of design strategies to promote low-impact and improved social housing, offering comfort and energy efficiency, and responding to local climatic, technological, and social conditions. Passive solutions incorporating natural conditioning are especially appropriate in temperate climates and warmer regions with significant temperature swings and good solar radiation; conditions that are typical of many countries in the region. The conventional approach to comfort is based on a simple energy balance, using artificial heating and cooling to provide adequate conditions when the building fails to provide them. Traditional bioclimatic methodologies, based on the charts of Olgyay [4, 5] and Givoni [6], identify key strategies but have two drawbacks. On one hand, they consider each strategy individually, and although several strategies are usually used simultaneously, some work well together, while others may be incompatible. They also analyze conditions at a specific point in time, while indoor conditions will often depend on strategies that affect future conditions, such as thermal inertia and time lag. So, following an evaluation of traditional bioclimatic procedures, this chapter presents a new design approach to select suitable combinations of design strategies and evaluate their effectiveness in achieving comfort by building designs for natural conditioning.

2 Traditional Bioclimatic Methodologies

This section reviews different approaches to the bioclimatic design process that have evolved over the last 50 years with an emphasis on graphic tools developed for architects, and their application in the range of climates found in the southern hemisphere. They all follow a similar process that compares the existing outdoor temperature and humidity with the indoor conditions needed to ensure thermal comfort. The difference between the existing and required conditions is used to detect the appropriate design strategies. In this framework, four methods are considered, starting with the characteristic response for each basic climatic type.

It should be noted that the whole concept of bioclimatic design and changes of strategies needed in different climates have been known since Greek and Roman times when large empires started to spread over different climatic regions and regional building variations were recognized. Up to seven climatic regions were identified by early geographers such as de Sacrobosco [7], ranging from uninhabitable cold northern climates to excessively hot climates. These differences became more important in the colonial period when British, French, German, Dutch, Spanish, and Portuguese territories extended over widely different climatic regions.

This required a deeper knowledge of the design strategies and bioclimatic resources needed for the design of government buildings and housing in each zone, in the era before air conditioning was available. Systematic research undertaken into comfort conditions and building performance intensified because of military requirements during both world wars, leading to the development of thermal stress research, comfort studies, and bioclimatic methodologies. These are presented in the following four subsections.

2.1 Solutions for Different Climate Types

The standard texts on bioclimatic design describe the typical climates and the corresponding architectural design solutions that have been developed in response to these environmental conditions. The tropical climates are often divided into warm humid equatorial, hot dry desert, monsoon, or transition climates. Additionally, this classification can include cooler upland climates, humid maritime desert climates, and continental climates found in regions between the tropics. In sub-tropical and higher latitudes, the classification can include the climate of the Mediterranean Region with hot dry summers and cool wet winters, cool mid-latitude, and cold Arctic and Antarctic climates. An initial design solution is suggested for each of these climates, often derived from vernacular responses. Early references include Maxwell Fry and Jane Drew [8, 9]. Many standard texts such as [4, 5, Chap. 2] and [10, Chap. 6] start with this sequence before presenting more detailed methods. This approach can provide an initial indication of architectural solutions that respond to the local climate but have limitations. They usually indicate a single solution, though there may be equally effective alternatives. Also, they do not consider the transitions between different climate types. Another relevant factor is the difference between building types, as housing requires day and night comfort, while schools and offices are normally used by day.

2.2 Olgyay's Bioclimatic Chart

Victor Olgyay's Bioclimatic Chart [4, 5] relates the external climate conditions of temperature and humidity to the range of conditions that fall within the comfort zone. The chart also proposes a variation in the comfort zone for winter and summer seasons, an early recognition of "adaptive comfort". When external conditions of temperature and humidity are outside the comfort zone, the chart indicates the favorable modifications that can be achieved using three mechanisms: air movement, humidification, and solar radiation. The chart shows the intensity of solar radiation,

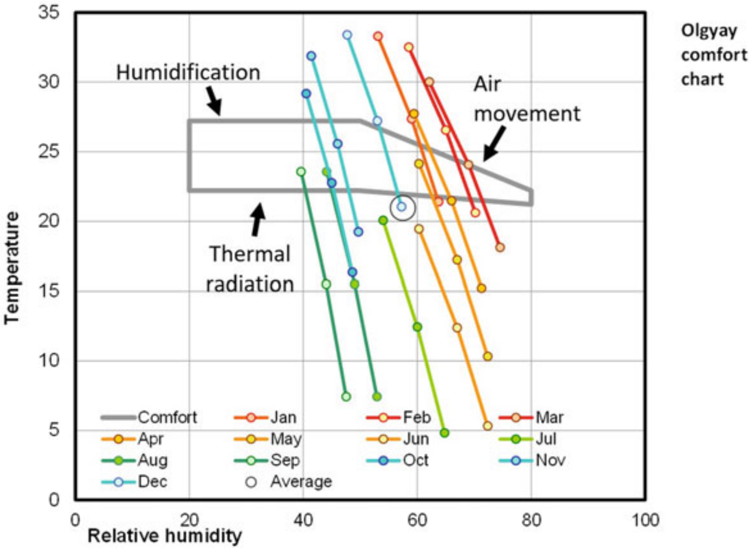

Fig. 1 Adaption of the Olgyay Bioclimatic Chart [4, 5] with SI units, with average monthly temperature and relative humidity for Catamarca, Argentina

the velocity of air movement, or the amount of water evaporated that is needed to achieve comfort.

These mechanisms only include direct impacts on the occupants (see Fig. 1). For example, the chart considers solar radiation on the body, but does not indicate the indirect effect of passive solar systems. These include the direct cooling effect of cross ventilation with air movement over the body but do not include the night cooling achieved with selective ventilation.

The text includes a clear recognition that, in addition to the strategies included, other resources are needed to achieve comfort. Olgyay's book [4, 5] provides extensive guidance on the use of thermal inertia though this bioclimatic design resource does not appear in the chart. The book is influential, and even after 60 years, it is still in print.

2.3 Givoni's Bioclimatic Chart

Givoni [6] developed an update on Olgyay's Chart, incorporating three new strategies based on building performance rather than just direct physiological responses (see Fig. 2): thermal inertia, passive solar strategies, and selective ventilation.

Thermal inertia will reduce indoor temperature variation, which is especially useful in climates with a high diurnal range.

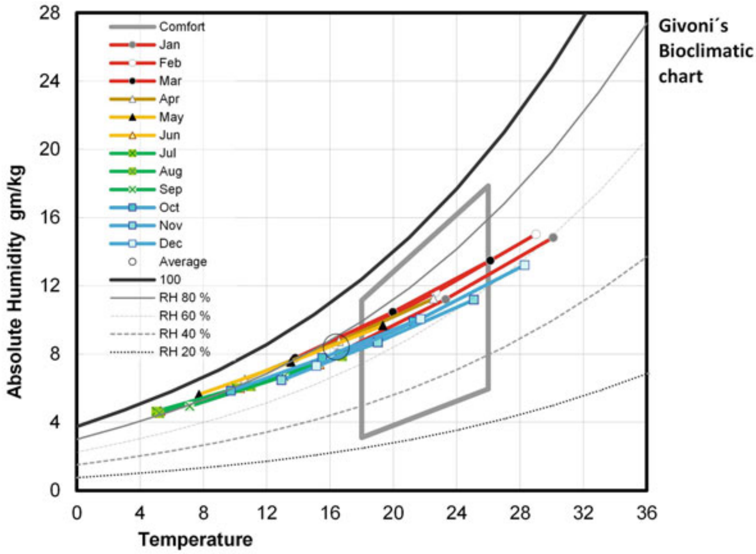

Fig. 2 Adaptation of Givoni's Bioclimatic Chart

The chart emphasizes the resources for hot climates though it is also effective in cool climates. Passive strategies such as direct solar gain increase indoor temperatures, though thermal inertia and insulation are needed to control temperature swings and conserve heat gains. The strategy of selective ventilation uses the favorable difference between indoor and outdoor air temperatures to improve indoor comfort, by opening and closing windows. When indoor temperatures are cool and outdoor temperatures are comfortable or warm, increased ventilation can warm the interior. Conversely, when indoor temperatures are hot at night but the outdoor temperature is comfortable or cool, ventilation can also improve comfort. Therefore, the psychrometric chart is used as a base for the analysis of climate concerning comfort and appropriate bioclimatic strategies applying a format with a horizontal temperature axis and a vertical absolute humidity axis, widely understood and used for air conditioning. The basic chart shows 16 strategies, although 5 are active systems: conventional heating, cooling, fan-assisted air movement, two-stage evaporative cooling, and dehumidification. Most of the strategies combine bioclimatic design resources.

2.4 Mahoney Tables

The Mahoney Tables [10, 11] were developed in response to one of the limitations of the basic climatic classification. This is illustrated by the case of West Africa where the climate varies gradually from a tropical warm humid equatorial climate on the coast to the fringe of the Sahara Desert to the north. In the two extremes, design solutions are clear with different bioclimatic strategies, but the problem remains of defining the changing design responses to the slow climatic variations as the latitude increases. Where is it necessary to change from a lightweight construction to components with high thermal inertia? Where is a change required from effective cross ventilation to limited air movement and protection from hot dusty winds? Where is the change needed from an open urban layout that promotes cooling breezes to a compact urban form to achieve protection from the sun and wind?

The Mahoney Tables offer a menu of design options that correspond to climate conditions based on the following analysis. Firstly, the annual average temperature is used to determine the comfort zone, directly responding to the adaptive comfort studies by [12] and [13]. The introduction of comfort limits for day and night is another innovation, recognizing that the daytime maximum requires a different range from the nighttime minimums. The average monthly maximum and minimum temperatures are then compared with these comfort zones, establishing the average comfort sensation, warm, cool, or neutral for night and day in each month. These comfort conditions are then compared to the climate, identifying the strategies needed for each month, called "Indicators".

- Cross ventilation: essential if conditions are warm, relative humidity is high, and temperature swings are low.
- Cross ventilation: desirable if conditions are warm and humidity is high.
- Thermal inertia: needed when temperature swings are over 10 degrees.
- Thermal insulation: needed if day temperatures are cold.

Two additional indicators are used for situations where protection from heavy rain is needed, and where outdoor sleeping on the roof provides comfortable conditions in desert buildings with high inertia. The total number of months with each indicator is used to obtain the appropriate design recommendations in the final tables. The first table of recommendations provides initial design guidance for project layout, orientation, and spaces between buildings, the second provides detailed guidance on the thermal properties of walls and roofs and window design.

The systematic application of the Mahoney Tables can use spreadsheets or simple programs to transform the initial climatic data into a design guide. This automatic process avoids possible errors in the application to tell the designer *what* to do but does not allow the designer to follow the sequence and understand *why*. However, some limitations of the Mahoney Tables should be noted. They were developed in 1975 when computers were very limited for simulating alternatives and test results. They provide one design solution for each location but, in many cases, alternative bioclimatic resources can provide equally comfortable results.

2.5 Climate Consultant

Milne et al. [14] developed a tool based on Givoni's bioclimatic chart, presenting an advance, with additional bioclimatic strategies, using daily or hourly climate data rather than monthly means. Version 4 adds features such as graphic screens and an explanation of the psychrometric chart. It also automatically creates a list of design guidelines based on the attributes of each unique climate and then displays a sketch illustrating how each guideline applies. The chart indicates the percentage of time each design strategy can be used to improve comfort, providing the designer with a clear guide to the importance of each strategy.

3 Current Trends

In the half-century since the introduction of bioclimatic design methods with a systematic and scientific base, there have been several developments, some of which favor more energy-efficient and thermally comfortable projects and others that do not promote low-impact architecture. This section presents the most important of these influences.

3.1 Rising Expectations

Although poverty and the lack of physical and economic resources are still critical limitations in many regions of the world, large proportions of the population have benefited from improved conditions and expect continuing improvements in the quality of life. This includes better, larger, and more comfortable homes, easier travel, access to technology, and better diets, implying larger environmental impacts. In the residential sector, expectations of improved comfort may lead to an important increase in energy demand. Improved indoor conditions, better building envelopes, and more efficient environmental control installations will also further increase comfort expectations, narrowing the temperature range of acceptable conditions.

3.2 Air Conditioning

Modern air conditioning, introduced by Carrier in 1923 [15], was beginning to be used in the pre-war period in offices and industries where climate control was essential for productivity. In the post-war period, the use of air conditioning spread to the tropics in offices, clothing, and electronic industries, allowing Singapore, Hong Kong, Japan, and Korea to compete in world markets.

Rising expectations in the residential sector have also led to an increased and widespread demand for air conditioning in recent decades. This trend is a result of three factors: reduction in the cost of small A/C units, improvements in energy efficiency, and better access to electricity networks over the years, combined with the aforementioned rising expectations. However, the wider distribution of air conditioning units has additional consequences. As designers, users, and producers of buildings recognize the possibility of achieving comfort through artificial conditioning, there is less incentive to plan energy-efficient buildings through improved architectural design and construction.

3.3 Architectural Trends

Another factor related to rising expectations and increased dependence on air conditioning is the current trends in architectural design. These include the tendency to use larger glazed openings and reduce solar protection. The increased use of air conditioning also allows designers to ignore the consequences of undesirable orientations and less efficient building shapes. This is also related to the training of building professionals which still requires an additional emphasis on sustainable and energy-efficient design.

3.4 New Materials

Over the decades, there has also been progress in developing new materials and improvements for existing components. In this context, new technologies in glass production have introduced the possibility of lower costs and larger windows. At the same time, new technological advances allow glass with lower heat transfer, through low transmission and heat-reflecting glass. However, in many regions, the adoption of double-glazing and heat-reflecting treatments have been slow. New and improved insulating materials have also been developed such as glass wool, mineral wool, and plastic foam in sheets or sprayed.

These low-density materials allow very low thermal transmission at accessible prices, allowing a sustained improvement in thermal performance over time with stricter building regulations in many developed countries, though in most of Latin America and other warmer climates, thermal performance standards are still not mandatory.

Another development is the tendency toward lightweight building systems with limited thermal inertia. Even when improved thermal insulation is incorporated, in many cases, these low-heat capacity buildings will need artificial conditioning for thermal comfort, especially in climates with significant outdoor daily temperature swings.

3.5 Simulation and Computer Tools

The use of computers allows new tools to evaluate building performance, dimension heating and cooling installations, and simulate thermal comfort. These tools include highly complex programs to simulate energy performance, thermal comfort, and environmental impacts over a typical year, using detailed virtual building models and hourly climate data. However, these programs do not provide useful output at the early stages of the design process. Another advance is the availability of detailed climatic data for most cities of the world, often with hourly measurements. Where ground-based meteorological data is not available, for example, solar radiation intensity and remote sensing provide design data [16, 17].

4 Comfort Triangles

Comfort Triangles [18] were developed as a bioclimatic design tool to overcome some of the limitations of the existing graphic and numerical methods presented in previous sections. The bioclimatic design resources and techniques modify the external environment to obtain more favorable indoor conditions. These are the result of three changes in the outdoor temperature variations shown in Fig. 3.

- The incorporation of thermal mass in the building envelope tends to reduce the indoor temperature variation (1) as a proportion of the outdoor temperature swing (2).
- It also produces a time lag or delays in the indoor peak temperature with respect to the outdoor maximum (3).
- The internal heat sources and solar gains combined with thermal insulation produce an increase in the indoor average temperature compared to the outdoor average (4).

The result of this combination can often achieve indoor comfort without the need for heating or cooling using conventional energy.

These modifications depend on complex combinations of thermal insulation, thermal mass, selective and cross ventilation, internal and solar heat gains, and other bioclimatic design resources. The indoor conditions usually depend on the modification of external conditions several hours beforehand. For example, the thermal inertia of a roof delays the peak outdoor impact on indoor conditions for several hours. A passive solar system such as direct gain or an unventilated mass wall stores solar heat received during the day to provide indoor comfort at night up to 8 hours later, while night ventilation cools the interior to improve comfort the following morning.

However, conventional tools compare the external environmental conditions with comfort requirements at the same time, without considering the time delay induced by the building. Another limitation of the charts is the impact of internal gains and metabolic heat of the occupants which will modify the indoor climate. The Comfort

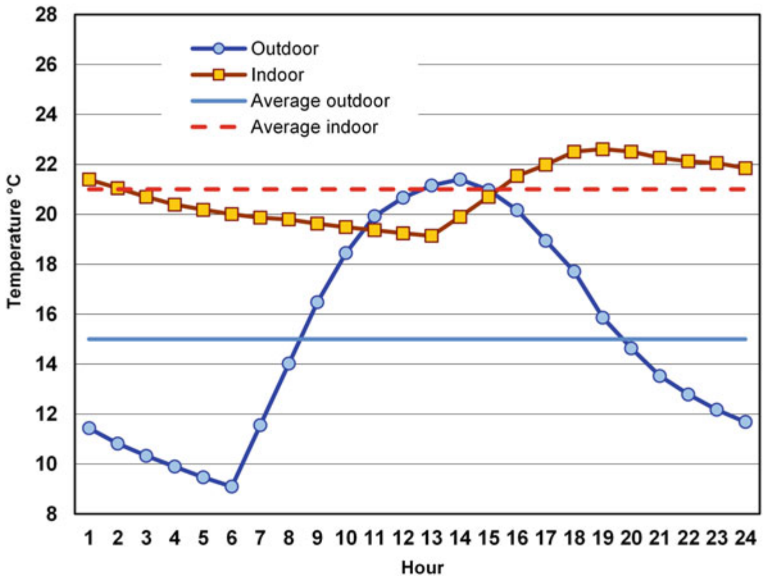

Fig. 3 Indoor and outdoor temperatures showing the modification achieved by bioclimatic design resources, (1) and (2) show reductions in temperature swing, (3) shows the difference between average outdoor and indoor temperature, while (4) shows the time lag or delay between outdoor and indoor peaks

Triangles, therefore, analyze daily outdoor temperature swings and average daily temperatures, comparing these with the range of conditions that provide comfort, assisting in the selection of appropriate bioclimatic design resources, Table 1.

The dynamic daily variations of indoor and outdoor temperatures are defined on the triangle chart by the average temperature and the range, the difference between the maximum and minimum daily temperature. The average temperature is shown on the horizontal scale, while the range is shown on the vertical scale. A point on the scale corresponding to these two values represents the daily temperature variation. This is compared to the triangle which shows the combinations of conditions for thermal comfort. The truncated triangle shows that, as average temperatures reach the maximum and minimum comfort limit, the comfort range is reduced. The basic triangle is for typical sedentary activity, but alternative triangles indicate comfort conditions for higher levels of metabolic activity, outdoor comfort (where expectations are different), and rest at night.

An example explains the tool, using selected temperature measurements from records made every 15 min over 1 year in a living room and outdoors in the shade, made in Buenos Aires. Figure 4 shows the average of hourly temperature measurements over a 5-day period, comparing an indoor space with passive bioclimatic strategies with simultaneous outdoor measurements, and presents the comfort triangles for the same data, showing the modifications due to building design, materi-

Table 1 Bioclimatic strategies and their effect on average indoor temperature and range

N°	Code	Bioclimatic strategies	Impact on average indoor temperature	Impact on the indoor temperature range	Type of strategy
1	VC	Cross ventilation	Lower temperature	No change in range	Design, adjustable
2	IT	Thermal inertia	No change	Reduce indoor range	Design, fixed
3	GD	Internal gains by day	Higher average	Increase range	User control
4	GN	Internal gains by night	Lower average	Reduce range	User control
5	GS	Solar gains	Higher average	Higher indoor range	Design
6	VD	Daytime ventilation	Higher average	Higher range	Adjustable
7	VN	Nighttime ventilation	Lower average	Lower range	Adjustable
8	AT	Thermal insulation	Increase in average	No change in range	Design, fixed
9	SP	Solar protection	Average unchanged	Without change	Design, adjustable
10	HU	Humidification	Lower temperature	Reduction in range	Adjustable

Average: Daily average of hourly temperatures
Range: Temperature swing: difference between the maximum and minimum daily temperatures
Strategy: Adjustable or constant, all require building design responses
GD: Internal gains by day: for example, classrooms, offices
GN: Internal gains by night: for example, bedrooms

als, and user adjustments such as changes in ventilation and resulting improvements in indoor comfort. The naturally conditioned room was occupied without artificial heating or cooling.

The impact of bioclimatic design strategies changes when they are combined in the same building [19, 20]. The following examples show some of the key combinations:

- Solar gains will increase the internal temperature range as well as the average indoor temperature, so thermal inertia must be incorporated to control the indoor temperature range. Improved thermal insulation in the building envelope will also enhance the effect of solar gains.
- Selective ventilation by day will take advantage of higher midday temperatures to warm the interior when the difference is favorable, enhanced by thermal inertia and insulation. Similarly, night ventilation will lower the indoor temperature, but thermal inertia will maintain cooler indoor conditions till the next day.
- Humidification will lower the temperature, but the increased humidity can reduce the temperature range. This strategy will be more effective when the temperature range is higher, as high-temperature ranges are usually associated with low humidity. Moderate ventilation may also be required to avoid an accumulation of humid air.

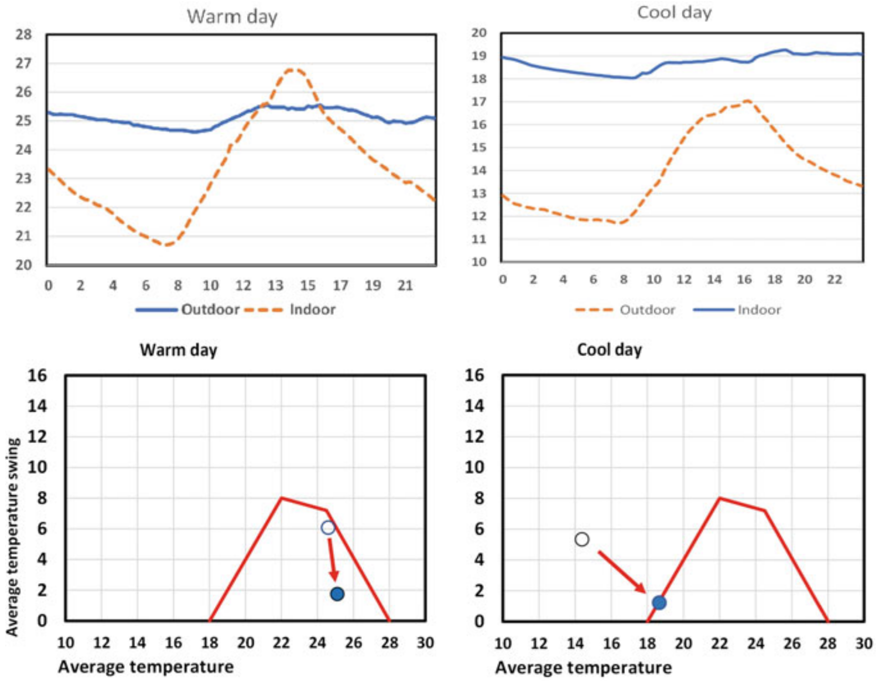

Fig. 4 Indoor and outdoor temperatures on warm and cool days in the same space, average hourly values (above), and average daily swings with average temperatures in the comfort triangles (below)

The application of different strategies may also vary in different months of the year as temperatures change. For example, cross ventilation needs openings in opposing facades, a permanent design feature, but it is assumed that openings will be closed as temperatures drop below 26°C. Solar gains will be useful when temperatures drop below 20°C, but protection will be needed as temperatures increase. In both cases, the fixed design and construction can facilitate the effectiveness of these bioclimatic strategies, but occupants will operate windows and adjust shading to avoid discomfort according to the changing conditions.

Other strategies may remain constant depending on the building type. For example, there will be limited internal gains by day and night in housing in all months of the year, while in schools and offices, higher internal gains will correspond to daytime hours. Figure 5 shows the modification achieved with different bioclimatic design strategies to improve comfort, and the actual modification in practice as a result of a combination of strategies.

The Comfort Triangles have been incorporated into an electronic spreadsheet, with results for three different climates shown in Figs. 6, 7, and 8. The spreadsheet has the following characteristics:

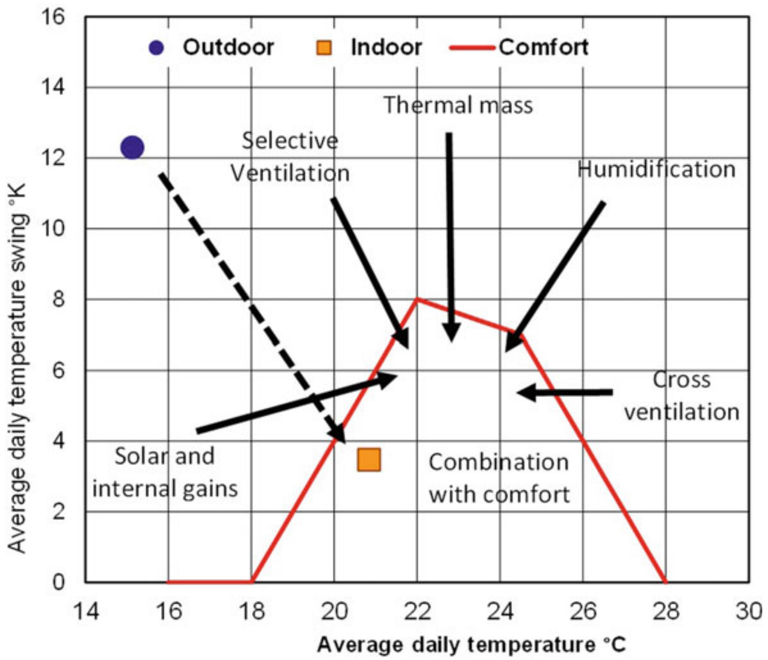

Fig. 5 The comfort triangle in red shows the combination of average temperature and daily swing that provides comfort. The black arrows show a modification of the external conditions to approach or achieve comfort, while the dotted arrow shows the actual modification with a combination of strategies, with the same data as Fig. 2

- The spreadsheet includes a climatic database of over 600 locations in Latin America and selected cities from other regions of the world.
- Once the location is selected from pull-down lists, the Comfort Triangle is shown according to country and region, and the activity level is chosen.
- The bioclimatic design resources can then be shown and the level of application is selected with different levels. For example, cross ventilation can be "high", "medium", "low", or "without movement", and solar gains can be "without sun", "limited", "average", or "high".
- The spreadsheet also calculates the number of months within or close to the comfort zone.

The impact of each bioclimatic design strategy can be changed, increased, or moderated when it is combined with others in the same building. The application of different strategies may also vary in different months of the year as temperatures change. For example, cross ventilation needs openings in opposing facades, a permanent design feature, but it is assumed that openings will be closed as temperatures drop below 25°C. Solar gains will be useful when temperatures drop below 20°C, but protection may be needed as temperatures increase above 25°C, especially with

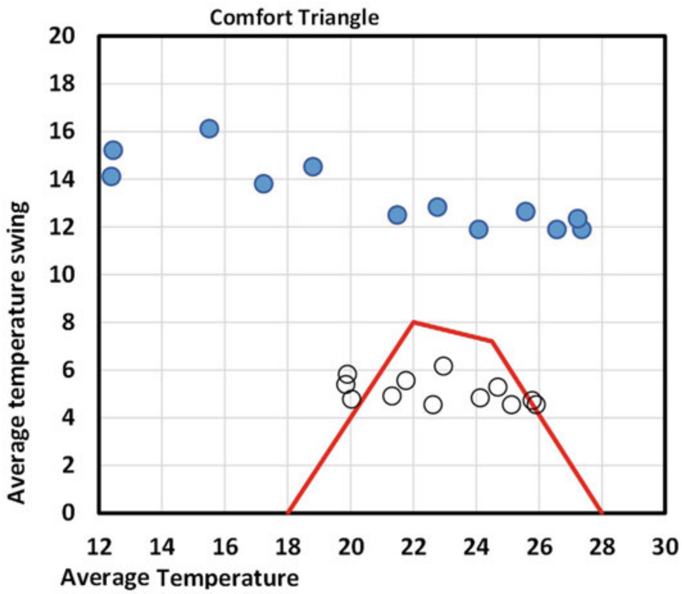

Fig. 6 Comfort Triangle and strategies in a hot dry climate: Catamarca, Argentina, latitude 28°S. Strategies include thermal inertia, limited internal gains, winter solar gains, and summer night ventilation, with good thermal insulation. An appropriate combination of strategies achieves comfort without heating or cooling for average conditions for 9 months of the year

larger glazed openings. In both cases, the fixed design and construction will allow the implementation of bioclimatic strategies, but occupants will operate windows for ventilation and adjustable shading to achieve comfort according to changing conditions.

The incorporation of the Comfort Triangles in an electronic spreadsheet demonstrates the following characteristics and advantages:

- At the initial stages of the design process, basic monthly climate data can be used to select and test design resources. Over 600 locations in Latin America and selected cities from other regions of the world have been incorporated into the database and tested.
- Comfort conditions are also variable depending on activity level and the time of day.
- The bioclimatic design resources have different levels or scales of application, for example, cross ventilation can be "high", "medium", "low", or "without movement", and solar gains can be "without sun", "limited", "average", or "high".
- The visualization also shows the number of months within or close to the comfort zone. This shows the contribution of design to achieving very low energy demand and zero emissions.

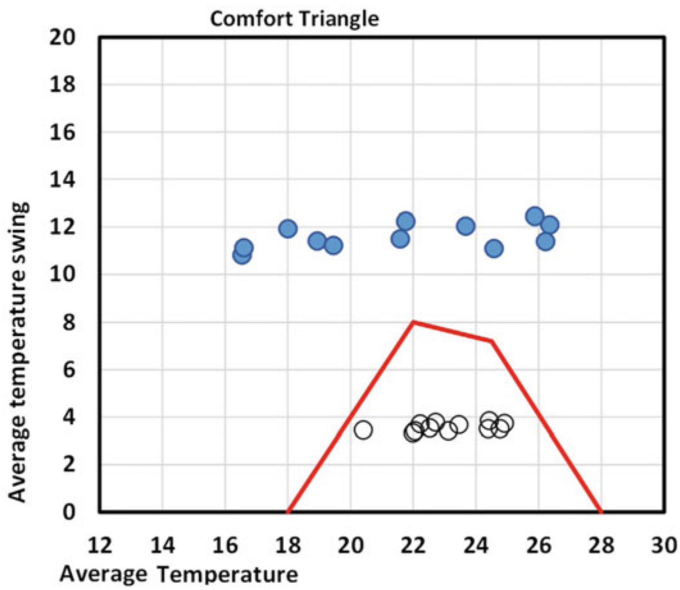

Fig. 7 Comfort Triangle and strategies in a sub-tropical warm humid: Posadas, Argentina, latitude 27°S. Strategies include cross ventilation, limited solar and internal gains, moderate thermal mass, and good thermal insulation

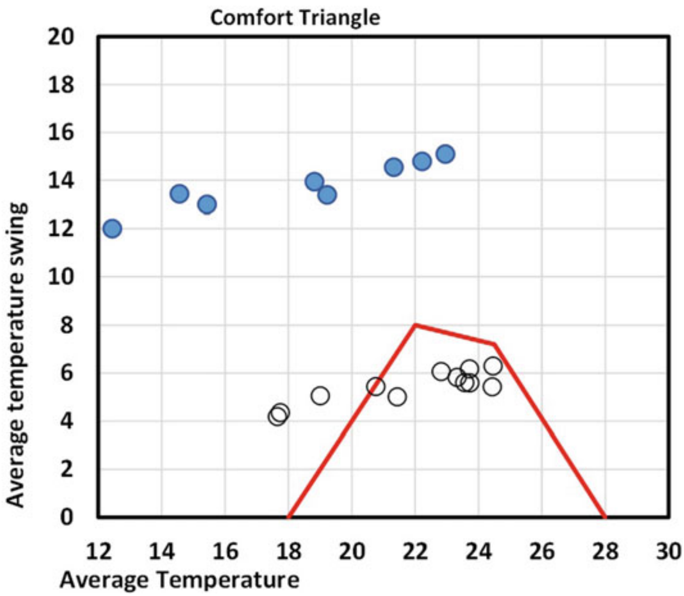

Fig. 8 Comfort Triangle and strategies in a cool mid-latitude climate: Bahia Blanca, latitude 38°S. Strategies include high thermal mass, solar gains, and very good thermal insulation. Partial heating required in 3–4 months

The modifications achieved in naturally conditioned buildings in different climates were measured in Ecuador, Mexico, Costa Rica, Chile, and Argentina and plotted the Comfort Triangles, to show the effect of different bioclimatic design resources on the urban and architectural scale [21]. Examples include lightweight and heavyweight construction, houses with passive solar systems, earth construction, and different levels of thermal insulation. The measured modifications were also compared with simulations of indoor temperature.

The application of Comfort Triangles in the design process was also tested in a wide range of climates in postgraduate courses in Argentina, Ecuador, Mexico, and Paraguay, with measurements to confirm the effective modification of indoor conditions in existing naturally conditioned buildings. An evaluation in Mexico [22] analyzes the application in different regions of the country with comparisons with the Mahoney Tables and Givoni's Bioclimatic Chart. The spreadsheet [23] includes the Olgyay and Givoni graphs, as well as adaptive comfort charts.

5 Conclusions

The Comfort Triangles offer a different way to visualize the favorable modification of external conditions using passive bioclimatic strategies. They emphasize the importance of variable thermal performance with heat flows in and out of the building envelope. This relates to many bioclimatic strategies which modify the temperature over time:

- Passive solar design uses solar absorption by day, the transmission of heat for storage in the materials, and restitution of heat to indoor spaces as temperatures decline in the evening and night.
- Daytime ventilation can increase indoor temperatures, taking advantage of warmer midday conditions, while night ventilation can be used for cooling.
- Variable internal gains during the daily cycle also contribute to temperature variations over time that can contribute to improving indoor comfort.

In cold climates, with heat losses for many months of the year, the design strategies of compact form, well-insulated building envelopes, and the incorporation of solar gains are easy to understand and incorporate in the design. The management of variable and dynamically changing conditions, typical of cool, temperate, and warmer climates are more difficult for designers to understand and apply during the design process.

This parallels other new challenges that designers face, such as mitigation and response to climate change, global warming, and low-impact materials. This change requires the development of new capacities and tools in a rapidly changing world both in education and in professional practice. The Comfort Triangles were developed to contribute to this challenge.

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References

1. Ara Begum R, Lempert RJ, Ali E, Benjaminsen TA, Bernauer T, Cramer W, Cui X, Mach K, Nagy G, Stenseth NC, Sukumar R, Wester P (2022) Point of departure and key concepts. In: Pörtner HO, Roberts D, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (eds) Climate change 2022: Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK and New York, https://www.ipcc.ch/report/ar6/wg2/
2. United Nations Environment Programme (2021) 2021 Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector. Nairobi, Kenya, https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf
3. IEA (2019) Global status report for buildings and construction 2019. Tech. rep., Integrated Environmental Assessment–United Nations Environment Programme, Paris, France, https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019
4. Olgyay V (1963) Design with climate. Princeton University Press, Princeton, US, Bioclimatic Approach to Architectural Regionalism Chapter 2
5. Olgyay V (1998) Arquitectura y Clima. Manual de diseño biocli-mtico para arquitectos y urbanistas, Spain, GG, Barcelona
6. Givoni B (1969) Man. Climate and architecture, Elsevier, London
7. de Sacrobosco J (1949) Tractatus de Sphæra [Treatise on the Sphere]. Ferrara, English Translation by Lynn Thorndike, http://www.esotericarchives.com/solomon/sphere.htm
8. Fry M, Drew J (1956) Tropical architecture in the humid zone. Batsford, London, UK
9. Fry M, Drew J (1965) Tropical architecture in the dry and humid zones. Batsford, London, UK
10. Koenigsberger OH, Ingersol J, Mayhew A, Szokolay S (1976) Manual of tropical housing and building, Part 1: Climatic design. Longmans, London, UK
11. Koenigsberger OH, Mahoney C, Evans JM (1970) Climate and house design, design of low-cost housing and community facilities, vol 1. United Nations, New York, USA
12. Nicol F, Humphreys M, Sykes O, Roaf S (1995) Standards for thermal comfort: indoor air temperature standards for the 21st century. Chapman and Hall, London, UK
13. Nicol F (2000) International standards don't fit tropical buildings: what can we do about it. In: Gonzalez E et al (eds) Memorias Conferencia internacional sobre confort térmico y comportamiento térmico de edificaciones COTEDI, Universidad del Zulia. Maracaibo, Venezuela
14. Milne M, Liggett R, Benson A, Bhattacharya Y (2009) Climate consultant 4.0 develops design guidelines for each unique climate. In: 38th ASES national solar conference 2009, SOLAR 2009, vol 8. Buffalo, New York, pp 4559–4593
15. Banham R (1969) The architecture of the well-tempered environment. Architectural Press, London, UK
16. NASA (2022) Prediction of worldwide energy resources POWER project. https://power.larc.nasa.gov/
17. WBG (2022) Global solar atlas world bank group. https://globalsolaratlas.info/map
18. Evans JM, de Schiller S (1988) Diseño Bioambiental y Arquitectura Solar. EUDEBA Editorial de la Universidad de Buenos Aires, Buenos Aires, Argentina, Ediciones previas
19. Evans JM (2001) Las Tablas de Mahoney y los Triángulos de Confort. In: Actas Conferencia internacional sobre confort térmico y comportamiento térmico de edificaciones, Maracaibo, Venezuela

20. Evans JM (2003) Evaluating comfort with varying temperatures: A graphic design tool. Energy Build 35:87–93. https://doi.org/10.1016/S0378-7788(02)00083-X
21. Evans JM (2007) The Comfort Triangles, a new tool for bioclimatic design. PhD thesis, Technical University of Delft, Delft, Netherlands, https://repository.tudelft.nl/islandora/object/uuid
22. Fuentes Freixanet VA (2004) Clima y Arquitectura. Universidad Autónoma Metropolitana, México D, F., México
23. Evans JM (2022) e-triangulos.xlsx Triángulos de Confort. Spanish and English versions available from sau@fadu.uba.ar

The Tropical Climate Matrix: An Architectural Design Tool for the Tropics

Laura Rendón Gaviria, Daniela Borja Zuluaga, and Manuela Yepes Ocampo

Abstract Currently, one of the main causes of environmental deterioration is the increasing rates of power consumption that, at the same time, are a consequence of numerous actions in all sectors. In the architecture and design field, the lack of good environmental comfort conditions in buildings is the main cause behind increased power consumption, because improperly ventilated and illuminated buildings, require mechanical strategies to regulate indoor environmental conditions. This is the reason why it is fundamental to develop tools that allow designers to incorporate environmental control strategies into design processes, to guarantee optimal indoor bioclimatic conditions. Thus, the objective of this chapter is to develop a tool that defines bioclimatic strategies for the first stages of building design and to generate good comfort conditions inside buildings. First, an analysis of climatic conditions in different climates was made in two Colombian cities: Medellin and Barranquilla, and then monthly comfort indexes were defined with their corresponding climatic correction strategies to guarantee comfort conditions, before finally proposing architectural and building strategies to achieve these climatic corrections. As a result, a highly usable tool is created, that can be used in the first stages of the design process by bioclimate experts and also users with little experience.

Keywords Andean tropics · Environmental comfort · Architectural design · Bioclimatic strategies · Design tool

L. Rendón Gaviria (✉) · D. Borja Zuluaga · M. Yepes Ocampo
Faculty of Architecture and Engineering, Institución Universitaria Colegio Mayor de Antioquia, Medellín, Colombia
e-mail: laura.rendon@colmayor.edu.co

D. Borja Zuluaga
e-mail: dborja@est.colmayor.edu.co

M. Yepes Ocampo
e-mail: myepeso@est.colmayor.edu.co

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1 Introduction

Power consumption has increased globally by more than 50% in recent decades due to factors such as demographic growth, urban migration, and accelerated economic development [1]. Moreover, the lack of good environmental comfort conditions inside buildings directly affects their power efficiency, so it becomes fundamental to include bioclimatic and environmental control strategies in the building design process. Such strategies should generate optimal thermal, lighting, and acoustics conditions in those buildings. Additionally, it is important, especially in developing countries such as Colombia, to establish more regulations and standards to incorporate these strategies. Furthermore, most design processes do not include insights on environmental comfort or only add them in the project's last stages. However, there is still no clear and complete regulatory framework in Colombia that looks to improve indoor environmental comfort conditions. According to Parra Correa [2], only 63% of surveyed Colombian professionals, specialists in bioclimatic design, construction, or consulting, have included bioclimatic strategies in their design processes.

Paradoxically, nowadays, there are innumerable analog and digital tools, at every level of complexity, that aim at defining bioclimatic strategies to optimize environmental conditions in buildings [3–6]. But as has been previously mentioned, their use is limited or included in less suitable stages of the design process. There are few comfort indexes developed for tropical climates, especially for Colombia [7]. Additionally, the existing indexes have been developed for specific climates, and/or they do not simultaneously consider the three variables of Temperature, Relative Humidity, and Ventilation. In this way, most of these tools focus on a single aspect of environmental behavior, making it almost impossible to analyze them all and integrate the indicated criteria within projects [8]. These are the reasons why it is essential to develop tools that may provide applicable guidelines for the first stages of the project. These guidelines should only require general information about the project, and at the same time, should be simple enough to be used by most professionals without them needing to be experts. By doing so, it would contribute to removing environmental comfort barriers in the Global South and improving the habitability conditions of buildings in these areas where environmental comfort analysis is not within the scope of the projects.

Given this, the objective of this chapter is to develop a user-friendly tool that allows defining applicable bioclimatic strategies for the first stages of building design in the tropics, to guarantee good habitability and comfort conditions inside buildings. This tool is based on the Grille Climatique developed by the architect Le Corbusier in the 1950s.

2 Environmental Comfort in the Andean Tropics

In the tropical climatic context, the main variations of environmental conditions appear thanks to changes in the height above sea level, instead of experiencing seasonal changes during the year. In this zone of the planet, prevailing climates are between warm–dry and warm–humid, the latter being a climate that has high temperatures and relative humidity throughout most of the year. Specifically, the representative Andean Tropic climatic contexts used here, have an Af—Tropical rainforest climate without a dry season (Medellin), and Aw—Tropical savanna climate with a short dry season (Barranquilla), under the Köppen–Geiger climatic classification.

Several authors define solar control and radiation protection, as well as rain management, as the key factors for Andean tropical architecture. According to Olgyay [9], in the Tropics, the roof is the main barrier to a building's environmental defense. This considering that in places near the Equator, solar radiation has an intense and almost perpendicular impact on the land and buildings, practically making solar and shading design necessary in any construction [10]. In this vein, Saldarriaga [11] defines tropical architecture as "shaded and permeable," which considering its climatic and social surroundings must mitigate the building's thermal gains, in the best way possible. Also, according to Stagno [12], preparing spaces passively, not only improves the energy efficiency of the building but also benefits the people inside who may have a greater capacity to self-regulate their temperature and better adapt to climatic conditions.

Considering that the fundamental factors of environmental comfort in the Andean tropical strip revolve around the thermal environment of buildings, it can be concluded that this is one of the main topics to evaluate the first stages of architectural design. This is especially relevant, bearing in mind that aspects such as orientation and building shape have a profound effect on the internal thermal comfort of spaces.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) defines thermal comfort in its standards as "the condition of mind that expresses satisfaction with the thermal environments" [13]. Although the evaluation of thermal comfort is subjective and personal, over the years several simple mathematical methods have been developed, and they manage to define the environmental conditions a space must have for most of its occupants to consider it comfortable, with Olgyay's Bioclimatic chart [14, 15], Givoni's Bioclimatic chart or Psychrometric chart, Comfort triangles [16], and the Climatic Grille of Le Corbusier [17] standing out.

3 Methodology

The methodology of this research project consisted of two general stages: (i) Weather identification where climatic conditions were identified in two representative cities of the Andean tropical climatic context: Medellin (Lat. 6° 15′ N; Long. 75° 34′ W) and Barranquilla (Lat. 10° 58′ N; Long. 74° 48′W), to analyze the main atmospheric conditions that affect the environmental comfort of people inside buildings in the tropics; and, (ii) Development of a tool which included comfort zone identification, the definition of climatic correction strategies to outline appropriate indoor comfort conditions as per the climatic context of the location, and finally, the definition of architectural and constructive strategies to achieve these climatic corrections.

3.1 Documentary Review

Apart from research on the specific tool of Le Corbusier's Grille Climatique, a review of issues related to thermal comfort, different analogous tools to calculate the comfort zone or its definition, as well as the specific environmental needs of the architecture found in the tropical zone was carried out.

3.2 Identification of Le Corbusier's Climatic Grid

> It is necessary to regulate and usefully rectify the overflowing of excessive climates, and to do so make architectonic devices with conditions able to guarantee well-being and comfort [18]

A complete investigation was made on the Grille Climatique of Le Corbusier. This is a graphical methodological tool, that summarized the rules to create an architecture that is universal and adaptable to a place considering its environmental conditions. Mainly the matrix origin, creation year, and context were analyzed, (See Fig. 1). Thus, it was evident that a large swathe of Le Corbusier's professional work focused on standardizing the project process, more than the product itself, which was proven with the invention of different tools that helped him to apply bioclimatic, environmental, or technical criteria when designing projects [17].

Le Corbusier's Grille Climatique includes three vertical sections, each one divided into 12 columns corresponding to the months of the year. The first vertical section, Part A, (données climatiques) contains the climate information of the place being

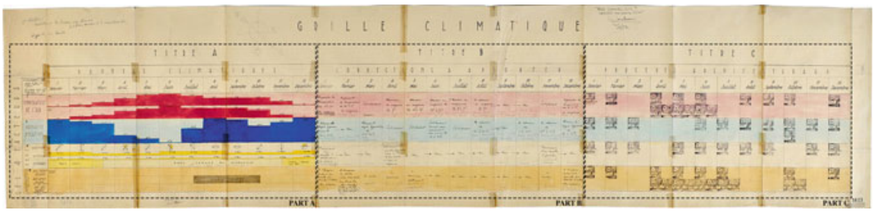


Fig. 1 Grille Climatique of Le Corbusier. Adapted from [15]

intervened. Horizontally, the matrix is divided into four rows, corresponding to the variables to consider air temperature, relative humidity, wind, and radiation, and each row into one, two, or three sub-rows based on the data displayed on each variable. In addition, the table has an extra space indicating the geographic information of the place corresponding to the table and the project involved.

Part B (corrections á to apporter) consists of the necessary modifications or corrections to apply to climatic variables to reach the optimal comfort conditions of a person inside the space. The information displayed in this section is the number of degrees or humidity percentages that would have to be increased or decreased to achieve a comfort zone. It also recommends air speed or periods at which ventilation must be completely blocked, and periods, when radiation must be avoided or attracted, are identified. For months when corrections are not required, the "satisfactory" legend appears. It is important to point out that Le Corbusier, to define these corrections, defined the following ideal or recommended internal climatic conditions to guarantee a comfortable space (See Table 1).

The third section, or Part C (procédés architecturaux), consists of the architectural processes that allow obtaining these optimal conditions within the specific climatic context of each zone. Different stamps indicate the code, the name of the solution applied, and the location of the section where all the graphic solutions are annexed.

It is worth mentioning that, because the information is shown by month and not by season, this tool can be used in seasonal climatic contexts, as well as in the tropical strip.

3.3 Adaptation of Le Corbusier's Climatic Grid to Develop the Tropical Climatic Matrix (MCT, in Spanish)

After thoroughly analyzing the information in the previous stage, two pilot matrices were run with information from the cities of Medellin and Barranquilla, to simplify the verification process and analyze the coherence of the results obtained. This information proved that it is possible to use the tool for any other city or territory if the necessary climatic information is available.

The information collected was reviewed and data entry began in the Tropical Climatic Matrix (MCT), of climatic data, climatic corrections, and project strategies in 4 horizontal strips divided into Sections A, B1, B2, and C (See Fig. 2).

3.3.1 Section A

In the first section, the information displayed in the Tropical Climatic Matrix (MCT) is just as in the original: maximum and minimum monthly air temperatures (°C), average monthly relative humidity (%), and graphical information of both variables. Wind directions, frequencies (% of the time), and speed (m/s) also appear, as well

Table 1 Comfort conditions to calculate "climatic corrections" in Le Corbusier's Grille Climatique, by month. Calculated from Le Corbusier's Grille Climatique

	J	F	M	A	M	J	J	A	S	O	N	D
T_{max}	21°C	21°C	21°C	21°C	25°C	25°C	25°C	21°C	21°C	22°C	19°C	21°C
T_{min}	15°C	16°C	12°C	19°C	16°C	15°C	16°C	22°C	22°C	19°C	12°C	13°C
RH_{max}	55%	52%	54%	53%	50%	60%	62%	56%	53%	60%	60%	55%
RH_{min}	50%	47%	49%	53%	50%	55%	62%	51%	48%	55%	55%	50%
Vent.	Avoid sensitive wind			Sensitive wind between 1.0 and 1.5 m/s							Avoid all wind	
Solar Radiation	Harvest all	Harvest some, avoid on hot hours	Avoid	Prohibit all	Prohibit all	Prohibit all	Prohibit all	Prohibit all *Cloudy sky	Prohibit all *Cloudy sky	Prohibit all	Avoid	Harvest all

T_{max}: Maximum Temperature
T_{min}: Minimum Temperature
RH_{max}: Maximum Relative Humidity
RH_{min}: Minimum Relative Humidity
Vent: Ventilation
Solar Rad: Solar radiation

SECTION A													
MEDELLÍN		J	F	M	A	M	J	J	A	S	O	N	D
Temperature	Maximum												
	Minimum												
Relative Humidity													
Wind	Direction												
	Frequency												
	Speed at 10m												
	Corrected speed												
Radiation													

SECTION B1												
	J	F	M	A	M	J	J	A	S	O	N	D
Comfort Index with ventilation at 10m height												
Comfort Index with corrected ventilation												
Comfort Index without considering ventilation												
Radiation [Sun chart]												

SECTION B2												
	J	F	M	A	M	J	J	A	S	O	N	D
Corrections												

SECTION C												
	J	F	M	A	M	J	J	A	S	O	N	D
Strategies												

Fig. 2 Sections A, B1, B2, and C of the Tropical Climatic Matrix (MCT)

as an additional row, indicating the corrected wind speed (m/s), considering the roughness level of areas in urban surroundings, following the Hellmann Exponent Law (a Hellmann exponent of 0.4, corresponding to densely populated areas). All the ventilation information is also graphically shown in the schematic wind rose diagrams. Finally, the bottom row contains the global horizontal irradiance available every month (Wh/m^2), with its respective graphical reference indicating maximum and minimum azimuth and altitude angles.

Climatic data were extracted from the climatic file (.epw) of both cities, from Climate.OneBuilding.Org, and analyzed in Climate Consultant software version 6.0.

As mentioned above, one of the modifications is the way to display information. This is done with more images demonstrating numerical data, icons, and floor plans, to allow easier and more practical reading of the compiled information.

3.3.2 Section B

This section is divided into two parts, B1 and B2. The first part contains one of the main modifications made to Section B, the one that generates the greatest contribution and innovation of the tool: the combination of climatic factors to define the Comfort Index of spaces. This is a significant improvement over the original version because it considers the environmental factors together (as they appear) and shows how their combination impacts the comfort sensation of human beings, instead of defining corrections to each factor (e.g., temperature and humidity) without considering the effect of some factors on the others.

To do so, equations to calculate climatic comfort are used (equations 2, 3, 4, and 5), developed by González [19], which are specifically designed considering the climatic conditions of Colombia (defining a different equation for each city according to its height above sea level). This method uses the main climatic parameters: air temperature, relative humidity, and wind speed, given that relative humidity and temperature data are included without considering solar radiation. After applying the defined equation, the result is a value representing the Comfort Index (CI) of the people. This index is a numerical value between zero and 15, representing different comfort states such as 0–3—Very hot; 3.1–5—Hot; 5.1–7—Warm; 7.1–11—Comfortable; 11.1–13— Somewhat cold; 13.1–15—Cold; and >15: Very cold [19]. Although numerous comfort indexes have been developed, they are designed for only one type of building (e.g., office building, hospital, school, etc.), and/or work for a specific climate, which would limit the usage of the MTC tool, because it would not allow its use for any type of space in any climatic context. The index proposed by González [19] is designed for any of the Andean tropic climates and considers the height above sea level as a key factor for climatic conditions in this part of the planet. It also makes the calculation possible with or without wind (depending on data availability).

As mentioned before, this investigation uses two equation types considering the availability of wind speed information. This is important because there are cases where it is not easy to calculate or obtain wind speed data. CI calculations for both situations are as follows: with wind (corrected) and without wind.

For altitudes between 0 and 1,000 m above sea level, considering wind speed (1)

$$CI = (36.5 - T_s)(0.05 + 0.04\sqrt{s} + h/250) \tag{1}$$

For altitudes between 0 and 1,000 m above sea level, without considering wind speed (2)

$$CI = (36.5 - T_s)(0.05 + h/250) \tag{2}$$

For altitudes between 1,000 and 2,000 m above sea level, considering wind speed (3)

$$CI = (34.5 - T_s)(0.05 + 0.06\sqrt{s} + h/180) \tag{3}$$

For altitudes between 1,000 and 2,000 m above sea level, without considering wind speed (4)

$$CI = (36.5 - T_s)(0.05 + h/180) \tag{4}$$

Where:
CI = comfort index
T_s = air temperature (°C)
h = relative humidity (%)
s = wind speed (m/s)

Additionally, Section B2 contains similar modifications to those considered by Le Corbusier regarding temperature, relative humidity, radiation, and ventilation, to achieve comfortable indoor conditions. However, they are comprehensively shown as general recommendations (e.g., solar protection and natural ventilation). These recommendations are taken from the psychrometric chart following the criteria from ASHRAE 55 Standard and Current Handbook of Fundamentals Model [13].

3.3.3 Section C

According to the climatic corrections defined in Sections B1 and B2, some general architectural strategies were laid down based on the graphic representation of Le Corbusier for the floor plan and elevation according to each category. The main difference with the reference tool is that the strategies appear individually for each "correction" so that the user can analyze its suitability, relevance, and hierarchy level, as well as how to apply the tool in each project depending on its requirements. The strategies are classified in the Tropical Climatic Matrix in three categories, as indicated in the following table (Table 2):

These solutions are the climatic corrections to be applied to the building and location. This will allow providing basic applicable design guidelines in the first stages of the design process, that should not compromise the building's style or structure, but have flexible enough guidelines so that the architect applies as they deem fit. Thus, the user will be able to analyze the climatic conditions in Section A, to understand which environmental requirements or climatic corrections must be implemented to obtain a good Comfort Index (Sections B1 and B2) and, finally, obtain bioclimatic design guidelines aiming at improving the indoor environmental conditions, these guidelines applying to any project without prior project information (Section C).

To define the recommended strategies, in addition to the specific corrections laid out in Section B2, the combination of environmental variables in every month was considered, for example: If in January the climatic corrections are solar protection, cooling by evaporation, and natural ventilation, it is recommended to protect the eastern and western facades (East and West) and especially the southern facade that receives solar radiation all the day at this time of the year. It is also recommended to open the northern and eastern facades to allow the entrance of predominant ventilation and humidity.

4 Results

> The desirable procedure will be to work with and not against natural forces and to make use of their potentialities to create better living conditions...The procedure for building a climatically balanced house is divided into four steps, of which the last is the architec-

Table 2 Classification of architectural strategies

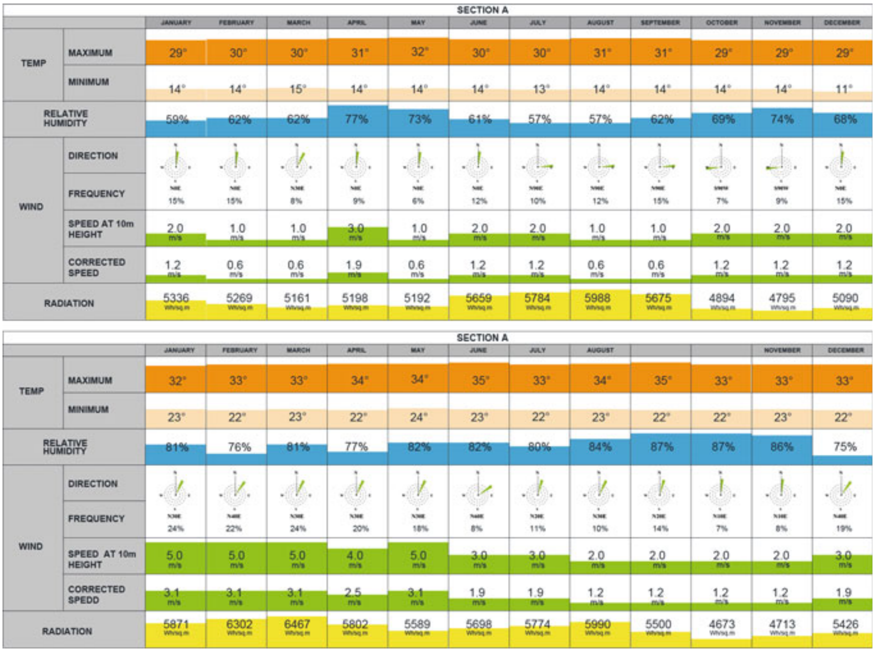
Strategy	Description	Code
Humidity: H Stamps	Humidification by bodies of water	H1–H2–H3
	Humidification by vegetation	H4–H5–H6
	Green walls	H7–H8–H9
Ventilation: V Stamps	Cross-ventilation through Windows	V1–V2–V3
	Ventilation through openwork surfaces	V4–V5–V6–V8
	Ventilation with wind-conducting elements at the edge of the facade	V4–V5–V6
	Ventilation through raised roofs	V7
	High ceilings	V9
	Chimney effect	V10
Solar protection: R Stamps	Solar protection with vertical elements on eastern and western facades and predominantly on the southern facade with a horizontal element	R1
	Solar protection with vertical elements on eastern and western facades and predominantly on the northern facade with a horizontal element	R2
	Solar shading with horizontal elements on eastern and western facades	R3
	Solar protection with vertical elements on eastern and western facades	R4
	Solar shading with vegetation on eastern and western facades	R5
	Recessed windows	R6

> tural expression. The expression must be preceded by the study of climatic, biological, and technological variables... [14]

The following are the four sections of the Tropical Climatic Matrix tool, with data and results corresponding to both types of climates analyzed (See Figs. 3–6).

It is important to consider that the available climatic information depends on current databases. Analyzing the climatic data available for places within the scope, it was identified that some of the information is not updated or is inaccurate compared with the climate perception in these cities. Thus, it is necessary to gather updated climatic information to improve the accuracy of the results obtained using the tool. Despite the previous statement, it was verified that this dynamic tool is completely customizable to the environmental conditions of any territory with sufficient climatic information, especially in the Andean tropics.

As mentioned above, on reviewing the literature, it was possible to verify that there are few comfort indexes for tropical climates, especially for Colombia [7]. Addition-



SECTION A		JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
TEMP	MAXIMUM	29°	30°	30°	31°	32°	30°	30°	31°	31°	29°	29°	29°
	MINIMUM	14°	14°	15°	14°	14°	14°	13°	14°	14°	14°	14°	11°
RELATIVE HUMIDITY		59%	62%	62%	77%	73%	61%	57%	57%	62%	69%	74%	68%
WIND	DIRECTION												
	FREQUENCY	15%	15%	8%	9%	6%	12%	10%	12%	15%	7%	9%	15%
	SPEED AT 10m HEIGHT	2.0 m/s	1.0 m/s	1.0 m/s	3.0 m/s	1.0 m/s	2.0 m/s	2.0 m/s	1.0 m/s	1.0 m/s	2.0 m/s	2.0 m/s	2.0 m/s
	CORRECTED SPEED	1.2 m/s	0.6 m/s	0.6 m/s	1.9 m/s	0.6 m/s	1.2 m/s	1.2 m/s	0.6 m/s	0.6 m/s	1.2 m/s	1.2 m/s	1.2 m/s
RADIATION		5336 Wh/sq.m	5269 Wh/sq.m	5161 Wh/sq.m	5198 Wh/sq.m	5192 Wh/sq.m	5659 Wh/sq.m	5784 Wh/sq.m	5988 Wh/sq.m	5675 Wh/sq.m	4894 Wh/sq.m	4795 Wh/sq.m	5090 Wh/sq.m

SECTION A		JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST			NOVEMBER	DECEMBER
TEMP	MAXIMUM	32°	33°	33°	34°	34°	35°	33°	34°	35°	33°	33°	33°
	MINIMUM	23°	22°	23°	22°	24°	23°	22°	23°	22°	22°	23°	22°
RELATIVE HUMIDITY		81%	76%	81%	77%	82%	82%	80%	84%	87%	87%	86%	75%
WIND	DIRECTION												
	FREQUENCY	24%	22%	24%	20%	18%	8%	11%	10%	14%	7%	8%	19%
	SPEED AT 10m HEIGHT	5.0 m/s	5.0 m/s	5.0 m/s	4.0 m/s	5.0 m/s	3.0 m/s	3.0 m/s	2.0 m/s	2.0 m/s	2.0 m/s	2.0 m/s	3.0 m/s
	CORRECTED SPEDD	3.1 m/s	3.1 m/s	3.1 m/s	2.5 m/s	3.1 m/s	1.9 m/s	1.9 m/s	1.2 m/s	1.2 m/s	1.2 m/s	1.2 m/s	1.9 m/s
RADIATION		5871 Wh/sq.m	6302 Wh/sq.m	6467 Wh/sq.m	5802 Wh/sq.m	5589 Wh/sq.m	5698 Wh/sq.m	5774 Wh/sq.m	5990 Wh/sq.m	5500 Wh/sq.m	4673 Wh/sq.m	4713 Wh/sq.m	5426 Wh/sq.m

Fig. 3 Section A of the Tropical Climatic Matrix: Climatic characterization. On the top Medellín, on the bottom Barranquilla

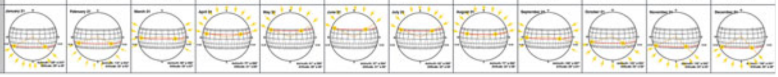
ally, the indexes there are, have been developed for specific climates, and/or they do not simultaneously consider the three variables of temperature, relative humidity, and ventilation. It is important to mention that Section C of the MCT displays the CI calculation considering these three variables and, it does not consider the effect of solar radiation for its calculation. Therefore, it is possible to expect overheating in spaces that are more exposed to this solar radiation. Detailed information regarding sunlight is also displayed.

The stamps from Section C of the MCT, correspond to architectural layouts suggested in each specific case considering the featured climatic conditions and the necessary corrections. Each strategy suggested considers the most efficient façade to apply it on. If several stamps on the same topic appear in the same month, it means that there are different options to choose from. For example, in Medellín, several humidification strategies are recommended every month, due to the relative humidity levels and wind speed and direction. Therefore, the user can choose from humidification by bodies of water, humidification by vegetation, or installing a green wall, depending on the project.

Figures 6–8, show all the layouts of those strategies mentioned in the MCT of both cities.

SECTION B1 (Medellín) — COMFORT INDEX CALCULATION

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
COMFORT INDEX WITH VENTILATION AT 10m HEIGHT	6.25	5.68	5.68	7.85	6.96	6.40	6.10	5.76	6.14	7.00	7.37	6.92
	WARM	WARM	WARM	COMFORTABLE	WARM	WARM	WARM	WARM	WARM	WARM	COMFORTABLE	WARM
COMFORT INDEX WITH CORRECTED VENTILATION	6.00	5.52	5.52	7.55	6.79	6.15	5.85	5.59	5.96	6.75	7.13	6.68
	WARM	WARM	WARM	COMFORTABLE	WARM	WARM	WARM	WARM	WARM	WARM	COMFORTABLE	WARM
COMFORT INDEX WITHOUT VENTILATION	5.86	5.72	5.72	7.41	7.06	6.03	5.68	5.68	6.11	6.72	7.15	6.63
	WARM	WARM	WARM	COMFORTABLE	COMFORTABLE	WARM	WARM	WARM	WARM	WARM	COMFORTABLE	WARM
RADIATION (SUN DIAGRAM)												



SECTION B1 (Barranquilla) — COMFORT INDEX CALCULATION

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
COMFORT INDEX WITH VENTILATION AT 10m HEIGHT	4.40	4.21	4.40	3.72	3.97	3.80	3.73	3.76	3.86	4.32	4.28	3.98
	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM
COMFORT INDEX WITH CORRECTED VENTILATION	4.22	4.03	4.22	3.58	3.81	3.68	3.61	3.66	3.76	4.20	4.17	3.84
	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM
COMFORT INDEX WITHOUT VENTILATION	3.55	3.36	3.55	3.04	3.21	3.21	3.15	3.28	3.38	3.78	3.74	3.33
	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM	WARM
RADIATION (SUN DIAGRAM)												

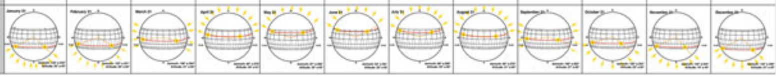


Fig. 4 Section B1 of the Tropical Climatic Matrix: Calculation of comfort indexes and sunlight angles. On the top Medellín, on the bottom Barranquilla

SECTION B2 (Medellín)

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
CORRECTIONS	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation	Solar protection Evaporative cooling Natural ventilation

SECTION B2 (Barranquilla)

	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER	DECEMBER
CORRECTIONS	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling Air conditioning Dehumidifier	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling Air conditioning Dehumidifier	Solar protection Natural ventilation cooling Air conditioning Dehumidifier	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling	Solar protection Natural ventilation cooling

Fig. 5 Section B2 of the Tropical Climatic Matrix: Definition of recommended general climatic strategies. On the top Medellín, on the bottom Barranquilla

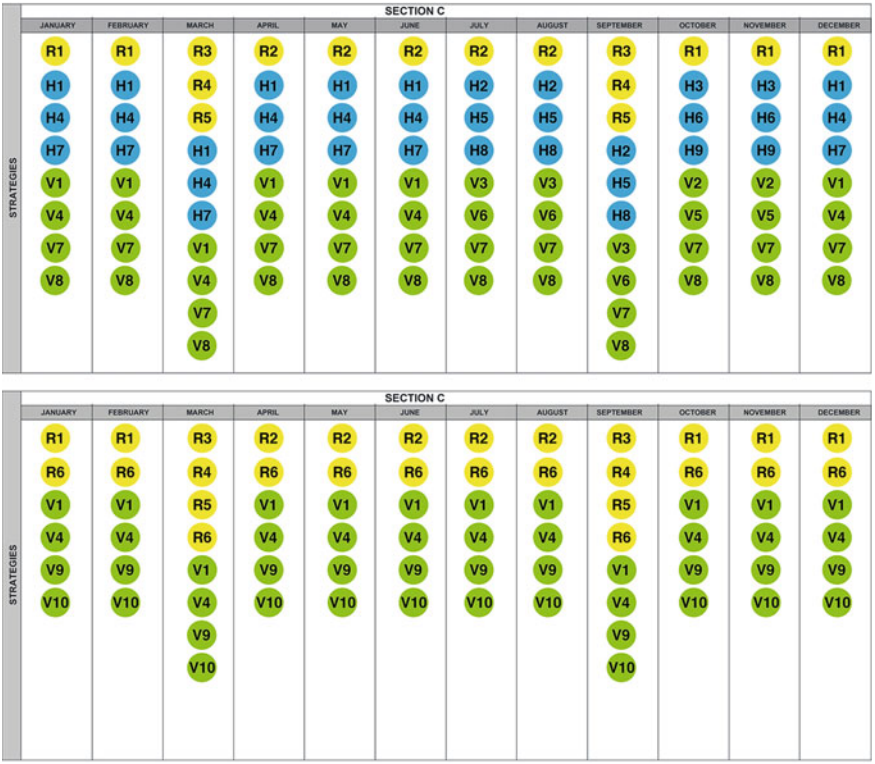


Fig. 6 Section C of the Tropical Climatic Matrix: Definition of specific architectural strategies (each stamp matches the specific architectural strategy diagram. V: Ventilation strategies, H: Humidification strategies, and R: Solar radiation strategies). On the top Medellín, on the bottom Barranquilla

Subsequently, there is an additional list of precautions or recommendations to obtain better results or not affect other environmental factors when applying the strategies.

How to prioritize:

- To promote comfort in months with a Comfort Index other than Comfortable, it is recommended to comply with the strategies of the months that registered the CI results furthest from Comfort.
- If the strategy type is prioritized, where ventilation is preferred, it is recommended to apply the strategies defined for those months with greater average wind speeds and those that represent the recommendations for most of the year.
- If the priority is relative humidity, it is recommended to prefer those strategies defined for months with a lower average relative humidity.
- If it is necessary to choose a single radiation strategy, it is recommended to choose the one corresponding to months with a higher average solar radiation.

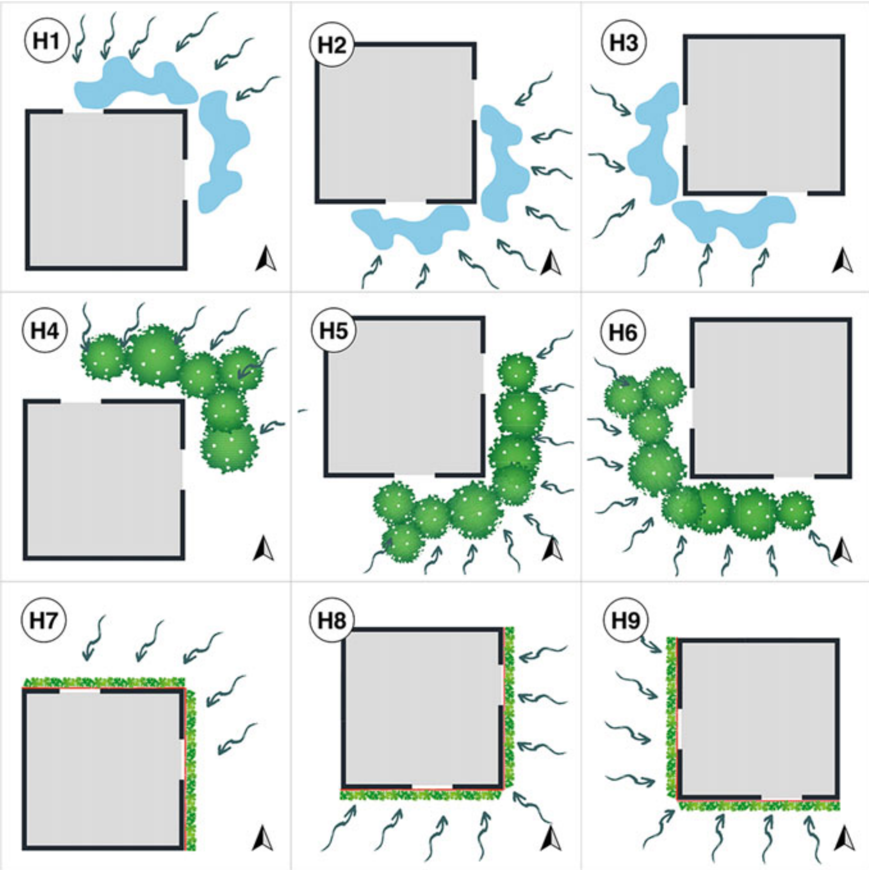


Fig. 7 Relative humidity strategies. H1, H2, and H3: Humidification by bodies of water on the northeastern, southeastern, and southwestern facades. H4, H5, and H6: Humidification by vegetation on the northeastern, southeastern, and southwestern facades. H7, H8, and H9: Green walls on the northeastern, southeastern, and southwestern facades

Please consider:

- When applying solar protection on facades, the amount of indoor daylight will also be reduced. Verification of the amount of sky blocked by these solar protections is recommended, as well as their colors and materials to favor light reflection that improves indoor daylighting availability.
- It is important to consider the risk of rain entering due to ventilation solutions such as openwork walls, high ceilings, and other façade perforations. It is recommended to plan these strategies in spaces that can get wet, using additional protections like eaves or complementing these openings with systems that can be closed.
- To increase indoor thermal comfort in warm climates, it is recommended to complement the tool's strategies, with a selection of low transmittance materials

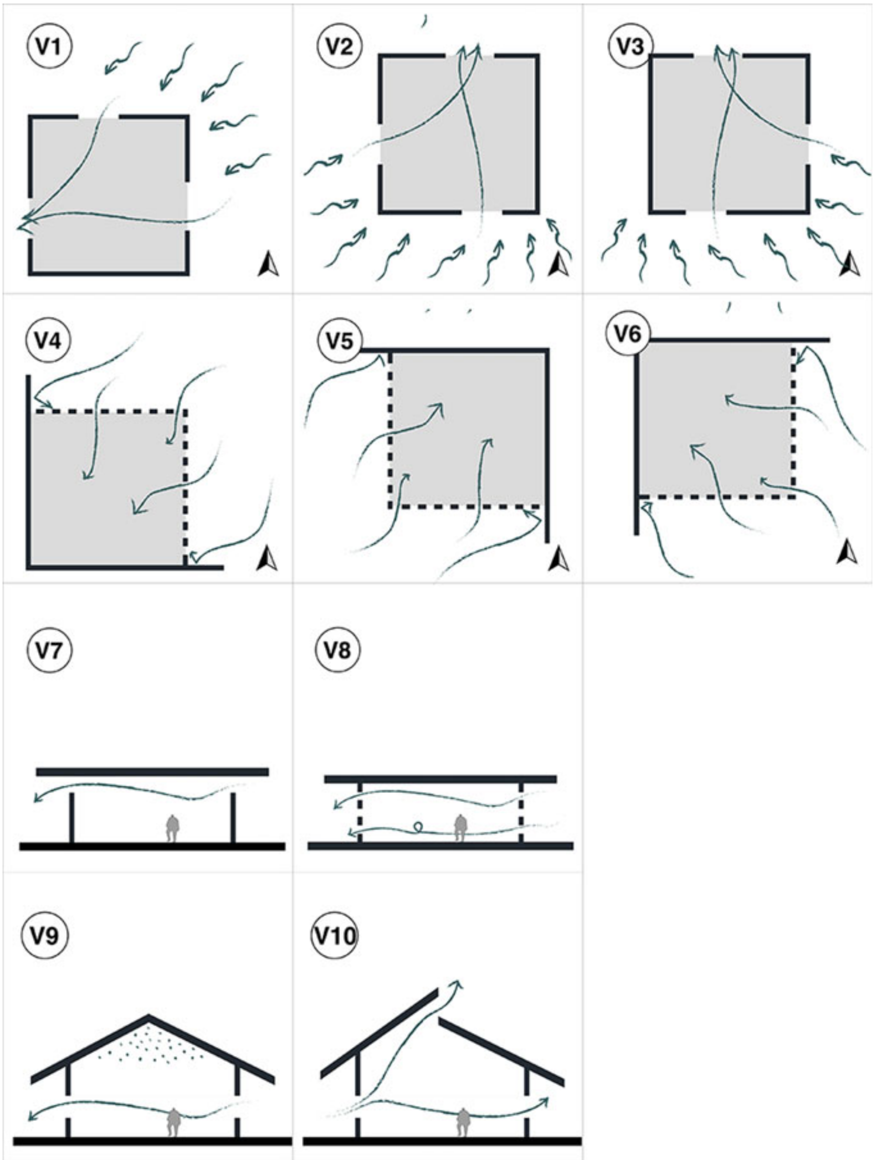


Fig. 8 Ventilation strategies. V1, V2, and V3: Cross ventilation through windows on the northeastern, southeastern, and southwestern facades. V4, V5, V6, and V8: Ventilation through openwork surfaces on the northeastern, southeastern, and southwestern facades. V4, V5, and V6: Ventilation with wind-conducting elements at the edge of the facade. V7: Ventilation through raised roofs. V9: High ceilings. V10: Chimney effect

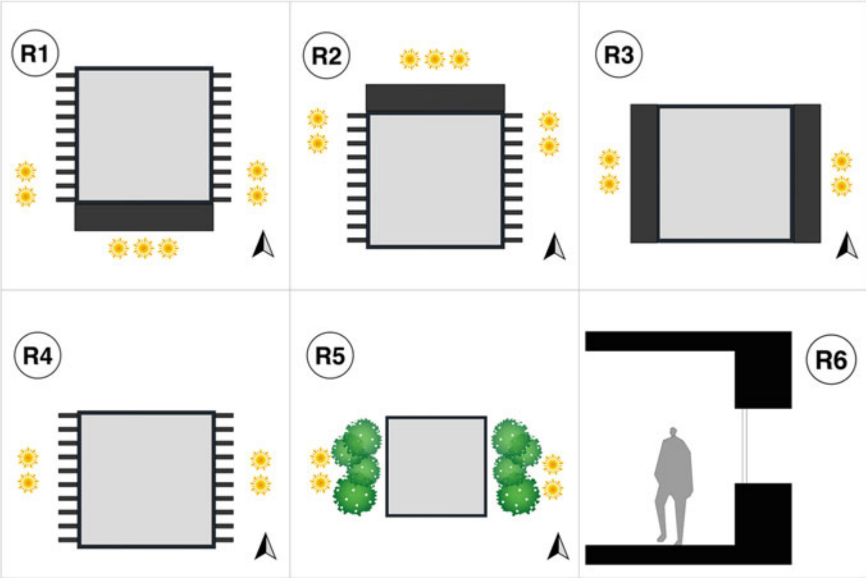


Fig. 9 Solar radiation strategies. R1: Solar protection with vertical elements on eastern and western facades and predominantly on the southern facade with a horizontal element. R2: Solar protection with vertical elements on eastern and western facades and predominantly on the northern facade with a horizontal element. R3: Solar shading with horizontal elements on eastern and western facades. R4: Solar protection with vertical elements on eastern and western facades. R5: Solar shading with vegetation on eastern and western facades. R6: Recessed windows

(U value) especially on the roof, that help to isolate heat transference due to the great amount of solar radiation these surfaces are exposed to.

- It is important to consider the shadows cast by neighboring buildings. It is recommended to analyze the shading of surrounding constructions to verify whether there are periods of the year or facades that do not need their own shading. If this is the case, R strategies must be discarded for those facades where shading is no longer necessary.

5 Discussion and Conclusions

One of the main contributions of this investigation is the fact that the tool has a very good relationship between its simplicity and potential. In other words, it is a tool that, despite being simple to use and not requiring in-depth technical knowledge on bioclimatic aspects, can provide relevant information for the environmental improvement of spaces being designed. As was already mentioned, the high level of usability is remarkable: this tool can be used by non-expert bioclimatic users. It can even be stated that it mainly targets them, which fulfills the objective of closing the gap still present in the area, because only a few people technically manage the bioclimatic concepts and tools, or they are not properly applied to the projects. Moreover, it is a tool that aims at improving habitability conditions for buildings in countries where environmental control and comfort are not yet high-priority or inherent subjects in architectural design. This is relevant because it helps remove barriers to environmental comfort in the Global South and at the same time, provides design and construction professionals with elements so that they include environmental optimization strategies in buildings, thus providing better habitability conditions, better performance of people in their indoor activities, improvement in health conditions, and reduction of building's power dependency, among others.

It is important to mention that the MCT can also be applied (with its necessary modifications) to other types of spaces that require environmental controls, such as farms, greenhouses, production plants, etc., which diversify and extend the influence of the MCT to an interdisciplinary field. In addition, this tool is conceived to be applied in the first stages of a project, a feature that provides another great strength: It requires the definition of little information on the project as an input, to generate the architectural guidelines. In this regard, there is a significant difference between this and other tools, given the fact that most of them require some building characteristics to be defined beforehand to generate the recommended strategies.

The Tropical Climatic Matrix displays more graphical information, and this is an innovation for a reference tool. Specifically, for radiation information, there are schematic solar diagrams that precisely indicate the maximum and minimum azimuth and altitude angles, which allows choosing one solar protection strategy or another. The user can also calculate, with a good level of detail, the size and rhythm of these elements, considering the angles of solar rays impacting the facades. Another distinguishable contribution made by the tool compared to other tools of its class is that strategies and recommendations appear individually by façade, according to the needs and influence of each climatic variable on them. This allows the MCT user, to decide which strategies to use considering their formal needs, esthetic taste, topography, and budgetary or technical aspects, among others.

Similarly, the MCT is sufficiently flexible so it can be applied to any building regardless of its use or typology, considering that the designer will apply the strategies in the best possible way depending on the project's needs.

Especially in cities with noticeable topographies such as Medellín (so common in the Andean tropic zone), it is important to consider the major climatic changes generated by differences in heights above sea level, which creates climatic information that does not represent the entire territory. Also, the need to gather updated climatic information about the Andean tropic cities is evident, to improve the accuracy of the results obtained using the tool.

References

1. Omrani S, Garcia-Hansen V, Capra B, Drogemuller R (2017) Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. Build Environ 116:182–194. https://doi.org/10.1016/j.buildenv.2017.02.012
2. Parra Correa E (2020) Propuesta de una metodología para la optimización multi-objetivo de estrategias bioclimáticas en edificaciones a través de modelos paramétricos. Master's thesis, Universidad de San Buenaventura, Medellín, Colombia
3. Wagdy A, Fathy F (2015) A parametric approach for achieving optimum daylighting performance through solar screens in desert climates. J Build Eng 3:155–170. https://doi.org/10.1016/j.jobe.2015.07.007
4. Negendahl K, Nielsen TR (2015) Building energy optimization in the early design stages: A simplified method. Energy Build 105:88–99. https://doi.org/10.1016/j.enbuild.2015.06.087
5. El Daly H (2014) Automated fenestration allocation as complying with leed rating system. Alexandria Eng J 53:883–890. https://doi.org/10.1016/j.aej.2014.09.011
6. Toutou A, Fikry M, Mohamed W (2018) The parametric based optimization framework daylighting and energy performance in residential buildings in hot arid zone. Alexandria Eng J 57:3595–3608. https://doi.org/10.1016/j.aej.2018.04.006
7. García A, Olivieri F, Larrumbide E, Ávila P (2019) Thermal comfort assessment in naturally ventilated offices located in a cold tropical climate, Bogotá. Build Environ 158:237–247. https://doi.org/10.1016/j.buildenv.2019.05.013
8. Mackey C, Roudsari M (2018) The tool(s) versus the toolkit. In: Humanizing digital reality, vol 9. Springer, Singapore, pp 93–101. https://doi.org/10.1007/978-981-10-6611-5-9
9. Olgyay V (1968) Clima y arquitectura en Colombia. Facultad de Arquitectura. Universidad del Valle, Cali, Colombia
10. Salazar J (2003) Protección solar en edificaciones. Fundamentos teóricos. In: VII Encuentro nacional de estudiantes de arquitectura, Universidad Nacional de Colombia, sede Medellín, Grupo EMAT, Medellín, Colombia
11. Saldarriaga D (2019) La influencia del balcón abierto en la reducción de la carga térmica y en el comportamiento de la ventilación natural para edificios residenciales en altura. Caso de estudio Medellín. Master's thesis, Universidad de San Buenaventura, Colombia
12. Stagno B (2004) Climatizando con el clima. In: A TI (ed) III Encuentro de arquitectura, urbanismo y paisajismo tropical. Instituto de Arquitectura Tropical, San José, Costa Rica, p 22
13. ASHRAE (2017) ANSI/ASHRAE standard 55-2017 thermal environmental conditions for human occupancy
14. Olgyay V (1963) Interpretación Climática
15. Arauza Franco M (2009) Adecuación de los triángulos de confort, para la condiciones climatológicas dominantes en la República Mexicana. Master's thesis, Universidad Autónoma Metropolitana, Mexico
16. Evans JM (2007) The comfort triangles: A new tool for bioclimatic design. PhD thesis, Technological University of Delft, Netherlands
17. Martín Fuentes D (2016) Le Corbusier y la Grille climatique: Herramientas para la inclusión de variables termodinámicas y sensoriales en el proyecto arquitectónico. PhD thesis, Universitat Politècnica de València, España
18. Corbusier Le (1985) Oeuvre complète 1952–1957. Les Editions d'Architecture, Zurich, Switzerland
19. González OC (1998) Metodología para el calculo del confort climático en Colombia. IDEAM 47

Indoor Air Quality

Air Quality in Latin American Buildings

Constanza Molina, Benjamin Jones, and Giobertti Morantes

Abstract The air people breathe has a significant impact on their health, comfort, productivity, and well-being. Indoor air is important because it is where most exposure to airborne contaminants occurs. However, it is not always possible to know the composition of contaminants in indoor air, its variability, and changes over time, so suitable metrics are needed to regulate indoor air, and its quality improved efficiently, sustainably, and at the lowest possible cost, along with its relationships with health risks or comfort. To improve indoor air quality, source control, targeted ventilation, and space ventilation are the most effective intervention strategies, in that order. However, increasing the ventilation rate is not always a solution, especially in highly polluted cities. In many Latin American countries, there is a lack of understanding about the problems caused by poor air quality. This is aggravated by the prevalence of fuel poverty. Poor IAQ has an unavoidable impact on government spending on health care, social care, and social security. This chapter describes metrics for determining the most important airborne contaminant sources in Latin American buildings, the variables that affect IAQ, and how contaminants may be controlled and regulated to minimize their impact on a population's health and well-being.

Keywords Indoor air quality · Exposure · Ventilation · Politics

C. Molina (✉)
School of Civil Construction, Pontificia Universidad Católica de Chile, Santiago, Chile
e-mail: cdmolina@uc.cl

B. Jones · G. Morantes
Department of Architecture and Built Environment, University of Nottingham, Nottingham, UK
e-mail: Benjamin.Jones@nottingham.ac.uk

G. Morantes
e-mail: Giobertti.Morantesquintana@nottingham.ac.uk

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1 Air Quality in Buildings

The air people breathe is composed of a complex mix of chemicals of varying quantities and toxicity. It is also linked to one of the world's top causes of mortality and morbidity. An airborne contaminant is something present in the air that would not ordinarily be there. If it is toxic, it is called a pollutant. Some contaminants are common elements that are generally safe, such as carbon dioxide. Others negatively affect human health, even at low levels. The quality of indoor air has been defined by its acceptability to occupants. ASHRAE Standard 62.2 [1] defines acceptable indoor air quality (IAQ) as "air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be contaminants at concentrations that are known to pose a health risk". Therefore, both the indoor concentration and toxicity of individual contaminants must be known before IAQ can be determined. However, the composition of contaminants varies between buildings and over time, as a function of the lives and habits of occupants, and of building technologies and appliances [2].

Some contaminants are frequently monitored in the ambient, or outdoor, air to indicate their quality: particulate matter, also known as particles,[1] ground-level ozone (O_3), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). They are called criteria pollutants because they adversely affect health and well-being. Most research has focused on the outside air, yet people spend most of their time indoors, usually in their homes [3, 4]. This makes buildings the primary place where exposures to airborne pollutants occur. The Commission of Social Determinants of Health is the organization established by the WHO to study health equity worldwide. It finds that home and work conditions are two of many social determinants of health [5]. IAQ is generally unregulated beyond the chemical composition of some domestic goods and toxins in working environments.

The United Nations' Sustainable Development Goals (SDGs) are a set of 17 international priorities to provide "peace and prosperity for people and the planet, now and into the future" [6]. Goal 3 strives to ensure a healthy life for people of all ages by including a health-related indicator of air pollution mortality. The SDG indicators were updated in 2018 to provide an assessment of progress and the likelihood that each of the 195 participating countries will meet the goals by 2030. For example, 53% of the air pollution mortality goal has been achieved in Barbados, Cuba, Grenada, Saint Lucia, Dominica, Paraguay, El Salvador, Jamaica, Saint Vincent and the Grenadines, Mexico, Belize, Suriname, the Dominican Republic, and Honduras, which represent the mode. And 84% of the smoking prevalence goal has been achieved in Barbados, Antigua and Barbuda, The Bahamas, Brazil, Dominica, Belize, Dominican Republic, and Guatemala. 57% of the 195 countries have achieved 90% of the household air pollution goal [6]. Despite the Latin American and Caribbean countries showing unremarkable low air quality levels, more than

[1] Particles are the type of pollutant rather than a single compound and are normally reported according to their mass concentration. For example, the mass fraction of particles with aerodynamic diameters smaller than 2.5 or 10 μm are reported as $PM_{2.5}$ or PM_{10}, respectively.

50% of the countries have less than a 10% probability of reaching that target. Barbados, Venezuela, Puerto Rico, Trinidad and Tobago, the Virgin Islands, and Antigua and Barbuda are the only countries to have more than a 90% probability of reaching the target [6]. Finally, Haiti has made an 18 and 94% improvement in air pollution mortality and smoking prevalence, respectively, but 0% progress in household air pollution. Haiti has a 0% chance of meeting the target for residential air pollution.

The following sections describe the current knowledge on the determinants of indoor air quality, metrics for determining the most important airborne contaminants and sources in Latin American buildings, how contaminants may be controlled and regulated to minimize their impact on a population's health and well-being, and barriers that must be overcome before implementing changes in building stocks.

1.1 Indoor and Outdoor Sources of Pollution

Indoor contaminants are either directly released from sources, when they are known as primary contaminants, or they are formed within the indoor environment after their release when they are known as secondary contaminants. They are also classified by their physical state (gaseous or particulate), their impact on health (criteria or non-criteria pollutants), or their source type[2] (outdoor sources, such as the infiltration of outdoor pollutants or those released from soil; indoor sources, such as combustion stoves or heaters; or particulates resuspended by occupant movements or cleaning activities).

Over the past 70 years, new materials and technologies have been adopted by the construction industry to increase the environmental performance of buildings. These have adversely affected IAQ and occupant health when materials emit contaminants, lifestyles and personal habits change emissions, such as the burning of incense, or when reductions in the airtightness of buildings occur without additional ventilation [7, 8]. Conversely, the prevalence of some contaminants has decreased due to restrictions on the use of some chemicals in building materials and consumer products, and changes in occupant behaviors, for example, formaldehyde is restricted as a preservative in reconstituted wood products and indoor smoking has been reduced.

Gases, particulate matter, and volatile organic compounds (VOCs) are the most prevalent pollutants found in buildings. VOCs are organic chemical compounds that evaporate under normal indoor temperatures and pressures. Construction materials, tap water, household items (such as plastics), and human breath are also common sources of VOCs. Most VOCs are present in low concentrations indoors, frequently below the detection limit of most sensors. Table 1 shows the most common contaminants found indoors and their likely indoor and outdoor sources. Table 2 shows common airborne contaminants and possible health outcomes.

[2] Sources are defined by ASHRAE 62.2 as "an indoor object, person, or activity from which indoor air contaminants are released, or a route of entry of contaminants from outdoors or sub-building soil" [1].

Table 1 Air pollutants, main type, and possible indoor or outdoor sources

		Main type		Related sources	
Pollutant		Indoor	Outdoor	Indoor	Outdoor
Criteria pollutant	Particulate matter ($PM_{2.5}$)	✓	✓	Smoking, cooking, heating, consumer products, building materials, soil (resuspension), infiltration of foreign particles	Soil (erosion, resuspension), sea salt, combustion (biomass, industrial, fuel)
	Sulfur dioxide (SO_2)		✓	Infiltration of foreign particles	Combustion (biomass, industrial, fuel)
	Nitrogen dioxide (NO_2)		✓	Smoking, burning appliances (for cooking/heating), infiltration	Combustion (industrial, fuel)
	Ozone (O_3)		✓	Reaction with precursors (NOx, CO, and VOCs)	
	Carbon monoxide	✓	✓	Combustion (biomass, fuel) for cooking/heating, smoking	Combustion (biomass, industrial, fuel)
VOC[a]	Benzene	✓		Smoking	Petrochemical activities
	Formaldehyde	✓		Building materials (paints, glues, varnishes, lacquers, wooden products), cleaning (detergents, disinfectants, softeners), smoking, heating, cooking, candle/incense burning, and air fresheners	–
	Trichloroethylene	✓		Construction products (varnishes, paint removers)	–
	Tetrachloroethylene	✓			
	Naphthalene	✓		Consumer products with mothballs	–
	Xylenes	✓		Smoking	Petrochemical activities
Other air pollutants	Polycyclic aromatic hydrocarbons[b]	✓		Combustion (biomass, fuel) for cooking/heating, smoking	Combustion (industrial, fuel)
	Radon	✓		Underlying rocks and soils	–
	Biological agents	✓	✓	Bacteria, viruses, fungi, mold, and bacterial spores	Spores, pollen, animal/human dander

[a] Volatile Organic Compounds
[b] Benz[*a*]anthracene, benzo[*a*]pyrene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, chrysene, dibenzo[a, h]anthracene, benzo[*ghi*]perylene, and indeno[$1, 2, 3 - cd$]pyrene

Table 2 Common indoor contaminants and possible health outcomes

Pollutant		Plausible health outcomes											
		Mortality									Morbidity		
		All cause	Cardiovascular (general)	Respiratory (general)	Lung cancer	COPD	ALRI	IHD	Stroke	Cancer	Asthma	Respiratory	Cardiovascular
Criteria pollutant	Particulate matter ($PM_{2.5}$)	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
	Sulfur dioxide (SO_2)	✓	✓	✓	✓						✓	✓	
	Nitrogen dioxide (NO_2)	✓	✓	✓	✓						✓	✓	
	Ozone (O_3)	✓	✓	✓								✓	✓
	Carbon monoxide	✓	✓	✓							✓	✓	✓
VOC[a]	Benzene				✓					✓			
	Formaldehyde									✓	✓	✓	✓
	Trichloroethylene									✓			
	Tetrachloroethylene									✓			
	Naphthalene									✓		✓	
	Xylenes									✓			
Other air pollutants	Polycyclic aromatic hydrocarbons[b]				✓					✓			
	Radon				✓								
	Biological agents										✓	✓	✓

[a] Volatile Organic Compounds
[b] Benz[*a*]anthracene, benzo[*a*]pyrene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, chrysene, dibenzo[*a*, *h*]anthracene, benzo[*ghi*]perylene, and indeno[1, 2, 3 − *cd*]pyrene

Indoor pollutant concentrations and individual exposures are geographically and temporally heterogeneous. This is due to a combination of factors, including the local and surrounding environment, pollution sources, building design, and occupant behavior.

1.2 Removal Mechanisms

A minimum ventilation rate is required to maintain acceptable IAQ by diluting contaminants and providing oxygen for combustion (see Sect. 3.2). However, higher airflow rates are required to dissipate heat gains during the cooling season and to maintain the thermal comfort of occupants. The difference between the two airflow rates is normally the recirculation rate of a mechanically ventilated building that uses fans, ductwork, and an air handling unit to moderate the properties of supplied air. A naturally ventilated building exclusively uses the action of the wind and temperature differences to move air and so cannot moderate the properties of air or recirculate it. The pressure differences across natural ventilation openings are very small and so filters cannot be used. If outdoor air quality is unacceptable, then a naturally ventilated building may be inappropriate unless air intakes can be located away from pollution sources. Natural ventilation openings are normally sized to dissipate heat gains in the cooling season and so they should be more than capable of providing enough air for acceptable IAQ when controlled correctly. Ventilation rates for IAQ are either a requirement integrated into a country's building codes or mandated by a project's standards. They are specified according to the room's occupancy; the presence of pollution sources, such as combustion appliances; or expected highly pollutant events. However, ventilation is not the only mechanism for removing pollutants from breathed air. Others include aerosol deposition onto surfaces, pathogen biological decay, and filtering. These removal mechanisms are influenced by space volume and the behavior of a contaminant (see Sect. 3.2).

Deposition refers to the loss of indoor particulates that attach themselves to surfaces and fall out of suspension. Its rate is usually lower than that of ventilation and depends on a pollutant's properties (mass, diameter), the surface area-to-volume ratio of a room, the room air velocity, and the surface area of any furniture. Deposition rates are especially important when ventilation is restricted. However, their prediction and measurement are highly uncertain [9, 10]. Particulate dynamics also affect deposition rates, for example, particulates may coagulate, condensate, evaporate, or change their mass. This, in turn, affects indoor concentrations [11].

The biological decay rate only affects pathogens and is a function of their half-life, the time for half of all of the pathogens present in a space to become incapable of growth or damage. This process is known as denaturing or inactivation. In devices, such as UV emitters, the biological decay rate is used as the system's rate of biological inactivation.

Finally, a filter removes particulates from the indoor air by trapping them. Filter efficiency is the fraction of particulates trapped and varies with particulate size and

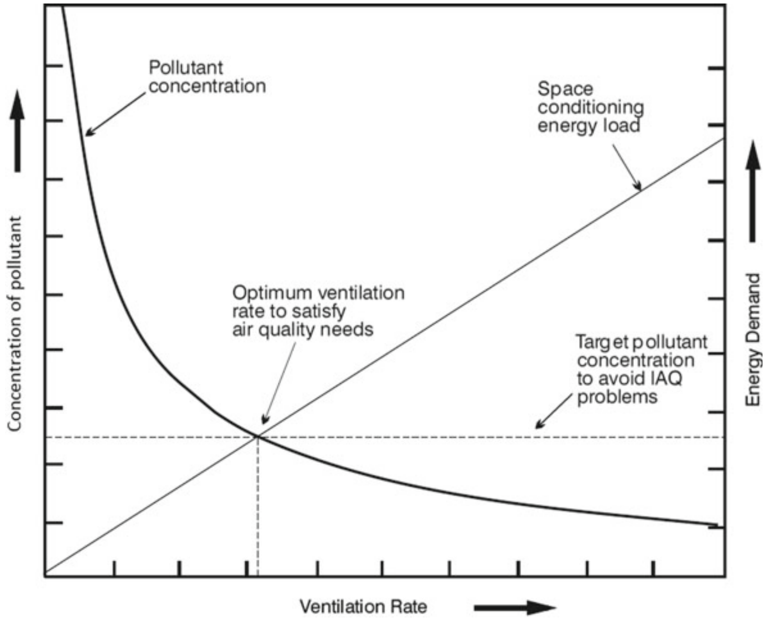

Fig. 1 Relationship between contaminant concentration, energy, and ventilation rate [12]

the filter type. For example, a MERV 1 filter traps <20% of to 99% HEPA filters. It is possible to filter some gaseous pollutants using a catalyst, but byproducts of the reaction can be harmful in some circumstances.

When increasing the ventilation rate, there is a law of diminishing returns for the maximum contaminant concentration (see Fig. 1). Furthermore, increasing the ventilation rate also increases conditioning energy demand. Therefore, it is always best to start resolving IAQ problems in the worst ventilated rooms because this achieves the greatest effects on health for the least cost. Figure 1 also shows a linear relationship between the ventilation rate and the space conditioning load, and that there is a trade-off between the contaminant concentration and the energy demand. It is possible to reduce the ventilation energy demand using heat recovery systems and by ventilating only when required. This requires an initial focus on source control, and then the identification and control of the most harmful contaminants in a room over time (see Sect. 3).

The most common metric of ventilation is a volume flow rate with units of L /s or m^3/s. These metrics are generally used to keep the concentration of a contaminant below a prescribed threshold, dissipate heat gains during the cooling season, and to maintain the thermal comfort of occupants. It is also common to use an air change rate, with units of 1/h, which are used to purge a room of contaminants in a prescribed period. Air change rates are also useful for comparing the ventilation rates in two rooms with different geometries. The processes are described in Sect. 3.2.

1.3 Exposure-Response Pathway

Many indoor contaminants have the potential to cause direct and indirect harm. The risk of a susceptible person becoming unwell is related to the mass of the contaminant inhaled, known as the *dose*, and the dose required before a disease occurs. The dose is higher when there is a higher concentration of pollutants in a place, increasing the risk of harm, and when the metabolic rate of occupants is high. Exposure is defined as the contact between airborne contaminants and a person. Total cumulative exposures in a room, E_t, as a function of time are determined by Haber's law of total exposure, which is the sum of exposures in a number of rooms, E_i, and the time-weighted personal exposure to the pollutant emitted by personal activities, $E_{\mathrm{pact,j}}$ (1).

$$E_t = \sum_i E_i + \sum_j E_{\mathrm{pact},j} \tag{1}$$

Exposure is defined as the product of the contaminant concentration, C_i, in a room and the time spent in it, t_i. There then must be some form of interaction between the pollutant and the human [13], which is generally inhalation. Because the contaminant concentration varies with time, an expression of total exposure is 1.

$$E_t = \frac{1}{T}(\sum_i \int C_i dt_i + \sum_j \int C_{\mathrm{pact},j} dt_j) \tag{2}$$

where T is the total time spent in each microenvironment and each personal activity [14].

Normally, exposure models are defined for specific ages and genders which may vary by activity and place. Mccurdy and Graham [4] analyzed US activity data and identified variables that showed that the time spent indoors, outdoors, and in vehicles has a statistically significant effect for each age and sex cohort. They recommend that exposure studies initially consider age and gender, and then consider the level of physical activities of individuals. The daily maximum temperature, the month of the year, and the day of the week are also important drivers.

Klepeis et al. [3] analyzed time-activity data for over 5000 US citizens, classifying it into 10 locations. They show people spend most of their time indoors (average 87%), primarily at home (average 69%), but that this might range from 34 to 98%. Koehler et al. [15] also studied personal exposures to air pollution and their variability by microenvironment or location (home, work, transit, eateries, and others). Results showed greater variability within-person data, which depends on the location. The highest exposures to $PM_{2.5}$ were in transit and eateries due to proximity to traffic and cooking sources, but the higher total integrated exposure was at home.

2 Researching Building Stocks

2.1 Describing a Building Stock

Buildings stocks are nearly always heterogeneous and often large. Ideally, data to describe existing buildings is obtained from large-scale field studies and surveys. Methods to evaluate the building performance are either direct, such as field measurements that use portable or stationary equipment, and indirect, such as modeling and simulation techniques. Indirect methods are often quicker and cheaper and can be used to understand future interventions. Computational models have been used by many countries to estimate changes attributable to policies in the energy demand and indoor environment quality in both buildings and building stocks. These stock models are an effective tool for decision-making, and some Latin American countries have developed and applied a limited set of archetypal or representative buildings, for example, Brazil [16, 17] and Chile [18].

However, there are uncertainties in model buildings and in the information required by them, which may restrict their usefulness [19]. The first is a function of the natural heterogeneity of a stock. The second is random variability which makes it possible to obtain different predictions for the same case. The third is parametric ambiguity where required data may not exist in suitably disaggregated forms. Finally, the acquisition and processing of data can introduce systematic errors. Other problems occur when the stock model suffers from oversimplification, is opaque, or has insufficient modularity [20].

To overcome these issues, recent models use advanced clustering methods to reflect the variability between groups of buildings and sampling methods to account for variability in the descriptive parameters, generate distributions of predictions, and to quantify uncertainty in them (see Fig. 2). The way predictions are assessed and presented to stakeholders is crucial. Results should not disguise the range of probable outcomes or measured values, but highlight those that are more likely to occur and those that are extreme and hence unlikely.

Modelers should also apply global sensitivity analyses to identify the input parameters that have the greatest effect on the predictions of the model. These parameters can highlight targets for remediation or a need for future field surveys when data is scarce [8, 22]. These strategies are helpful for nations with limited data, such as Latin American countries, where modeling studies of indoor environmental parameters are scarce.

Model predictions may differ from measured data and so an update or calibration process can be carried out by combining the predictions with new data or in situ measurements [19, 23–25].

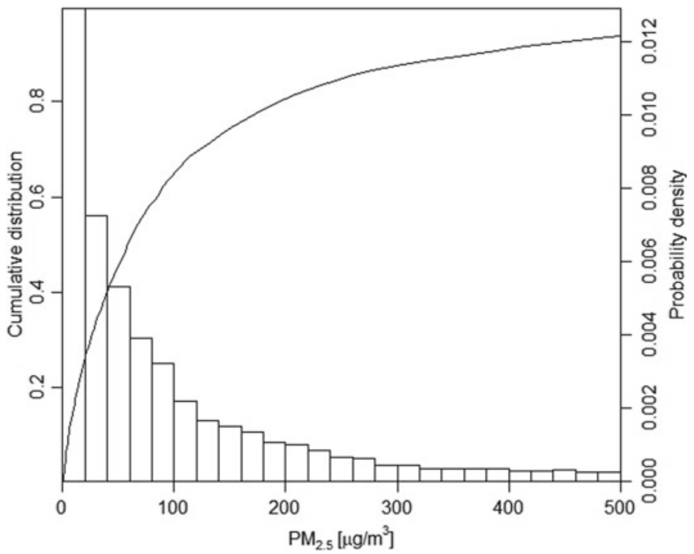

Fig. 2 Predictions of indoor $PM_{2.5}$ concentrations for the Chilean stock during winter, considering indoor sources only and infiltration with an exhaust fan as the only contributors to ventilation [21]

3 Assessing Indoor Air

3.1 Approaches

Indoor contaminant concentrations vary between buildings and zones within a building. This is due to factors that include the local environment, pollution sources, building design and use, and occupant behavior. IAQ in Latin American buildings is often assessed using measurements of CO_2, CO, and particulate matter, and research has focused on school and university buildings [26]. Other pollutants of interest include radon [27], NO_2 [28], and $PM_{2.5}$ [29]. Instantaneous measurements record concentrations at a specific time and location, and continuous sampling in a single location may not capture the variability present in others. Consequently, data from a large number of buildings and locations are required, whose acquisition can be expensive and time-consuming.

Personal exposures can be assessed using the direct and indirect methods described in Sect. 2.1. Directly identifying individual sources of pollution in situ requires complex analyses (see Sect. 3.3). Conversely, indirect approaches rely on simplifying assumptions, and must consider uncertainty (see Sect. 2.1). Several approaches are used to minimize the oversimplification of temporal and spatial distributions of IAQ parameters. Three methods depend on the partitioning of the airspace or the desired level of spatial information. They range from basic models with (i) a single well-mixed zone to (ii) multi-zone models, and then to (iii) more sophisticated models

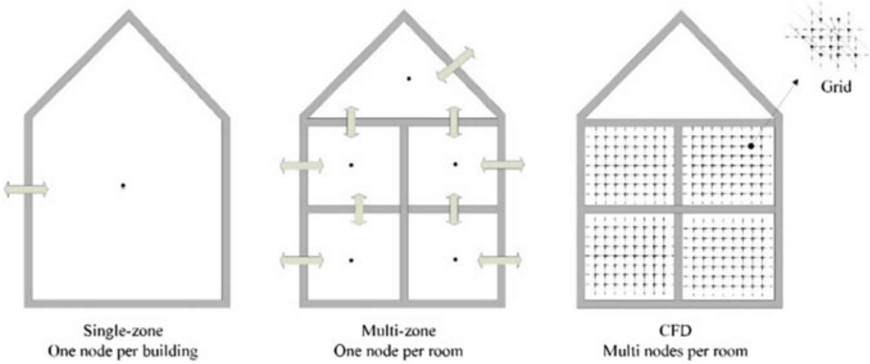

Fig. 3 Three different approaches to model the IAQ in a building. Left: Single well-mixed models; Middle: multi-zone well-mixed models; Right: CFD model. Each dot or node represents a well-mixed volume. Based on [30]

employing a non-uniform distribution of contaminants using Computational Fluid Dynamics (CFD) (see Fig. 3). The method defines the level of complexity, resolution, and detail used to represent the indoor air in a building.

Each method has drawbacks. Single-zone models with well-mixed air consider just one volume of air, which is typically homogenous in temperature and contaminant concentration. Multi-zone models consider several zones linked via airflow paths, such as doors. The contaminant concentrations in a building, or each zone, are then estimated over time using these two methods. Airflows between each zone and between each zone and the outdoor air are computed iteratively by ensuring equations where the mass through the system is conserved at each time step. Finally, a CFD model may be used to assess the distribution of a contaminant within a space and to determine flow velocities, providing further spatial detail (see Fig. 3). As detail increases, so does the required computational power and the simulation time. All predictions can be compared or calibrated using measured data to provide validation. The accuracy of the model can then be determined by its ability to predict indoor air contaminant concentrations.

3.2 Modeling Contaminant Concentrations

The concentration of a contaminant, $C(t)$, at a moment in time, t (h), in a well-mixed indoor space with volume, V (m^3), is given by the solution to a mass-balance equation

$$C(t) = C_{ss} + (C(0)) - C_{ss})e^{-(\lambda+\kappa)t} \tag{3}$$

Here, λ is the air change rate (1/h), κ is the deposition rate (1/h), and $C(0)$ is the contaminant concentration when $t = 0$ hours (h). The right-hand side of Eq. (3) is split into two parts: on the right is a time-dependent function, and on the left is a time-independent constant. As time increases, the concentration increases with time, and eventually the time-dependent part trends to zero leaving a steady-state concentration, C_{ss} (4).

$$C_{ss} = \frac{\lambda P C_b}{\lambda + \kappa} + \frac{G}{(\lambda + \kappa)\, V} \tag{4}$$

Here, C_b is the background concentration, G is the contaminant emission rate, V is the space volume (m^3), and P is a dimensionless penetration coefficient that represents the filtering effect of the building envelope. It has limiting values of 0 and 1 that depend on the characteristics of an airflow path and the contaminant. $P = 1$ for contaminants that are not filtered by the envelope, such as gases, or for all contaminants when the opening is large, such as a window. However, some contaminants, such as particulates, are filtered. Then, $P < 1$ when the airflow path is a small crack. The units of $C(t)$ and G also depend on the contaminant type. For a gas, such as CO_2, they have units of parts per million (ppm) and cubic centimeters per hour (cm^3/h), respectively. Equation (4) shows that C_{ss} is a function of the removal mechanisms and decreases as the removal rate increases. The time taken to reach the steady-state concentration is dependent on the room volume. The bigger the volume, the longer the time. This is known as the *reservoir effect*.

These equations can only be assumed to be correct when the emission is a point source, mixing occurs rapidly throughout due to random internal air movements, the concentration of the contaminant is the same everywhere, the space does not leak, and when $P\lambda, \kappa, G$ are constant. If any of these three parameters changes, then all calculations must be re-started from $t = 0$ h, when $C(0)$ is reset.

The equations only consider $P\lambda$, and κ to be removal mechanisms, and so may not apply to some contaminants, such as VOCs in some environments (see Sect. 1.2). They do apply to inert gases, such as CO_2, when $\kappa = 0$ and $P = 1$, or to $PM_{2.5}$ when $\kappa = 0.39$ and $P = 0.8$ [31].

When designing regulation and standards, the steady-state concentration C_{ss} can be used to set a ventilation rate, λV (m^3/s), so that a threshold contaminant concentration is never reached. For example, a steady-state CO_2 concentration can be used to indicate the ventilation rate when the emission rate is known. When $G = 5$ cm^3/s per person [32], the ventilation rate is $\lambda = 10$ L /s per person, $\kappa = 0$/h, and the ambient CO_2 concentration is $C_b = 500$ ppm. The steady-state concentration can be calculated to be $(500 + 5/(10 \times 10^{-3}) = 1000$ ppm. Accordingly, when a CO_2 concentration is above 1000 ppm in any room, then the ventilation rate is less than 10L /s per person.

The time-dependent element of Eq. (3) can be used to set an air change rate, λ (1/h), required to dissipate a fraction of a contaminant concentration over a specific period of time. For example, after a cleaning activity, a gaseous contaminant is no longer emitted so that $G = 0\ \text{cm}^3/\text{s}$. Then, to lower its concentration in the indoor air by 95% over time period T, the required air change rate is (5)

$$\lambda = -\ln(1 - 0.95)T^{-1} - \kappa \tag{5}$$

When $T = 20\,\text{min}$ (or $0.33\,\text{h}$) and $\kappa = 0/\text{h}$, the required air change rate is $\lambda = 9/\text{h}$. This is converted to a ventilation rate by multiplying λ by the space volume.

3.3 Measuring IAQ

Measuring contaminant concentrations requires complex and costly equipment, which often requires expert knowledge to use and maintain. For their measurements to be meaningful, the equipment must be calibrated frequently.

One of the most cost-effective contaminants to measure is CO_2, which is commonly done using non-dispersive infrared gas sensors (NDIR), where the absorption of the characteristic wavelengths of infrared light is measured and used to estimate the CO_2 concentration in air. CO_2 sensors are prone to a gradual changing of the scale of zero, known as zero-*drift*, and so they require frequent calibration. Non-scientific sensors, such as those used to operate ventilation, can self-calibrate by determining the ambient concentration during a prolonged period of inoccupancy.

Optical particle counters (OPCs) are commonly used to measure temporal changes in $PM_{2.5}$ concentrations. The $PM_{2.5}$ concentration is inferred from the light scattering properties of the particles sampled, which vary by source and composition. Accordingly, OPC measurements must be scaled by a calibration factor, a multiplier derived from concurrent gravimetric sampling. A gravimetric sampler collects $PM_{2.5}$ on a filter over the defined sampling period. The filter's mass is determined before and after the sampling period allowing for the calculation of an average $PM_{2.5}$ concentration. OPCs are often most sensitive to $PM_{2.5}$ of a particular size, and so OPCs capable of disaggregating $PM_{2.5}$ concentrations by their diameter can be used to select an appropriate OPC for a particular source.

Gas chromatography can be used to separate and analyze compounds found in the air, such as VOCs. There is a range of methods for doing this, which are described by Helmig [33]. The equipment is both bulky and expensive but has a high resolution.

3.4 Metrics to Evaluate Exposure Consequences

Policymakers often strive to reduce the energy demand of buildings by sealing them up or by limiting ventilation rates. An unintended consequence could be a reduction of the quality of indoor air with corresponding negative health effects for individuals and increased burdens on public healthcare systems. Current standards specify a minimum ventilation rate that is fundamentally set for odor control and that is also assumed to minimize contaminant exposures and, therefore, protect occupant health. Accordingly, there is a need for performance-based health-centered IAQ metrics supported by our best knowledge of health effects. They must be measurable, achievable, and have a positive impact on the physical and mental health of occupants of buildings.

An air quality standard or norm should identify when the quality of indoor air is unacceptable and be based on its effects on human health and comfort, acknowledging that they may not be immediate. Health-adjusted life years (HALY) are measures of health over time and give weighted years a person of cohort lives with a disease and/or disability. Disability is weighted by its effect on a person's life in general, and so can account for mental illness. There are two key HALY metrics. The first is the disability-adjusted life year (DALY), which measures the disease burden in a population, expressed as the sum of the number of years lost due to morbidity and mortality, where a value of 0 represents no loss. In the case of IAQ, the disease burden is a measurement of the difference between the current health status of a population of building occupants and an ideal situation where they all live into old age, free of disease and disability. The second is the quality-adjusted life year (QALY), which reflects the quality of life of a person or cohort but is the approximate inverse of a DALY because it considers the health gained from an intervention where a value of 1 represents a year lived in perfect health and 0 is death. Both the QALY and DALY can be used to assess the financial values of exposures to poor IAQ and interventions designed to minimize it. Other metrics include money, premature deaths, or working days lost.

The DALY metric has been used to estimate the population average annual cost of chronic air contaminant inhalation in U.S. residences [34] (see Fig. 4). It estimates that the most harmful contaminant is particulate matter with a diameter of $\leq 2.5\mu g/m^3$ ($PM_{2.5}$), by an order of magnitude. These particles are small enough to bypass biological defenses and are linked to chronic respiratory and cardiovascular diseases, and cancer [35]. The [36] recommends mean $PM_{2.5}$ concentrations in all air breathed by a person is less than $15\mu g/m^3$ per day and $5\mu g/m^3$ per year. Mean annual external concentrations exceed the WHO limit in many cities making the provision of unfiltered ventilation a health risk in those areas. There are also many internal sources (see Table 1), such as cooking, and behavior modification and adequate ventilation should be encouraged. The contaminant sources described in Fig. 4 also exist in the houses of other countries, and so its findings can be extrapolated outside of the U.S.A.

3.5 *Regulating IAQ*

IAQ is governed by an ever-expanding number of regulations and standards. Many standards for non-domestic buildings aimed to control odor, which led to a common minimum ventilation rate of 7.5 L/s per person. This was increased to 10 L/s per person in many building types to account for other contaminants, such as those

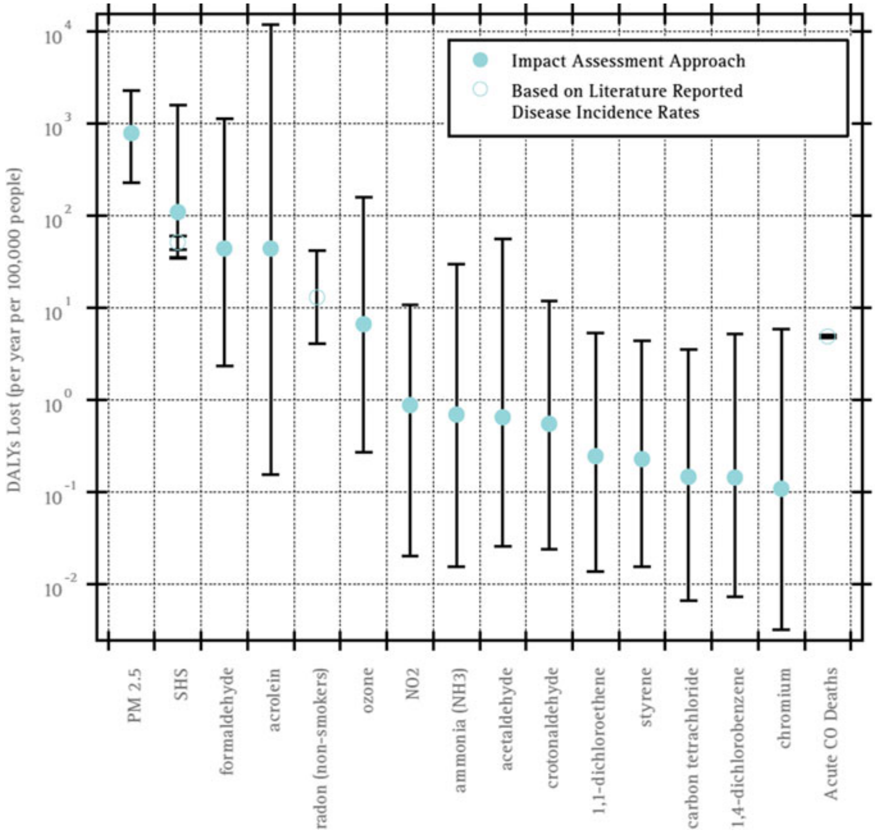

Fig. 4 Estimated population-averaged annual cost, in DALYs, of chronic air contaminant inhalation in U.S. residences. Reproduced from [34]. Technical Note AIVC 68. Residential Ventilation and Health. Brussels: Air Infiltration and Ventilation Centre

released by materials and furnishings [37]. The regulation of ventilation rates in houses generally aims at controlling moisture and diluting the byproducts of combustion. However, these are evolving to consider pollutant sources and harm. The ANSI/ASHRAE 62.2 standard [1] aims at providing *acceptable* IAQ in residential buildings (see Sect. 1.1).

Standards that give threshold values establish them for a population by considering the effects of exposure on public health [38]. Table 3 presents a summary of threshold values for air pollutants in indoor settings. Many Latin American countries apply the IAQ standards of international bodies or other countries [38, 39]. Accordingly, the values of the World Health Organization and the U.S. Environmental Protection Agency values are considered here because they are most often applied in Latin American countries.

Table 3 Threshold values for main indoor and outdoor air pollutants

Pollutant		Indoor/occupational		Threshold	By
		Units ($\mu g/m^3$)	Time		
Criteria pollutant	Particulate matter ($PM_{2.5}$)	5	1 year	Guideline	WHO
		15	24 h	Guideline	WHO
		15	1 year	Standard	US EPA
		35	24 h	Standard	US EPA
		65	24 h	Standard	ASHRAE
	Sulfur Dioxide (SO_2)	40	24 h	Guideline	WHO
		80 (0.03*)	1 year	Standard	US EPA
	Nitrogen	10	1 year	Guideline	WHO
	Dioxide (NO_2)	25	24 h	Guideline	WHO
		100 (0.05*)	1 year	Standard	US EPA
		1800 (1*)	15 min	Standard	NIOSH/US EPA
	Ozone (O_3)	200 (0.1*)	8 h	ELV/Standard	OSHA/US EPA
		100	8 h	Guideline	WHO
	Carbon monoxide	4***	24 h	Guideline	WHO
		10***	8 h	Guideline	WHO
		55***(50*)	8 h	PEL/Standard	OHSA/US EPA
		35*	8 h	REL/Standard	NIOSH/US EPA
VOC[a]	Benzene	No safe level of exposure can be recommended			
	Formaldehyde	0.1***	30 min	Guideline	WHO
		0.1***	30 min	Standard	ASHRAE
	Trichloroethylene	2	Whole life	ELV	VGAI
		2.3	Whole life	Guideline****	WHO
	Tetrachloroethylene	250	1 year	Guideline	WHO
	Naphthalene	10	1 year	Guideline	WHO
		9	1 year	REL	OEHHA
	Xylenes	22000	1 h	REL	OEHHA
Other air pollutants	Polycyclic aromatic hydrocarbons[b]	No safe level of exposure can be recommended			
	Radon	200*****	1 year	Guideline	Canada
	Biological agents	200	1 year	Guideline	EU

[a] Volatile Organic Compounds
[b] Benz[*a*]anthracene, benzo[*a*]pyrene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, chrysene, dibenzo[*a*, *h*]anthracene, benzo[*ghi*]perylene and indeno[1, 2, 3 − *cd*]pyrene
* ppm
** ppb
*** μm^3
**** excess lifetime cancer risk of 1:1,000,000
***** Bq/m^3
****** CFU/m^3
REL: Recommended exposure limit; PEL: Personal exposure limit; WHO: World Health Organization; USEPA: United States Environmental Protection Agency; VGAI: Valeurs Guides de qualité d'Air Intérieur, France; OEHHA: Office of Environmental Health Hazard Assessment, USA; Government of Canada, Residential Indoor Air Quality Guidelines, 2016; EU: European Union

The WELL Building Standard [40] focuses on the people in buildings and identifies over 100 policies, design strategies, and performance metrics that can be implemented to enhance the health and well-being of building occupants. IAQ is one very important factor.

Most standards are in a state of constant flux and are updated frequently as new knowledge becomes available. They are challenging to develop because they must support innovative and flexible design approaches so that designers can deliver high-performing sustainable buildings for the people who occupy them, without compromising the needs of regulators, policymakers, and building owners [41].

4 Barriers to Change

There is currently little or no regulation in many Latin American countries that ensures acceptable IAQ in new and existing buildings. This may stem from a general lack of awareness of the issues caused by unacceptable IAQ and a perception that this issue is not a priority. Therefore, it is important for construction professionals, academics, and learned societies to lobby their governments for changes in the law to require acceptable IAQ. It is easier to regulate new buildings because appropriate measures and systems can be implemented at the design stage. Later changes can be implanted that require changes to existing buildings when they are renovated.

The implementation of IAQ regulation will be a non-trivial process. Finance, public awareness campaigns, and the need to make the case against competing concerns in the construction industry will be required. Regulations must be agreed upon by stakeholders and legislated for. A process for checking adherence to regulations must be implemented. Therefore, political engagement is essential.

It is in the interest of governments to regulate IAQ because the negative effects increase government expenditure on health care, social care, and social security, and reduces economic growth. The impacts on children are particularly important as this has the potential to reduce their educational attainment and future earning potential. Sick children require parental care that limits their ability to earn. Adults with chronic illnesses caused by poor IAQ may be unable to work and become a burden on the state rather than contributing tax. These consequences are likely to affect several government ministries, such as housing, health, and social security. Here, it is important to acknowledge that each of these ministries has competing agendas.

The academic community can support change by providing peer-reviewed evidence that shows the most cost-effective interventions using multi-criteria cost-benefit analyses [42]. Scientific funding bodies need to be encouraged to fund research into geographic and building stock appropriate regulations. Business can be engaged to create a new industry that seeks to provide solutions. And, if the supporting regulation is performance based, so that it gives targets rather than mandating solutions, it will encourage design innovation. Learned societies need to mediate between business, government, and academics to drive change. They can follow the examples of ASHRAE, REHVA, and the CIBSE.

Implementing change in existing houses poses a significant barrier to change. Many houses are not airtight and are poorly constructed [21]. The costs of heating or cooling them may be significant. Fuel poverty affects householders who may face the unseemly choice between comfort and acceptable air quality. It is particularly important to transition away from solid-fuel heating to avoid indoor contaminant emissions and the re-entry of smoke from the outside.

Stakeholders should be under no illusions that implementing a reduction to the harm caused by unacceptable IAQ in Latin American buildings is a significant challenge that will take time to succeed.

5 Summary

The indoor air is composed of a complex mix of particles, gases, and contaminants, varying in concentration and toxicity. Mechanisms for removing contaminants from indoor spaces include ventilation, aerosol deposition, pathogen biological decay, and filtering. It is possible to reduce the ventilation energy demand using heat recovery systems and by ventilating only when required. This requires an initial focus on source control and then identifying and controlling the most harmful contaminants in a room over time.

There is a lack of awareness of the issues caused by unacceptable IAQ in many Latin American countries, exacerbated by the prevalence of households affected by fuel poverty that may have to choose between comfort and acceptable air quality. Thus, policymakers must be aware of the unintended consequences of building interventions on indoor air quality, which would have adverse health outcomes for people and an increased burden on public health. Poor IAQ inevitably affects government spending on health care, social care, and social security while reducing economic development. Air quality standards or norms should establish the acceptability of indoor air, based on its short- and long-term effects on human health and comfort. It is important for construction professionals, academics, and learned societies to lobby their governments for changes in the law to require acceptable IAQ at the design stage. Implementing a reduction in the harm caused by the poor indoor air quality in Latin American buildings is a difficult task that will take time to complete.

References

1. ASHRAE (2019) Standard 62.2 user's manual: Based on ANSI/ASHRAE standard 62.2-2016: Ventilation and acceptable indoor air quality in residential buildings. Am Soc Heat Refrig Air-Condition Eng

2. Prasauskas T, Martuzevicius D, Krugly E, Ciuzas D, Stasiulaitiene I, Sidaraviciute R, Kauneliene V, Seduikyte L, Jurelionis A, Haverinen-Shaughnessy U (2014) Spatial and temporal variations of particulate matter concentrations in multifamily apartment buildings. Build Environ 76:10–17. https://doi.org/10.1016/j.buildenv.2014.02.010
3. Klepeis N, Nelson W, Ott W, Robinson J, Tsang A, Switzer P, Behar J, Hern S, Engelmann W (2001) The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. J Exposure Sci Environ Epidemiol 11:231–252. https://doi.org/10.1038/sj.jea.7500165
4. Mccurdy T, Graham SE (2003) Using human activity data in exposure models: Analysis of discriminating factors. J Exposure Sci Environ Epidemiol 13:294–317. https://doi.org/10.1038/sj.jea.7500281
5. Marmot M, Friel S, Bell R, Houweling TA, Taylor S (2008) Closing the gap in a generation: Health equity through action on the social determinants of health. Lancet 372:1661–1669. https://doi.org/10.1016/S0140-6736(08)61690-6
6. Lozano R, Fullman N, Abate D et al (2018) Measuring progress from 1990 to 2017 and projecting attainment to 2030 of the health-related sustainable development goals for 195 countries and territories: A systematic analysis for the global burden of disease study 2017. Lancet 392:2091–2138. https://doi.org/10.1016/S0140-6736(18)32281-5
7. Jones B, Das P, Chalabi Z, Davies M, Hamilton I, Lowe R, Mavrogianni A, Robinson D, Taylor J (2015) Assessing uncertainty in housing stock infiltration rates and associated heat loss: English and UK case studies. Build Environ 92:644–656. https://doi.org/10.1016/j.buildenv.2015.05.033
8. Hamilton I, Milner J, Chalabi Z, Das P, Jones B, Shrubsole C, Davies M, Wilkinson P (2015) Health effects of home energy efficiency interventions in England: A modelling study. BMJ Open 5:e007298–e007298. https://doi.org/10.1136/bmjopen-2014-007298
9. Nazaroff W, Gadgil A, Weschler C (1993) Critique of the use of deposition velocity in modeling indoor air quality. In: Modeling of indoor air quality and exposure, ASTM international, pp 81–104. https://doi.org/10.1520/STP13101S
10. Thatcher TL, Lai AC, Moreno-Jackson R, Sextro RG, Nazaroff WW (2002) Effects of room furnishings and air speed on particle deposition rates indoors. Atmos Environ 36:1811–1819. https://doi.org/10.1016/S1352-2310(02)00157-7
11. Nazaroff WW (2004) Indoor particle dynamics. Indoor Air 14:175–183
12. Liddament Martin W (1996) A guide to energy efficient ventilation. Tech. rep, Coventry, UK
13. Gaylor DW (2000) The use of haber's law in standard setting and risk assessment. Toxicology 149:17–19. https://doi.org/10.1016/S0300-483X(00)00228-6
14. Wilson WE, Mage DT, Grant LD (2000) Estimating separately personal exposure to ambient and nonambient particulate matter for epidemiology and risk assessment: Why and how. J Air Waste Manage Assoc 50:1167–1183. https://doi.org/10.1080/10473289.2000.10464164
15. Koehler K, Good N, Wilson A, Mölter A, Moore BF, Carpenter T, Peel JL, Volckens J (2019) The fort collins commuter study: Variability in personal exposure to air pollutants by microenvironment. Indoor Air 29:231–241. https://doi.org/10.1111/ina.12533
16. Schaefer A, Ghisi E (2016) Method for obtaining reference buildings. Energy Build 128:660–672. https://doi.org/10.1016/j.enbuild.2016.07.001
17. Triana MA, Lamberts R, Sassi P (2015) Characterisation of representative building typologies for social housing projects in brazil and its energy performance. Energy Policy 87:524–541. https://doi.org/10.1016/j.enpol.2015.08.041
18. Molina C, Kent M, Hall I, Jones B (2020) A data analysis of the Chilean housing stock and the development of modelling archetypes. Energy Build 206:109568. https://doi.org/10.1016/j.enbuild.2019.109568
19. Booth AT, Choudhary R, Spiegelhalter DJ (2012) Handling uncertainty in housing stock models. Build Environ 48:35–47. https://doi.org/10.1016/j.buildenv.2011.08.016
20. Sousa G, Jones BM, Mirzaei PA, Robinson D (2017) A review and critique of UK housing stock energy models, modelling approaches and data sources. Energy Build 151:66–80. https://doi.org/10.1016/j.enbuild.2017.06.043

21. Molina C, Jones B, Hall IP, Sherman MH (2021) CHAARM: a model to predict uncertainties in indoor pollutant concentrations, ventilation and infiltration rates, and associated energy demand in Chilean houses. Energy Build 230:110539. https://doi.org/10.1016/j.enbuild.2020.110539
22. Das P, Shrubsole C, Jones B, Hamilton I, Chalabi Z, Davies M, Mavrogianni A, Taylor J (2014) Using probabilistic sampling-based sensitivity analyses for indoor air quality modelling. Build Environ 78:171–182. https://doi.org/10.1016/j.buildenv.2014.04.017
23. Balaras CA, Dascalaki EG, Droutsa KG, Kontoyiannidis S (2016) Empirical assessment of calculated and actual heating energy use in hellenic residential buildings. Appl Energy 164:115–132. https://doi.org/10.1016/j.apenergy.2015.11.027
24. Cerezo C, Sokol J, AlKhaled S, Reinhart C, Al-Mumin A, Hajiah A (2017) Comparison of four building archetype characterization methods in urban building energy modeling (UBEM): A residential case study in Kuwait City. Energy Build 154:321–334. https://doi.org/10.1016/j.enbuild.2017.08.029
25. Sokol J, Davila CC, Reinhart CF (2017) Validation of a bayesian-based method for defining residential archetypes in urban building energy models. Energy Build 134:11–24. https://doi.org/10.1016/j.enbuild.2016.10.050
26. Valderrama-Ulloa C, Silva-Castillo L, Sandoval-Grandi C, Robles-Calderon C, Rouault F (2020) Indoor environmental quality in Latin American buildings: A systematic literature review. Sustainability 12:643. https://doi.org/10.3390/su12020643
27. Giraldo-Osorio A, Ruano-Ravina A, Varela-Lema L, Barros-Dios JM, Pérez-Ríos M (2020) Residential radon in Central and South America: A systematic review. Int J Environ Res Pub Health 17:4550. https://doi.org/10.3390/ijerph17124550
28. Kephart JL, Fandiño-Del-Rio M, Williams KN, Malpartida G, Steenland K, Naeher LP, Gonzales GF, Chiang M, Checkley W, Koehler K, Rosenthal J, Aguilar T, Burrowes V, Fung EC, Goodman D, Harvey SA, Herrera P, Lee A, Lee KA, Miele CH, Moazzami M, Moulton LH, Nangia S, O'Brien C, Simkovich S, Shade T, Stashko L, Villegas' Gomez A (2020) Nitrogen dioxide exposures from biomass cookstoves in the Peruvian Andes. Indoor Air 30:735–744. https://doi.org/10.1111/ina.12653
29. Benka-Coker ML, Peel JL, Volckens J, Good N, Bilsback KR, L'Orange C, Quinn C, Young BN, Rajkumar S, Wilson A, Tryner J, Africano S, Osorto AB, Clark ML (2020) Kitchen concentrations of fine particulate matter and particle number concentration in households using biomass cookstoves in rural Honduras. Environ Pollut 258:113697. https://doi.org/10.1016/j.envpol.2019.113697
30. Axley J (2007) Multizone airflow modeling in buildings: History and theory. HVAC R Res 13:907–928. https://doi.org/10.1080/10789669.2007.10391462
31. O'Leary C, Jones B, Dimitroulopoulou S, Hall IP (2019) Setting the standard: The acceptability of kitchen ventilation for the English housing stock. Build Environ 166:106417. https://doi.org/10.1016/j.buildenv.2019.106417
32. Griffiths M, Eftekhari M (2008) Control of CO_2 in a naturally ventilated classroom. Energy Build 40:556–560. https://doi.org/10.1016/j.enbuild.2007.04.013
33. Helmig D (1999) Air analysis by gas chromatography. J Chromatogr A 843:129–146. https://doi.org/10.1016/S0021-9673(99)00173-9
34. Borsboom W, Gids W, Logue J, Sherman M, Wargocki P (2016) Technical note AIVC 68. Residential ventilation and health. Tech. rep, Brussels, Belgium
35. Lewtas J (2007) Air pollution combustion emissions: Characterization of causative agents and mechanisms associated with cancer, reproductive, and cardiovascular effects. Mutat Res/Rev Mutat Res 636:95–133. https://doi.org/10.1016/j.mrrev.2007.08.003
36. World Health Organization (2021) WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Geneva, Switzerland
37. Persily A, Musser A, Leber DD (2006) A collection of homes to represent the US housing stock. Tech. rep, Washington, DC, USA
38. Abdul-Wahab SA, En SCF, Elkamel A, Ahmadi L, Yetilmezsoy K (2015) A review of standards and guidelines set by international bodies for the parameters of indoor air quality. Atmos Pollut Res 6:751–767. https://doi.org/10.5094/APR.2015.084

39. Morantes G, Pérez N, Santana R, Rincón G (2016) Revisión de instrumentos normativos de la calidad del aire y sistemas de monitoreo atmosférico: América Latina y el Caribe. Interciencia 41:235–242
40. WELL (2021) International well building institute. Accessed 08 Nov 2021 from https://www.wellcertified.com/
41. Persily A (2015) Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. Build Environ 91:61–69. https://doi.org/10.1016/j.buildenv.2015.02.026
42. Das P, Chalabi Z, Jones B, Milner J, Shrubsole C, Davies M, Hamilton I, Ridley I, Wilkinson P (2013) Multi-objective methods for determining optimal ventilation rates in dwellings. Build Environ 66:72–81. https://doi.org/10.1016/j.buildenv.2013.03.021

Evaluation of a Low-Cost Air Renewal System for Indoor Air Quality Control in a Climate Chamber

Eduardo Krüger and Renata Diniz

Abstract There is a growing concern about Indoor Environmental Quality (IEQ) in buildings as humans are spending longer in indoor environments, whether this is associated or not with climate change and vulnerability to extreme weather events. In the wake of the COVID pandemic, the need for indoor air quality control is likely to increase, the result of many adaptations in home environments to switch to remote work. In hot countries in the Global South, one of the alternatives is split A/C units with limited air renewal. While, odorless and colorless CO_2, commonly generated by occupants through respiration, is among the relevant indoor air pollutants. The purpose of this study is to evaluate a low-cost, responsive air-renewal system in a climate chamber equipped with a standard split A/C unit. The results show the system's feasibility in curbing IAQ concerns and also highlight the risk of negative impacts on indoor thermal conditions and on energy consumption on using A/C.

Keywords Indoor air quality · Indoor environments · Climate chamber · Responsive system

1 Introduction

In the Global South, climate change is likely to exacerbate heat loads, creating undesirable conditions for human performance and occupational health in indoor environments. In developing countries, particularly characterized by predominantly hot-humid conditions, climate change vulnerability is the highest. In their framework for causal pathways for climate-change-induced, heat-related impacts on working people, Kjellstrom et al. [1] showcase two main negative consequences, namely: health

E. Krüger (✉) · R. Diniz
Department of Civil Construction, Postgraduate Program in Civil Engineering, Universidade Tecnológica Federal do Paraná (PPGEC/UTFPR), Curitiba, Brazil
e-mail: ekruger@utfpr.edu.br

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and economy. Apart from outdoor occupations, such as the case of construction workers, and in mining and transportation sectors, a large part of indoor activities in low-income countries is performed indoors, in naturally-ventilated buildings with no running air-conditioning systems. Yet, the penetration of air conditioners in such economies is growing faster than income growth [2]. Global South countries such as India and Brazil have an air-conditioning penetration ranging between 20 and 30% per year, whereas the U.S. showed an annual increase of just 6% in 2014. In many cases, split A/C units are employed, which have the drawback of having either limited air renewal or none at all, just re-circulating indoor air. Even though buildings in hot countries are generally not airtight, air renewal through cracks may be insufficient to ensure Indoor Air Quality (IAQ) standards. Moreover, noise levels in urban centers end up increasing the demand for double-glazed windows with even greater airtightness.

A groundbreaking study on human occupancy in enclosed spaces, conducted by National Human Activity Pattern Survey (NHAPS) in the United States, and sponsored by the U.S. Environmental Protection Agency (EPA) showed that Americans and Canadians spend on average, 87% of their time in indoor environments, with low regional variations [3].

Given the continuous increase in human permanence in indoor environments, the relevance of studies that assess the impact of this trend on different aspects of human life is growing. Al horr et al. [4] reviewed several studies that correlated building environmental performance and the productivity of their occupants, attesting that user satisfaction with the workplace is proportionally linked to the comfort perception in the built environment.

Indoor comfort can be defined by the absence of unpleasant stimuli, providing well-being to building occupants. Feige et al. [5] point out that in an office environment, functional comfort (disturbances, interruptions, distance from work, and resources), psychological comfort (privacy, territoriality), and environmental comfort should coexist.

Although the definition of comfort has a broad theoretical spectrum, ranging from physical comfort and occupational health to environmental psychology, this study is limited to physical parameters directly related to Indoor Environmental Quality (IEQ). Moreover, the focus is on the Indoor Air Quality (IAQ) of a lab facility, a research topic that has gained greater importance since 2020 due to the SARS-CoV-2/COVID-19 pandemic, as enclosed environments with restricted air renewal have increased potential to spread the virus [6, 7]. Here lies the double risk of developing Sick Building Syndrome (SBS) while spreading the virus in indoor spaces, a risk that is higher in air-conditioned than in naturally-ventilated buildings.

To reduce the concentration of pollutants and increase IAQ levels, indoor spaces are typically ventilated by opening windows or by mechanical ventilation systems. Low IAQ results from the accumulation of pollutants, and has a negative impact on user comfort and health in the short, medium, and long term, and may cause eye and skin irritation, allergic reactions, coughing, sneezing, nausea, and breathing difficulties, among others. In this context, indoor air pollution can have external or internal sources, where higher IAQ levels depend on low concentrations of harmful contaminants for people's health [8].

The main sources of polluting substances are the occupants themselves, the activities and equipment used, construction materials, furniture, ventilation systems with either limited or no fresh air supply, and the outside air, which may contain pollutants produced by sources outside the building. The pollutants most frequently found in indoor air are odors, carbon dioxide, formaldehyde, volatile organic compounds, tobacco smoke, ozone, radon, nitrous oxides, and aerosols [9].

Doubling or overlapping windows is a low-cost solution when trying to improve the acoustic and thermal insulation of existing buildings. However, even though this solution may improve the energy efficiency of the building in the case of HVAC systems with increased airtightness, there could be deterioration in IAQ due to a decrease in air change rates [10].

The split system is the HVAC system mostly sold for indoor air conditioning purposes in Brazil [11]. The temperature reduction is achieved through heat exchanges between the appliance's refrigerant and the air circulating in the space to be cooled. As mentioned above, in many air-conditioned buildings in hot regions of the Global South that rely on split A/C units, their low IAQ is mostly due to the lack of adequate natural ventilation or mechanical ventilation systems that promote air renewal [12].

Therefore, the objective of this study is to evaluate a responsive air renewal system to ensure IAQ in an office-like environment from the viewpoints of comfort and energy efficiency. Even though the study was conducted in a test facility and not in an actual office environment, lessons learned can be of relevance in the context of office buildings in urban centers of the Global South. As previously discussed, the rapid increase of A/C usage in such buildings due to the combination of climate change impact, urbanization, and overall economic growth in developing countries will ask for cost-effective renewal solutions from one of the simplest A/C equipment available, such as the split system without air renewal.

2 Methods

For this study, measurements were made at the Cost-effective Bioclimatic Building Chamber (CBBC), built in 2018 at the Federal University of Technology of Paraná located in Curitiba, Brazil (at 25°26′S, 49°16′W, 910 m.a.s.l., with Köppen-Geiger's Cfb climate), an experimental facility comprising two independent indoor, office-like environments destined to Indoor Environmental Quality (IEQ) studies. The setup consists of two rotatable 5.4 m^2 container units with office-like interiors, both with conventional aluminum windows and split, high-wall A/C units. The building envelope and dimensions comply with existing Brazilian standards.

2.1 Local Climate

Curitiba is the coldest regional capital in Brazil and is located at a high elevation in the southern region of the country. The local climate is classified as temperate oceanic (Köppen-Geiger's Cfb climate), as it has mild summers with relatively cold winters with frequent frosts. The latest climatological normals (1981–2010) for Curitiba show that the average annual temperature is 17.4 °C with February being the hottest month (monthly mean of 21 °C), and July, the coldest (mean of 13.5 °C) [13].

2.2 The Facility

The concept of CBBC is based on the Brazilian Standard NBR 15.220/2003: Thermal Performance of Buildings, which defines the Brazilian bioclimatic zoning and construction strategies to optimize the building's thermal performance. It also complies with the Technical Quality Regulation for the Energy Efficiency Level of the Buildings (RTQ), a directive proposed for promoting energy-efficient buildings in Brazil. The envelope of the CBBC has a thermal transmittance (U value) of 0.87 W/(m^2K) and a thermal capacity (CT) of 122 kJ/(m^3K). A thorough description of the CBBC is shown by [14].

The two units were built from a high cube 40' shipping container and are identical in size (floor area of 5.4 m^2) and layout (See Fig. 1), offering the possibility of test comparisons (control versus experimental module). The rotatable structure allows independent testing of solar orientation and natural ventilation effects.

After the project's completion in 2018, a series of post-occupancy evaluations revealed that despite showing a fairly good overall satisfaction in terms of thermal, luminic, and acoustic parameters, some users complained about noise from outside sources (traffic). Noise levels were also measured with a Brüel & Kjaer B&K Type 2250-L class 1 sound level meter and analyzer during peak hours pointing to the need for acoustic treatment for the window. As a result, a second window was added to the existing one, creating an overlap of two windows, which lead to acceptable noise levels in the room during peaks (average equivalent noise level of 40.7 dB).

A side project analyzed the benefits of having the overlapped windows to IEQ in the experimental module "EM" [15]. However, despite the increased thermo-acoustic performance of the indoor environment, with negligible impacts on indoor daylighting levels, the greater air tightness of the CBBC resulting from the added window negatively affected IAQ related to occupancy of the facility, mainly carbon dioxide—CO_2 output, when the split A/C unit was in operation.

The EM has a double door (an internal wooden door and the original steel door of the container fitted with 15 mm Styrofoam). The north-facing, double window has a gross surface area of 1.26 m^2, and the original layer is composed of two sliding panes with 6 mm glazing. A second layer was attached externally and has tilt windows with 4 mm glazing [15]. The net ventilation area with opened windows is approximately

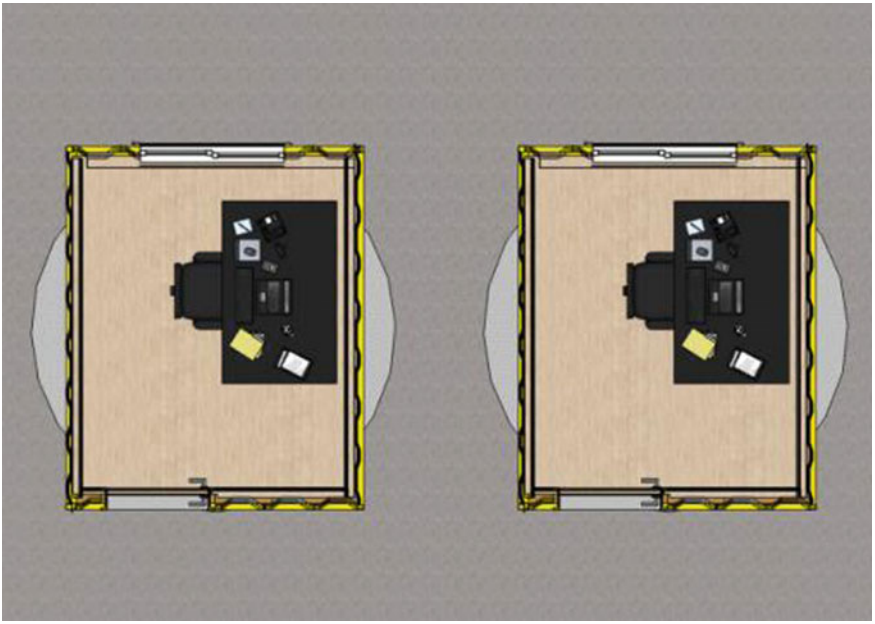

Fig. 1 Layout scheme of the two CBBC modules

0.6 m^2. The lighting system consists of three Phillips LED lamps, HUE White and Color Ambiance—Starter Kit E27, with adjustable color-correlated temperatures. As shown in Fig. 2, the internal layout has a workstation with an internet connection.

The energy-efficient split A/C unit (model PH9000TQFM5) has 9000 BTU/h and can reach an airflow of 500 m^3/h. Nevertheless, the unit does not provide air renewal, and infiltration rates through cracks are low (0.20 air changes per hour) to provide acceptable CO_2 levels when there are occupants inside.

2.3 *Air Renewal System*

The air renewal system for improving IAQ that would fit the small internal volume of the CBBC (13.5 m^3) consists of one inlet and one exhaust fan, diagonally positioned at two heights to more easily remove CO_2 concentrations, and with the inlet fan placed just below the A/C vent (See Fig. 2).

The inlet fan of the installed air renewal system (SicFlux Splitvent BIV) has a maximum air renewal capacity of 54 m^3/h and uses G4/M5 filters. The exhaust fan (SicFlux Sonora 10) has a maximum capacity of 105 m^3/h.

The air renewal system was provided with simple automation, setting up both fans when CO_2 levels exceeded a given threshold and disarming those when acceptable

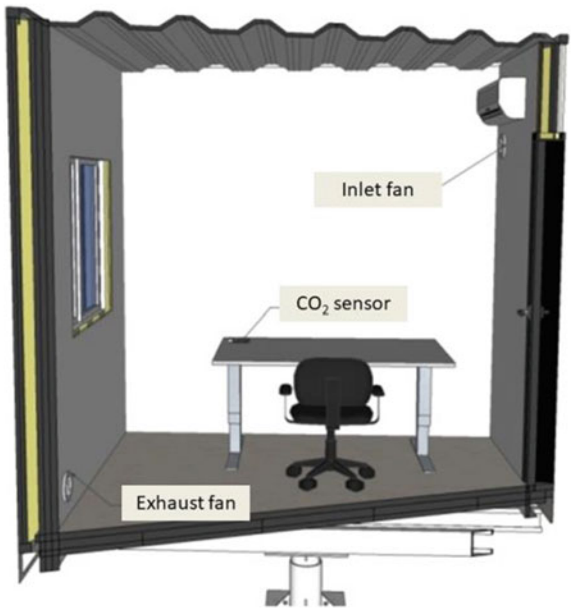

Fig. 2 Air renewal system implemented in the CBBC's experimental module

levels are reached. The low-cost, responsive air renewal system uses an Arduino Mega 2560 R3 interface that receives and interprets sensor signals with an electrically operated switch or relay that turns the fans on and off. The CO_2 sensor (Ccs811) measures parts per million (ppm) of carbon dioxide and was calibrated against a CO_2 meter Flex X-06 (Criffer), which measures within the range of 0–40.000 ppm with 1 ppm resolution.

2.4 Tests Performed with the Air Renewal System

Starting from the goal of the study, which was to evaluate the performance of the air renewal system at the CBBC from the viewpoints of comfort and energy efficiency, two distinct operation modes of the experimental module were compared: (1) opening the window once CO_2 levels generated by the occupant were inadequate, and (2) with automation using the responsive air renewal system. Tests were thus performed for a free-running thermal environment and with the A/C split unit turned on. In this chapter, the results are summarized with the following comparisons:

- Time needed to reach inadequate CO_2 levels in the office with one occupant (the limit of 1175 ppm was assumed for that, based on the occupation pattern and baseline CO_2 levels in outdoor areas in Curitiba) and time elapsed for reaching adequate IAQ levels with the air renewal system permanently switched on with one occupant;

- Defining the lower threshold—whether 600 or 900 ppm;
- Energy consumption for A/C with the minimum threshold of 900 ppm, with and without air renewal;
- Free-running mode with the opening of the window

Concurrently to the CO_2 monitoring at desk level, close to the occupant at a sitting position, relevant environmental data were gathered indoors and outdoors. Indoor variables were air temperature and humidity and globe temperature readings at 1.10 m in the middle of the room. A TagTemp stick temperature sensor (accuracy ±0.5 °C at 25 °C, resolution 0.1 °C) was enclosed in a 10 cm diameter plastic globe, painted gray for globe temperature readings. Air temperature and humidity were recorded by a HOBO UX100-003 logger (T: ±0.53 °C from 0° to 50 °C, RH: ±3.5% from 25 to 85%, resolution 0.14 °C at 25 °C and 0.07% at 25 °C and 30% RH). Spot measurements were taken of the airspeed with a hot-wire anemometer at desk level.

A multifunctional electric meter (B1C3 from Landis+Gyr) was connected between the power outlet and the A/C unit to allow measurements of the energy consumption for air-conditioning during sessions.

The thresholds used for the operation of the air renewal system were 1175 ppm (maximum allowed concentration for setting up the system, obtained for local conditions according to recommendations of the Brazilian standard NBR 16401-3, 2008) and 600 or 900 ppm (tentatively used as baseline concentrations for turning off the fans).

Tests were run during the summer months between January and March 2022 in Curitiba. Those summer months were relatively mild, with ambient temperatures reaching above 30 °C but with a daytime (from 6 am to 6 pm) mean of 21.4 °C, and daytime thermal conditions, in their majority, lying within the adaptive comfort zone for Curitiba for 90% thermal acceptability [16] and below it, with limited overheating during the day. Cold fronts occurred frequently during this period, rising in intensity in March. The rationale for choosing this period for analysis instead of months with less precipitation was that focusing on the summer period, the provision of air renewal might lead to overheating and to increases in cooling demand, which are parameters to be tested as per experimental design.

3 Results

The first test was to evaluate the time elapsed with one occupant performing light office work, seated. CO_2 output, in this case, was assumed to reach 0.3 1/min. Figure 3 shows the output reached in terms of parts per million of the indoor air without any air renewal, except for the estimated infiltration rate of approximately 0.2 ACH. On the same graph, the dashed line shows the CO_2 concentration departing from the same baseline conditions but with the air renewal system permanently switched on.

Without air renewal, the CO_2 levels will exceed permissible conditions in less than an hour, after around 50 min, whereas with a permanent air renewal, CO_2 levels

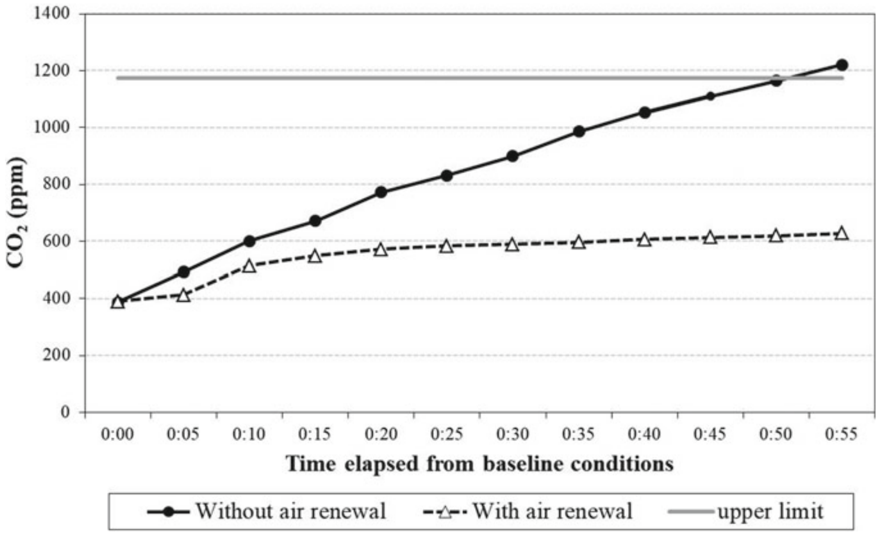

Fig. 3 CO_2 output for one occupant, with and without air renewal

tend to stabilize just above 600 ppm with the internal source (occupancy). Such observation was confirmed by testing the lower limit for switching off the responsive air renewal system. In both cases, the Arduino Mega 2560 R3 interface was set to turn the fans on and off when given thresholds were reached. Setting the upper threshold at 1175, 600, and 900 ppm was tested for automatically switching off the fans. Figure 4 shows CO_2 concentrations for the same two-hour timeframe hours with one occupant performing light desk work.

The graphs show that only for tighter control (900 ppm) is there a cycling behavior as the 600 ppm limit is just below the average CO_2 output for one occupant in the office, thus that threshold will virtually never be reached and the air renewal system would not disarm. With the threshold set higher, the system takes 30–40 min to renew the inside air and stop the fans, and 20 min to start running again, as the lower limit is close to saturation. Looking more closely at the energy consumption of the air-conditioning unit during those times, it was verified that the increase in A/C consumption during air renewal is more than two-fold than without, for an operating time of less than double.

Another useful test was to consider the simplest solution for dispersing a too-high concentration of CO_2 indoors, just by opening the window (See Fig. 5). The test was done on a hot day, with outdoor temperatures during the test lying around 30 °C.

During the 1.5 h monitoring period, a rising pattern of the CO_2 concentration in the indoor environment is noted, with a rate of approximately 100 ppm for every five-minute interval as previously shown in Fig. 3. Until the opening of the window, the A/C was in operation and at a setpoint of 22 °C. After the window was opened, the A/C was switched off to allow evaluating the increase in air temperature and

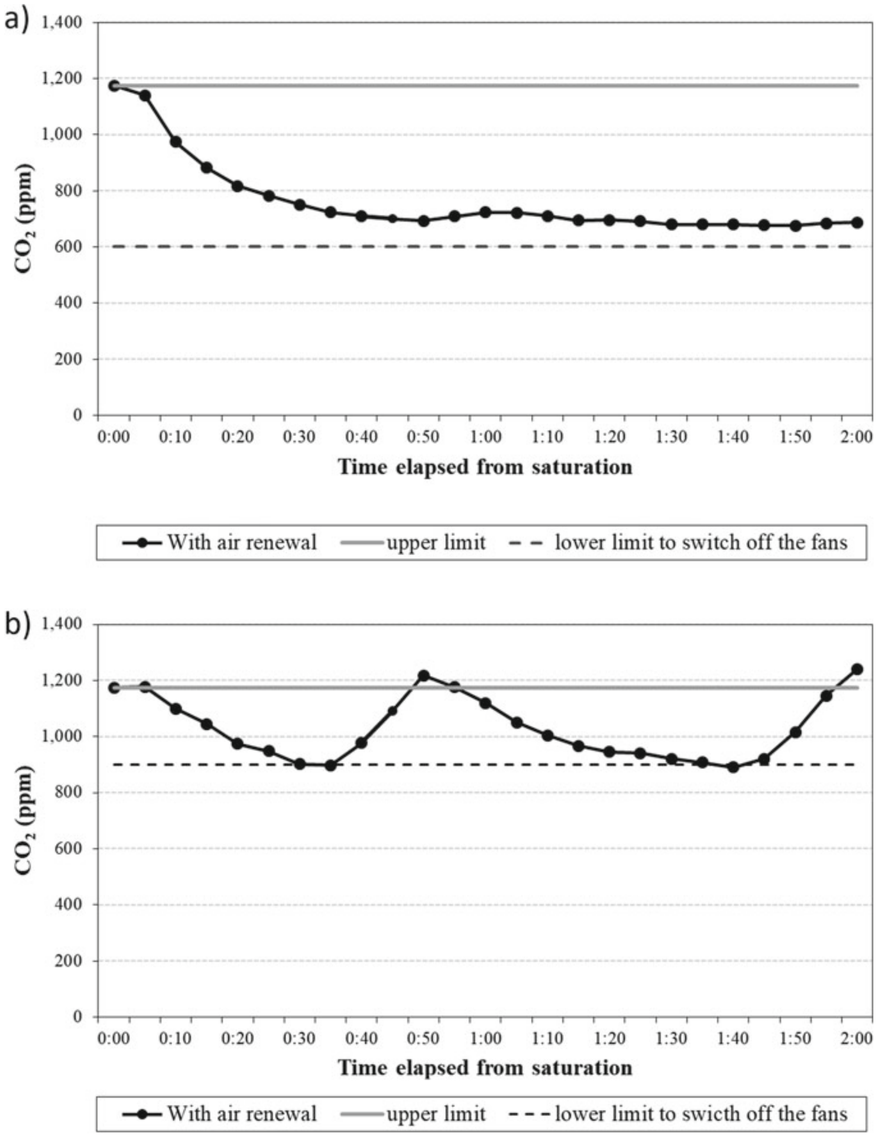

Fig. 4 CO_2 levels for one occupant, with lower thresholds of 600 ppm (a) and 900 ppm (b)

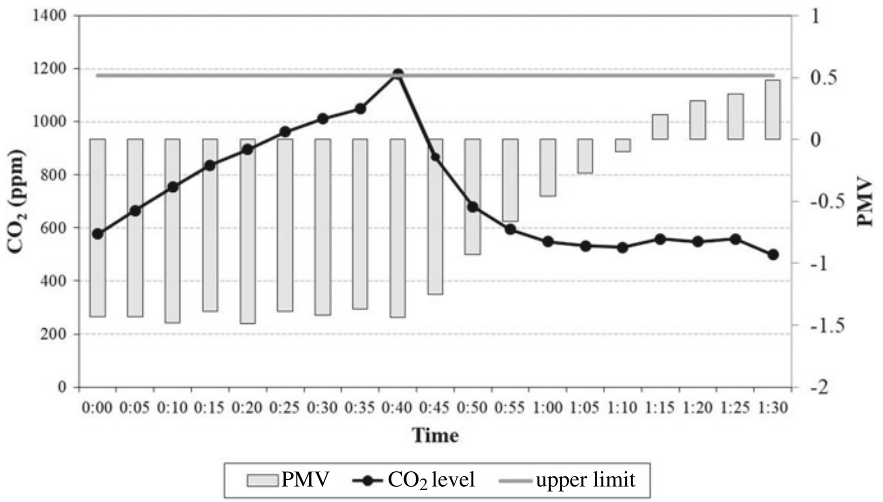

Fig. 5 CO_2 and PMV levels for one occupant, free-running office, with the opening of the window

comfort conditions in the room. From a measured indoor air temperature of 22 °C before opening the window, a final temperature of 27.4 °C was reached by the end of the evaluated period. Even if the window was closed just after the highest CO_2 concentration threshold adopted before as a lower limit, that of 900 ppm (See Fig. 4b), was reached, the increase in indoor temperature would already represent 1.7 °C. In terms of the PMV, to restore initial CO_2 levels from the start of the experiment, after 55 min, the change in PMV would reach 0.77 thermal vote, with a change in PPD of 33% and with an upward move from a Category IV thermal environment to Category III.

4 Discussion

Commercial Air-Handling Units (AHUs) are designed to supply clean air to indoor environments and their energy demand can be linked to the need for providing fresh air at controlled temperatures so as not to interfere with pre-existing cooling and heating processes in the space being conditioned. Heat exchangers or Energy Recovery Systems (ERS) are employed for that purpose, particularly in Zero-Energy Buildings (ZEBs) in cold climates [17]. The widespread use of such technologies is noticed in high-latitude climates in many cases due to restrictive building codes [18].

In Net-Zero Energy Buildings (NZEBs) that are generally very well insulated and airtight, Ng and Payne [19] have noticed that frequently the issue of ventilation in connection with ensuring adequate IAQ is either not dealt with or the design ventilation rate is not properly described. In addition, the consequences of increased energy use due to ventilation for IAQ reasons are seldom discussed.

The energy-saving potential of the use of ERS in supplying fresh air to the indoor environment in high-performance houses was evaluated by computer simulations in several climate zones in the U.S. compared with supply-only ventilation systems in several studies [20–22]. The benefits of employing ERS in air renewal systems are generally low, and in some cases, there can be even an increase in energy demand. Yet, significant energy savings can be expected when using “smart” ERS that use controllers based on time-of-use pricing and outdoor temperature conditions when compared with conventional ERS [23].

In conventional houses in northern Europe, the advantages of ERS coupled with IAQ ventilation can be smaller than in passive houses, as ventilation heat recovery systems perform better with improved airtightness [24].

But what about the Global South with its ever-increasing cooling demand? Climate change projections indicate that the demand for air- conditioning (AC) is expected to dramatically increase in developing countries in connection with population growth, growth in income, and comfort needs [25]. In this context, we may talk about a “cooling gap” that is not equally distributed in the Global South and is the largest in regions with high population density, severe climatic conditions, and low A/C ownership. The International Energy Agency (IEA) estimates an additional two billion residential A/C units in India and China alone by 2050 [26].

The move from naturally ventilated to air-conditioned buildings increases the risk of deleterious impacts on IAQ that can lead to sick-building syndrome (SBS) upsurges in homes [27]. In their study, Wong and Huang [27] compared CO_2 profiles of different A/C units deployed in bedrooms against those of naturally-ventilated bedrooms and found out that regardless of the type of A/C unit being used (including a window unit with an air vent open), CO_2 levels exceeded 1000 ppm during nighttime hours. Even though the observed CO_2 concentration levels do not pose life-threatening or hazardous situations, indoor conditions could generate headaches, nausea, dizziness, and fatigue for sleepers.

In this context, the air renewal system such as the one presented in this paper can be advantageous, by automatically controlling IAQ conditions from a set of predefined CO_2 levels.

Nevertheless, some barriers ought to be investigated in more detail in future research. The preliminary results obtained with the low-cost, air-renewal system (estimated cost of less than $200) show the complexity behind defining an adequate CO_2 threshold used as the trigger to start air renewal vis-à-vis the need to control a limited increase in A/C demand and a rise of indoor temperatures during the process. Other concerns should be with the noise-disturbance factor when fans are in operation so that the air-renewal times should be kept to a minimum.

5 Conclusions

The IAQ control system presented in this paper has a low cost and the results are preliminary at most. Limitations in the operation mode in terms of better defining the lower threshold for disarming the system, the running time of the fans, and the integration of outdoor thermal conditions in the control functions to avoid overheating and excessive increases in A/C demand still need to be circumvented. Even so, the simple automation, the ease of use of the system, and the immediate results in terms of desirable IAQ levels are some of its advantages. In the case of the climate chamber, the automated system will be key to longer-term residency in the indoor office environment and allow studies on occupant behavior, post-occupancy evaluations, and daylighting, among others.

As for the responsive system (in terms of immediate response to sensor readings, in this case, CO_2 levels in the room) discussed in this chapter, it is important to point out that the introduction of responsive elements in architecture is a research avenue per se. Following an approach that is apparently opposite to human-centered design, such systems are advantageous as they will follow an adequate operation following set standards. As opposed to automated, timer-regulated systems, indoor IEQ conditions are expected to increase while energy demand is expected to fall. In the case of the air renewal system tested here, a more human-centered approach would perhaps dictate that the user could open the window at will to improve IAQ conditions. However, this could lead to excess heat gains and, thus, to increased A/C demand. Future research could, therefore, focus on user satisfaction surveys regarding (1) a statically, tightly controlled office environment in terms of air quality, (2) a responsive air renewal system, and (3) total flexibility for the user to operate fans and openings at will. Additionally, the comparison should take into account energy demand and indoor comfort under each operating condition.

References

1. Kjellstrom T, Briggs D, Freyberg C, Lemke B, Otto M, Hyatt O (2016) Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. Annu Rev Public Health 37:97–112. https://doi.org/10.1146/annurev-publhealth-032315-021740
2. Santamouris M (ed) (2019) Cooling energy solutions for buildings and cities. World Scientific
3. Klepeis N, Nelson W, Ott W, Robinson J, Tsang A, Switzer P, Behar J, Hern S, Engelmann W (2001) The national human activity pattern survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Exposure Sci Environ Epidemiol 11:231–252. https://doi.org/10.1038/sj.jea.7500165
4. Al horr Y, Arif M, Katafygiotou M, Mazroei A, Kaushik A, Elsarrag E (2016) Impact of indoor environmental quality on occupant well-being and comfort: a review of the literature. Int J Sustain Built Environ 5:1–11. https://doi.org/10.1016/j.ijsbe.2016.03.006
5. Feige A, Wallbaum H, Janser M, Windlinger L (2013) Impact of sustainable office buildings on occupant's comfort and productivity. J Corp Real Estate 15:7–34. https://doi.org/10.1108/JCRE-01-2013-0004

6. Ai Z, Hashimoto K, Melikov AK (2019) Airborne transmission between room occupants during short- term events: measurement and evaluation. Indoor Air 29:ina.12557. https://doi.org/10.1111/ina.12557
7. Morawska L, Tang JW, Bahnfleth W, Bluyssen PM, Boerstra A, Buonanno G, Cao J, Dancer S, Floto A, Franchimon F, Haworth C, Hogeling J, Isaxon C, Jimenez JL, Kurnitski J, Li Y, Loomans M, Marks G, Marr LC, Mazzarella L, Melikov AK, Miller S, Milton DK, Nazaroff W, Nielsen PV, Noakes C, Peccia J, Querol X, Sekhar C, Seppänen O, ichi Tanabe S, Tellier R, Tham KW, Wargocki P, Wierzbicka A, Yao M (2020) How can airborne transmission of COVID-19 indoors be minimised? Environ Int 142:105832. https://doi.org/10.1016/j.envint.2020.105832
8. ASHRAE (2010) Guideline 10P. Interactions affecting the achievement of acceptable indoor environments, second public review
9. World Health Organization (2017) Evolution of WHO air quality guidelines: past, present and future. Regional Office for Europe
10. Derbez M, Berthineau B, Cochet V, Lethrosne M, Pignon C, Riberon J, Kirchner S (2014) Indoor air quality and comfort in seven newly built, energy-efficient houses in France. Build Environ 72:173–187. https://doi.org/10.1016/j.buildenv.2013.10.017
11. Costa F, Januzzi G, Lamberts R, Letschert V, Melo A, Borges K, Carvalho K, Goes S, Kishinami R, Karali R (2019) Estudo de impacto regulatório: diretrizes gerais e estudo de caso para condicionadores de ar tipo split system no Brasil. Projeto Kigali, Instituto Clima e Sociedade, Rio de Janeiro
12. Miller R, Miller MA (2017) Ar Condicionado e Refrigeração, 2nd edn. LTC, Rio de Janeiro
13. INMET (2021) Normais climatológicas [climate normals]. http://www.inmet.gov.br/portal/index.php?r=clima/normaisclimatologicas. Accessed 01 Jun 2021
14. Trevisan LYI (2019) Concepção, construção e verificação da aplicabilidade de uma câmara bioclimática de baixo custo em estudos de conforto ambiental [Design, construction and verification of the applicability of a low-cost bioclimatic chamber for IEQ studies. PhD thesis, Universidade Tecnológica Federal do Paraná
15. Celligoi G (2020) Influência das janelas no conforto ambiental de uma câmara bioclimática de baixo custo [Influence of windows on ieq in a low-cost bioclimatic chamber. Master's thesis, Universidade Tecnológica Federal do Paraná
16. ASHRAE (2020) ASHRAE standard 55-2020 – thermal environmental conditions for human occupancy
17. Alonso MJ, Liu P, Mathisen HM, Ge G, Simonson C (2015) Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries. Build Environ 84:228–237. https://doi.org/10.1016/j.buildenv.2014.11.014
18. Mardiana-Idayu A, Riffat S (2012) Review on heat recovery technologies for building applications. Renew Sustain Energy Rev 16:1241–1255. https://doi.org/10.1016/j.rser.2011.09.026
19. Ng LC, Payne WV (2016) Energy use consequences of ventilating a net-zero energy house. Appl Therm Eng 96:151–160. https://doi.org/10.1016/j.applthermaleng.2015.10.100
20. Lstiburek JW, Petit B, Rudd A, Sherman MH, Walker IS (2007) Whole house ventilation system options - phase 1 simulation study. https://www.buildingscience.com/documents/reports/rr-0701-whole-house-ventilation-systems-options/view
21. Sherman MH, Walker IS (2007) Energy impact of residential ventilation norms in the united states. https://escholarship.org/content/qt84s4t2n5
22. Rudd A, Henderson H, Bergey D, Shirey D (2010) ASHRAE 1449-RP: energy efficiency and cost assessment of humidity control options for residential buildings. Tech. rep., Atlanta, USA
23. Turner W, Walker I (2012) Advanced controls and sustainable systems for residential ventilation (LBNL-5968E). Tech. rep., Berkeley, CA, USA
24. Dodoo A, Gustavsson L, Sathre R (2011) Primary energy implications of ventilation heat recovery in residential buildings. Energy Build 43:1566–1572. https://doi.org/10.1016/j.enbuild.2011.02.019

25. Mastrucci A, Byers E, Pachauri S, Rao ND (2019) Improving the SDG energy poverty targets: residential cooling needs in the Global South. Energy Build 186:405–415
26. International Energy Agency (IEA) (2018) The future of cooling. https://www.iea.org/
27. Wong NH, Huang B (2004) Comparative study of the indoor air quality of naturally ventilated and air-conditioned bedrooms of residential buildings in Singapore. Build Environ 39:1115–1123. https://doi.org/10.1016/j.buildenv.2004.01.024

Visual Comfort and Daylight

New Dynamic Daylight Metric Based on the Local Context and the Perception of People in the Tropics

Lucas Arango-Díaz and María Beatriz Piderit-Moreno

Abstract One of the requirements to favor visual comfort in indoor environments, as well as to optimize energy efficiency, refers to guaranteeing sufficient daylight. Currently, some standards determine sufficient light levels to perform reading-writing tasks. These standards, which are based mainly on criteria generated in places located above the Tropic of Cancer, prioritize productivity over people's perception. Even though several authors have highlighted the importance of considering people's perceptions in determining sufficient daylight illuminances, there is no consensus on appropriate daylight levels to perform reading-writing tasks. In addition, although there are dynamic metrics for the analysis of daylight performance, the most popular ones propose generic reference illuminances as sufficient illuminances but do not consider the perception of people. This chapter reflects on the need to use dynamic daylight metrics that consider illuminances that people perceive as sufficient. A new dynamic metric, daDA, is presented for application in the Tropics. This metric considers the variability of the proportion of people in the Tropics who perceive a certain daylight level as sufficient depending on the availability of exterior daylight so that this is considered a contribution to removing the barriers to environmental comfort in the Tropics.

Keywords Daylight · Dynamic metric · Adaptability · Tropics · Luminous perception

L. Arango-Díaz (✉)
Facultad de Artes Integradas, Universidad de San Buenaventura, Medellín, Colombia
e-mail: lucas.arango@usbmed.edu.co

M. B. Piderit-Moreno
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mpiderit@ubiobio.cl

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1 Introduction

Daylight has taken on a dimension within sustainable architecture and developments in research regarding well-being and health associated with the integration of daylight, which goes beyond a game of lights and shades to exalt a space. This new dimension allows addressing its integration and effects from different approaches: (i) the search for sufficient lighting levels on the work plane to favor the performance of visual tasks; (ii) the power efficiency from the integration of daylight and artificial light systems; (iii) the control of glare probability to optimize visual comfort; (iv) the control of solar accessibility to avoid annoying brightness or excessive illuminance; (v) the circadian lighting design to favor people's health; and, (vi) the design of daylight effects or ambiances to generate or transmit emotions, among others.

From these approaches, it could be said, from a scientific point of view, that the ones related to sufficient illuminance on the work plane have advanced more than others because they have been more widely addressed and applied in recent decades. This advantage in progress, perhaps, is caused by the noticeable interest of humanity, for decades, to reduce the use of artificial light to favor power efficiency and increase labor or academic productivity based on optimizing visual comfort.

Under this approach of sufficient illuminance, although questions about the incorporation of daylight in architecture have mainly been focused on guaranteeing the necessary, sufficient, or proper lighting levels to perform given visual tasks, the responses have demonstrated two particularities.

Firstly, there is evidence of mixing the recommendations or guidelines for natural and artificially lit environments. Although currently, documents such as *CEN/TC 169/WG 11—Daylight* [1] recommend illuminances for naturally lit spaces, the document, *Lighting of Indoor Workplaces* [2], presents recommended illuminances for several types of visual tasks for artificially illuminated environments, serving as a guide in many contexts to determine the recommended illuminances of naturally lit spaces.

Secondly, despite efforts from Blackwell [3] and beyond determining the lighting levels that guarantee optimal performance in visual tasks, Boyce [4] has insinuated that, on the one hand, sufficient illuminance has been determined throughout history for reasons not necessarily related to comfort or visual performance but, even, for political or economic reasons of each country, the reason why it is not possible to arrive at a consensus on those lighting levels. On the other hand, it has outlined the differences between the illuminances required to improve visual performance and those illuminances preferred by people.

Despite these two situations, several authors have reported different lighting levels preferred or perceived as sufficient for reading and writing activities [5–12] and these differences have been explained from different points of view: physical or psychological states of people [13], preferences and expectations of people [11, 14], age of people [15], cultural factors specific to each location [16], visual adaptability of people [11, 17], indoor temperature [18], outdoor weather conditions [8, 11, 19] or the adaptation of people to external daylighting availability [20].

Considering all these views, it seems unlikely that a standard daylighting level is perceived as sufficient by the globe's entire population. Despite this, daylighting levels of 300 or 500 lux have now been adopted for typical reading and writing tasks in offices or educational spaces [21–24]. It is important to mention that these daylighting levels have been proposed by researchers in places above the Tropic of Cancer, therefore, their applicability may be questionable in other contexts such as the South of the planet or the intertropical strip. For this strip of the planet, beyond the scarcity of daylight studies, as expressed by Mangkuto et al. [25] and Kong and Jackubiec [8], climatic conditions, as well as daylight availability throughout the year, markedly differ from conditions at latitudes above the Tropic of Cancer, which could lead to greater differences in the perception of daylight sufficiency.

1.1 Visual Adaptability

Visual adaptability has been identified as one of the reasons for explaining differences in people's perception of daylight sufficiency. In the area of daylighting and visual comfort, visual adaptability has been addressed from several perspectives. On one hand, Jakubiec and Reinhart [26, 27] proposed a model of adaptive visual comfort called the Adaptive zone, which considers the possibility that people, reacting to a certain uncomfortable visual stimulus, direct their look elsewhere. Arguably, the authors consider adaptability as the possibility of moving the body and not necessarily from the mechanisms of the visual system. On the other hand, for several years, visual adaptability has been addressed in research on daylighting and visual comfort from the physiological point of view: it has been accepted that (i) the variation of the pupil diameter depends on the amount of light that falls upon the eyes; (ii) the transient adaptation based on the decomposition of photoreceptor pigments on the eyes depends on the changes in the amount of light; and, (iii) the adaptation of ganglion cell response levels according to the mean illuminance of the retina, so that the visual sensitivity is modified to discriminate targets in the visual field, are visual system adjustment mechanisms to adapt to the lighting conditions of the visual environment. It is evident that all these mechanisms influence the way a certain visual stimulus or a certain illuminance is perceived.

Now, beyond all these visual mechanisms contributing to adjusting our visual sensitivity in a relatively short time, adaptability has recently also been considered as the psychophysiological ability to adapt to environmental conditions in the long term and not immediately [20]. This means that if a person has been accustomed throughout his life to certain lighting conditions, he will end up adjusting his assessment of light sufficiency to his experience.

This long-term visual adaptability could resemble the logic of the adaptive thermal comfort model developed by Nicol and Humphreys [28]. In this model, the range of operating temperatures considered comfortable varies depending on the outdoor temperature that people in a certain area are accustomed to. Likewise, it could be considered that the range of daylighting levels considered sufficient or preferred by people could vary depending on outdoor daylight availability. This is equivalent to proposing that, in places with lower outdoor daylight availability, illuminances considered low in other contexts could be appreciated and considered sufficient. This is also known as visual expectation, which means that people judge the lighting level at a particular time according to what they would expect to find.

Given this, considering a lighting level generated in a specific place as a global standard is not very strategic or is simply just naïve. The differences between places located in the Tropics and those located above the Tropic of Cancer would not be minor. The Tropics are characterized by relative annual stability in climatic conditions and daylight availability, while in other regions of the planet, the seasons also mark differences in outdoor daylight availability.

To summarize, considering the long-term visual adaptability of people to determine sufficient daylighting levels, represents a commitment to eliminate barriers in the study of visual comfort in the Tropics, based on the inclusion of human factors and sociodemographic differences in studies and research on daylight.

1.2 Dynamic Daylight Performance Metrics: Calibration According to Visual Perception

Dynamic simulations, or Climate Based Daylight Modeling—CBDM, have been positioned above static simulations to determine the daylighting performance of indoor environments since the beginning of this century [29]. Its popularity is due to the ease with which daylighting performance of an environment throughout the year is valued from the point of view of daylighting sufficiency. In general terms, with these metrics, it is possible to determine the percentage of time that a point in space has a daylighting level or the percentage of space that has a certain daylighting level during a percentage of time per year.

Of these daylighting metrics, the most popular are: Daylight Autonomy—DA [30], Useful Daylight Illuminance—UDI [31–33], Continuous Daylight Autonomy—Dacon [34], Spatial Daylight Autonomy—SDA together with Annual Sunlight Exposure—ASE [21, 22], and SUDI—Spatial Useful Daylight illuminance [35]. However, despite their popularity, the need to consider people's perception in calibrating these metrics has constantly been sought, ever since Reinhart and Weissman [35]. Despite the previous statement, there is no consensus to date on which metric best describes people's perception of daylight sufficiency [11, 36]

This lack of consensus is generated, in part, by the inability to agree on the illuminances or daylighting ranges perceived as sufficient, as described above, and, in part, by the time specified in the spatial metrics, SUDI and SDA. In these, the specification of 50% of the time per year is common. According to Darula [37], this time percentage is used to ensure daylight sufficiency at least during half the year, in summer, when there is more availability of outdoor daylight. In view of this, it is evident that the applicability of this time percentage in intertropical locations should be reconsidered due to the relatively stable availability throughout the year, unlike localities above the Tropic of Cancer.

With this panorama, it is necessary to advance in the contextualization of metrics or to formulate a dynamic metric for the Tropics, that, on one hand, considers the daylighting levels perceived as sufficient by the population according to the so-called long-term adaptability and that, on the other, can modify the percentages of time used per year in latitudes below the Tropic of Cancer. It is estimated that this metric could contribute to the study of visual comfort in this area of the planet considering its particularities.

2 Method for Developing a New Dynamic Daylight Metric Associated with Outdoor Daylight Availability

Since there is a need to consider a dynamic daylight metric, that in the definition of the reference illuminances considers the variability of daylighting levels perceived as sufficient, in each geographical location, depending on outdoor light availability, based on the result of the doctoral thesis of Arango-Díaz [20], two dynamic daylight metrics for the tropics were formulated: Daylight Autonomy associated with outdoor daylight availability—daDA, and Spatial Daylight Autonomy associated with outdoor daylight availability—sdaDA. To formulate these metrics, logistic regressions were made from survey data and measurements in university classrooms located in four Colombian cities with different climatic conditions: Medellín (lat. 6°12′08″N; long.75°35′12″W; alt. 1491 mamsl), Cali (lat.3°22′32″N; long. 76°32′00″W; alt. 982 mamsl), Armenia (lat. 4°27′07″N; long. 75°46′00″W; alt. 1214 mamsl) and Manizales (lat. 5°01′44″N; long. 75°28′08″W; alt. 2078 mamsl).

The daDA metric is like DA, which means that it refers to the percentage of time per year that the daylighting level is equal to or greater than a reference illuminance. The difference lies in the way the reference illuminance is determined. Instead of estimating 300 or 500 lx, typical for reading and writing activities, this new metric considers that the illuminance perceived as sufficient by people varies depending on outdoor daylight availability. Therefore, given the differences in outdoor daylight availability between different geographical locations, the reference illuminances are specific to each place.

For this reason, when determining reference illuminances for each geographical location, two determining variables were coined: population percentage and percentage of time per year: In the process of formulating the metrics, [20] proposed valuing a given daylighting level in a geographical location according to the population percentage that considers it “dark” or “not dark”. For example, in a specific geographical location, 60% of the population may find that 300 lx is “not dark” and 40% consider it “dark”, while in another location it may be the other way around. This proposal helps to understand from another perspective the correct use of daylight based on the question: what daylighting level guarantees that more people perceive the environment as "not dark"?

When answering this question, it was discovered that in each geographical locality, there are variations in how a given daylighting level is perceived, according to the outdoor daylight availability at a specific time. This is equivalent to saying that, for example, 60% of the population that perceived a 300 lx illuminance as "not dark", may increase or decrease at other times of the year or hours of the day depending on the outdoor daylight availability. Facing this complexity, the reference to daylighting levels were determined according to the population percentage that perceived a given lighting level as "not dark" during a given percentage of time per year. Therefore, just as the expression DA [500 lx] refers to the use of the Daylight Autonomy metric with a reference illuminance of 500 lx, for example, the expression daDA [80%, 50%], refers to the implementation of the new metric with a specified reference illuminance to ensure that 80% of people perceive the daylighting level as non-dark during 50% of the time per year. Therefore, this new daDA metric is defined as the percentage of time per year that a point in an indoor environment equals or exceeds a reference daylighting level generated from the perception of daylight sufficiency by a percentage of people during a period per year. In the process of formulating the metric, it was considered convenient to find the reference illuminances according to the perception of the daylighting level as "not dark" for 80% of the population 50% of the time per year.

On the other hand, just as the sDA refers to the percentage of space that equals or exceeds a reference daylighting level during a certain percentage of the time, the sdaDA refers to the percentage of space that equals or exceeds, during a certain percentage of time per year, the reference illuminance generated based on the percentage of people who perceive the daylighting level as "not dark" during a certain period per year. Thus, sdaDA [60%, 75%/50%] refers to the percentage of space that for at least 50% of the time per year exceeds the specified reference daylighting level to ensure that 60% of people perceive the daylighting level as "not dark" during 75% of the time per year.

3 Results

After applying the method described to identify the reference daylighting level from the climatic file available for the city of Medellín [38] it was found that 691 lx is the reference daylighting level ensuring that 80% of that population perceives the daylighting level as "not dark" at least 50% of the time per year, i.e., daDa (80%, 50%) = 691 lux

Based on the definition of this reference daylighting level, computational daylight simulations were carried out in a hypothetical classroom with dimensions and materials typically used in the city of Medellin [20]. In the simulations, the submitted metric, daDA, and the DA metric were used. The simulation results are shown in Table 1 and, show great differences in the valuation of an indoor space when

Table 1 Result of the comparison of computer-simulated daylight in a hypothetical classroom

Daylight Metric	Reference illuminance	Results (%)
DA	300 lx	92.7
DA	500 lx	81.5
daDA	80%, 50%	67.0
sDA	300 lx/50%	100.0
sDA	500 lx/50%	99.3
sdaDA	80%, 50%/50%	72.1

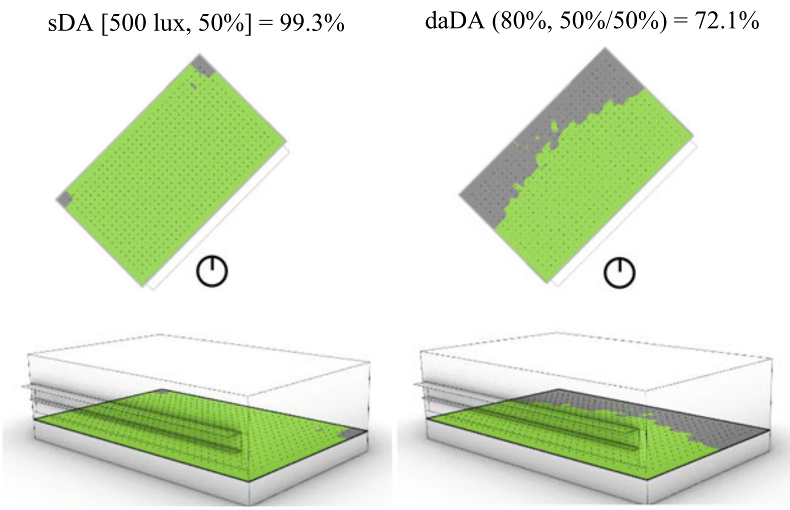

Fig. 1 Graphical comparison of results applying two metrics: sDA [500 lx, 50%] and daDA (80%, 50%/50%)

considering the perception of people and their adaptability to outdoor daylight availability compared to simulations with typical reference levels. These differences are not less than 14.5% between DA and daDA and 27.2% between sDA and SdaDA, that is, obviously the valuation of a given space from the computational simulation can significantly vary depending on the metric used and the daylighting levels adopted.

To complement the results, Fig. 1 graphically compares the results of the sDA [500 lx, 50%] and daDA (80%, 50%/50%) metrics. It is evident that the back of the room does not meet the minimum levels recommended for 80% of the population to perceive the daylighting level as sufficient for 50% of the time per year.

4 Discussion

This chapter discusses the importance of considering a dynamic daylight metric for the tropics with reference daylighting levels specified according to outdoor daylight availability and its influence on the variability of people's perception of daylight sufficiency. This discussion is relevant because it represents a significant step toward the study of visual comfort in the tropical context based on its particularities.

During the research, the impossibility of guaranteeing that 100% of people perceive a certain daylight level as sufficient was identified and, it was proposed to assess this daylighting level according to the population percentage that will perceive it as "not dark".

Additionally, the influence of long-term visual adaptability on people's perception was recognized and, this adaptability was related to outdoor daylight availability, as well as the adaptive thermal comfort model, relating adaptation to the average outdoor temperature. After recognizing the influence of the relationship between outdoor daylight availability at a given time and, average annual outdoor daylight availability on people's perception, it was also proposed to consider the percentage of time per year in which a population percentage would perceive a given daylighting level as "not dark". With these variables, as explained, the reference illuminances are estimated in the new daDA metric, which considers the perception of people in the intertropical range.

It is noticed that future approaches should consider not a reference value but rather a reference range to also control the perception of excessive illuminances. Additionally, for the application of the sdaDA metric, it is recommended to reconsider the specification of 50% of the time per year to run the computational simulation, since this is not consistent with the stability of outdoor daylight availability throughout the year in the Tropics compared to places with considerable climatic variations. Despite this, it is predicted that this metric could even be explored in geographical locations outside the intertropical range based on modifications to the reference illuminance, for example, in winter and summer.

5 Conclusions

This chapter submitted a new metric to calculate daylight, contributing to removing barriers for the effective study of visual comfort in places other than those located above the Tropic of Cancer.

This new metric represents a commitment to include the sociodemographic particularities of the intertropical strip in the assessment of daylighting performance of indoor environments and recognizes that commonly used metrics respond to the needs of another context. The application of the metric showed great differences from the application of typical daylight metrics, which are included in certification systems or minimum standards for visual comfort. It is estimated that the use of this new metric would contribute to a more accurate assessment of daylighting performance in indoor spaces located in the tropics and would be better aligned with the need to include people's perceptions in daylight analysis.

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References

1. CEN/TC 169 (2017) CEN/TC 169/WG 11 - Daylight
2. ISO/CIE (2005) ISO 8995:2002 CIE S 008/E-2001 Lighting of indoor work places. Technical corrigendum 1. Switzerland
3. Blackwell H (1959) The new quantitative method for establishing illumination levels for various visual tasks. In: Building illumination. The effect of new lighting levels, COUNCIL NAOS-NR, Cleveland, Ohio, USA
4. Boyce P (1996) Illuminance selection based on visual performance and other fairy stories. J Illum Eng Soc 25:41–49. https://doi.org/10.1080/00994480.1996.10748146
5. Arango-Díaz L, Hernandez YA, Gallego HW, Piderit-Moreno MB (2022) Differences in perception of daylighting sufficiency related to the geographical location in the context of university classrooms. J Green Build 17:181–209. https://doi.org/10.3992/jgb.17.2.181
6. Baker N (2000) We are all outdoor animals. In: Architecture city environment, proceedings of PLEA 2000, pp 553–555
7. IESNA (2000) The IESNA lighting handbook. New York, USA
8. Kong Z, Jackubiec J (2019) Instantaneous and long-term lighting design metrics for higher education buildings in a tropical climate. In: Proceedings of building simulation 2019: 16th conference of IBPSA, pp 1083–1090. https://doi.org/10.26868/25222708.2019.210728
9. Nezamdoost A, Wymelenberg KVD (2017) A daylighting field study using human feedback and simulations to test and improve recently adopted annual daylight performance metrics. J Build Perform Simul 10:471–483. https://doi.org/10.1080/19401493.2017.1334090
10. Roche L (2002) Summertime performance of an automated lighting and blinds control system. Lighting Res Technol 34:11–25. https://doi.org/10.1191/1365782802li026oa
11. Shafavi NS, Tahsildoost M, Zomorodian ZS (2020) Investigation of illuminance-based metrics in predicting occupants - visual comfort (case study: architecture design studios). Solar Energy 197:111–125. https://doi.org/10.1016/j.solener.2019.12.051
12. Vine E, Lee E, Clear R, DiBartolomeo D, Selkowitz S (1998) Office worker response to an automated venetian blind and electric lighting system: a pilot study. Energy Build 28:205–218. https://doi.org/10.1016/S0378-7788(98)00023-1
13. Pereira FO, Fonseca RW, Moraes LN (2012) Iluminação natural : Comparação entre percepção visual e medidas dinâmicas de avaliação. In: XII ENCAC - Encontro Nacional de Conforto no Ambiente Construído, Juiz de Fora, Brazil, pp 1–9
14. Maier J, Zierke O, Hoermann HJ, Windemut I (2017) Subjectivity of lighting perception and comfort: the role of preferences and expectations. Environ Behav 49:1105–1127. https://doi.org/10.1177/0013916516678905
15. van Bommel W, van den Beld G (2004) Lighting for work: a review of visual and biological effects. Lighting Res Technol 36:255–266. https://doi.org/10.1191/1365782804li122oa
16. Pierson C, Bodart M, Wienold J, Piderit M (2018) Discomfort glare from daylighting: influence of culture on discomfort glare perception. In: Proceedings of the conference on "Smarter lighting for better life" at the CIE midterm meeting 2017 23–25 Oct 2017, JEJU, Republic of Korea, International commission on illumination, CIE, pp 83–93. https://doi.org/10.25039/x44.2017.OP12

17. Alonso C, López J, Coch H, Serra R (2012) Visual adaptability in architecture: a physical and psychological approach. In: PLEA2012 - 28th conference, opportunities, limits & needs towards an environmentally responsible architecture, Lima, Perú
18. Chinazzo G, Wienold J, Andersen M (2021) Effect of indoor temperature and glazing with saturated color on visual perception of daylight. LEUKOS 17:183–204. https://doi.org/10.1080/15502724.2020.1726182
19. Bellia L, Fragliasso F, Stefanizzi E (2017) Daylit offices: a comparison between measured parameters assessing light quality and users' opinions. Build Environ 113:92–106. https://doi.org/10.1016/j.buildenv.2016.08.014
20. Arango-Díaz L (2021) Nueva métrica dinâmica de luz natural: relación entre la percepción de suficiencia lumínica y la disponibilidad lumínica exterior. PhD thesis, Universidad del Bío-Bío, Concepción, Chile. https://doi.org/10.6084/m9.figshare.21277719.v1
21. Heschong Mahone Group Inc (2012) Daylight metrics. Final project report, California, USA
22. IESNA - The Daylight Metric Committee (2012) IES LM-83-12. Approved method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). New York, USA
23. Mardaljevic J, Christoffersen J (2017) 'Climate connectivity' in the daylight factor basis of building standards. Build Environ 113:200–209. https://doi.org/10.1016/j.buildenv.2016.08.009
24. Saxena M, Heschong L, Van Den Wymelenberg K, Wayland S, Analytics IP (2010) 61 flavors of daylight. In: Proceedings of the ACEEE summer study 2010 on energy efficiency in buildings 2010, American council for an energy-efficient economy, Asilomar, CA, USA, pp 3-348–3-361
25. Mangkuto RA, Asri AD, Rohmah M, Soelami FN, Soegijanto R (2016) Revisiting the national standard of daylighting in Indonesia: a study of five daylit spaces in Bandung. Solar Energy 126:276–290. https://doi.org/10.1016/j.solener.2016.01.022
26. Jakubiec J, Reinhart C (2011) The 'adaptive zone' – a concept for assessing discomfort glare throughout daylit spaces. In: Proceedings of building simulation 2011: 12th conference of international building performance simulation association, vol 44, pp 2178–2185
27. Jakubiec J, Reinhart C (2012) The 'adaptive zone' - a concept for assessing discomfort glare throughout daylit spaces. Lighting Res Technol 44:149–170. https://doi.org/10.1177/1477153511420097
28. Nicol J, Humphreys M (2002) Adaptive thermal comfort and sustainable thermal standards for buildings. Energy Build 34:563–572. https://doi.org/10.1016/S0378-7788(02)00006-3
29. Reinhart CF, Wienold J (2011) The daylighting dashboard - a simulation-based design analysis for daylit spaces. Build Environ 46:386–396. https://doi.org/10.1016/j.buildenv.2010.08.001
30. Reinhart CF, Walkenhorst O (2001) Validation of dynamic radiance-based daylight simulations for a test office with external blinds. Energy Build 33:683–697. https://doi.org/10.1016/S0378-7788(01)00058-5
31. Mardaljevic J, Andersen M, Roy N, Christoffersen J (2012) Daylighting metrics: is there a relation between useful daylight illuminance and daylight glare probability? In: First building simulation and optimization conference, IBPSA England, pp 189–196
32. Nabil A, Mardaljevic J (2005) Useful daylight illuminance: a new paradigm for assessing daylight in buildings. Lighting Res Technol 37:41–57. https://doi.org/10.1191/1365782805li128oa
33. Nabil A, Mardaljevic J (2006) Useful daylight illuminances: a replacement for daylight factors. Energy Build 38:905–913. https://doi.org/10.1016/j.enbuild.2006.03.013
34. Reinhart CF, Mardaljevic J, Rogers Z (2006) Dynamic daylight performance metrics for sustainable building design. LEUKOS 3:7–31. https://doi.org/10.1582/LEUKOS.2006.03.01.001
35. Reinhart CF, Weissman DA (2012) The daylit area - correlating architectural student assessments with current and emerging daylight availability metrics. Build Environ 50:155–164. https://doi.org/10.1016/j.buildenv.2011.10.024
36. Nezamdoost A, Wymelenberg KGVD (2017) Revisiting the daylit area: examining daylighting performance using subjective human evaluations and simulated compliance with the LEED version 4 daylight credit. LEUKOS 13:107–123. https://doi.org/10.1080/15502724.2016.1250011
37. Darula S (2018) Review of the current state and future development in standardizing natural lighting in interiors. Light Eng 26:5–26
38. Meteonorm (2020) Meteonorm. https://meteonorm.com/

The Daylit Area and the Regional Aspect of Daylight Sufficiency Metrics

Raphaela Walger da Fonseca, Ethieny Rossato Kramer, Suelem Schier de França, and Fernando Oscar Ruttkay Pereira

Abstract The effectiveness of evaluating daylighting is dependent on the metrics employed to measure the building user satisfaction. Currently, the most used daylighting metrics, the spatial daylight autonomy (sDA) and the annual sunlight exposure (ASE) recommended by the Illuminating Engineering Society (IES LM 83-12) are based on the preferences of building users from the Global North (37°–48°N), although they are adopted worldwide. The following question thus arises: is it appropriate to adopt the same criteria for places with different cultures and climates? Seeking to answer this question, field research was carried out in Florianópolis, Brazil (27°S). A protocol like that which forms the basis of IES LM 83-12 was applied to four building environments at the Federal University of Santa Catarina. Interviews (132) were conducted, accompanied by simultaneous daylight measurements and computer simulation. The results were evaluated based on the sociocultural profile of the respondents. It was noted that the limits of sDA and ASE are more restrictive than the interviewees' perception. However, the difference in the results for each building showed that this contrast is more related to the effects of architectonic solutions on the visual perception of individuals than sociocultural and climatic aspects.

Keywords Daylight metrics · Regional aspect · User preferences

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R. W. da Fonseca (✉) · E. R. Kramer · S. S. de França · F. O. R. Pereira
Department of Architecture and Urbanism/CTC, Federal University of Santa Catarina, Florianopolis, Brazil
e-mail: raphaela.walger@ufsc.br

E. R. Kramer
e-mail: ethieny.rossato@grad.ufsc.br

S. S. de França
e-mail: suelem.franca@posgrad.ufsc.br

F. O. R. Pereira
e-mail: ruttkay.pereira@ufsc.br

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1 Introduction

Establishing representative metrics of the daylit area is connected to user perception. Thus, several factors, besides the actual amount of daylight, affect the determination of this area, including biological, physiological, and psychological aspects [1], which, in turn, can be influenced by local factors, such as the sociocultural reality of the individual [2]. However, the metrics proposed to define the daylit area, as well as the respective performance criteria, currently applied worldwide, were based on field research carried out in the United States [3], between latitudes 37–48°N, where cultural, socioeconomic, and climatic characteristics diverge from those found in the Global South. Consequently, it is important to verify the relevance of these indexes in places around the globe where the reality differs considerably from where the metrics originated.

The effectiveness of a performance metric is dependent on coherence between its conceptual definition, the basis for determining its criteria, and the context of its application. Concerning the conception of metrics aimed at the evaluation of naturally lit places, this chapter deals with those established in the recommendations of the Illuminating Engineering Society (IES) regarding the spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) in LM 83-12 [4], which deals with sufficiency of daylight illuminance and the potential risk of excessive sunlight penetration. The $sDA_{300/50\%}$ value is the percentage of the area which exceeds the minimum illuminance value of 300 lx, for 50% of the building occupation time over the period of a year, set from 08:00 to 18:00. The ASE1000/250h represents the percentage of the environment area which is exposed to illuminance above 1000 lx, referring only to direct solar radiation, for more than 250 h per year and is evaluated together with the $sDA_{300/50\%}$. As for the designation of criteria, the value of $sDA_{300/50\%}$ should exceed 75% for a favorable performance or 55% for a nominally accepted performance, whereas the exterior windows shall be modeled with interior blinds or shades aiming at blocking the direct sunlight, considering the $ASE_{1000/250h}$ should not exceed 2% of the analysis points of each window group adopted for the climate-based daylight modeling (CBDM) simulation. These targets were based on the preference of users of 61 offices, classrooms, and other environments, such as libraries and lobbies, located between the latitudes mentioned above [3], that is, a narrow context considering the wide application of the recommendations around the world.

As previously mentioned, user satisfaction with a daylit environment, a parameter employed to define the criteria of a metric, may be influenced by the factor location and its derivatives [5]. In this respect, the branch of environmental psychology that deals with the effects of the environment on behavior offers theoretical support for this consideration, defending environmental perception as the fruit of personal experience, based on the life experiences of an individual and, consequently, their culture and social conditions [6]. From this perspective, researchers in the area of environmental comfort recognize the influence of psychological factors, together with adaptation, acclimatization, and expectation, as elements in the adjustment of the criteria of a metric due to location and the climatic or socioeconomic context where it will be applied [7–9]. Such studies are more abundant in the area of thermal comfort, although they can also be found in the area of daylighting.

Concerning luminous environments, there have been several attempts to characterize user perception of the daylit area, considering different factors, but the location (socioenvironmental context) was not a core factor in these studies. Many authors have applied this approach to visual comfort, particularly when comparing the tolerance to the glare of subjects originating from different socioenvironmental settings. In this regard, Pierson et al. [10] reviewed 11 studies, the majority of which found evidence of the influence of this factor on user tolerance. However, in two cases, and their results, the influence of location was not observed. Most of these studies were conducted in locations above the Tropic of Cancer, in North America, Europe, and Asia, an exception being the work of Pierson et al. [10], where the inclusion of Chile brings a Latin American reality to this panorama.

As in the case of visual comfort, studies that address the perception of daylit areas have mainly been made in the northern hemisphere above a latitude of 23.5°. This is highlighted by the fact that of the 17 host cities in studies where the methodology was similar to that upon which LM 83-12 is based and/or involved the drawing of the daylit area by the interviewees, only two cities are located below the Tropic of Cancer (João Pessoa and Florianopolis), both in Brazil [1, 3, 11–15]. The former lies at the latitude of 7.2°S and the latter at 27.6°S. In the study that included both of these cities, 13 environments in 11 schools of architecture located in 10 cities were evaluated. Of these, only the results for the two Brazilian cities, along with Los Angeles and Miami in the US, showed an underestimation of fully daylit areas (criterium DA300/50%) by the users in comparison to the area obtained through simulation [1]. Although the two aforementioned US cities are located above the Tropic of Cancer, they are both significantly influenced by Latin American culture [16] and they are coastal, as are the Brazilian cities. These characteristics suggest that the inhabitants of these places would have a higher expectation regarding the daylit environment, influenced by the lifestyle observed in these cities, where outdoor activities are encouraged due to the coastal location and agreeable weather and/or sunny days are frequent during the year.

The inherent subjectivity of the elements that affect environmental perception makes the definition of metrics for building performance a challenging theme since, to be useful, they must faithfully express user preferences. Since human beings are at the core of the evaluation and the location directly influences their perception of space, the metrics need to represent the preferences of the population where they are employed. However, the indexes of LM 83-12 are applied worldwide through standards and certifications [17–19] based on the opinions of a specific population, whose sociocultural and climatic reality differs from those found in the southern hemisphere, where most nations are developing countries located in warm climates. Therefore, to promote improvements in the environmental comfort of buildings located in these regions, the perception of the local populations needs to be represented, to evaluate the need for adjustments to the metrics, as occurs with adaptative thermal comfort [8, 9].

In this context, the application of a research protocol, similar to that which originated the LM 83-12, to four environments located in Florianopolis, Santa Catarina, Brazil, is described herein. Two rooms chosen were in the same building where the room used by Reinhart et al. [1] is located, one of them similar in terms of architectural characteristics and use, and two rooms were located in another building on the same university campus. The aim was to verify whether previous results could be repeated or if new evidence would appear.

2 The Investigation Method

Analogously to the process that LM 83-12 [4], described by Heschong Mahone Group [3], originated, this study included a field survey for data collection followed by climate-based daylight metrics simulations. The results obtained from these two stages were then compared. However, after the consolidation of the LM 83-12 [4], the analysis of the metrics was focused only on the criteria of the norm and the evaluation of the differences of perception, taking into account the factor location.

The data collection encompassed the definition of the study sample, the site selection, and a survey involving experts and occupants. The survey was carried out in November and December within the course subject “Daylighting in the built environment” (PósARQ 1307), offered by the Graduate Program in Architecture and Urbanism (PósARQ) at the Federal University of Santa Catarina (Universidade Federal de Santa Catarina—UFSC).

The group of experts comprised seven master’s degree and doctoral students, familiar with the theme and having previously attended classes on the method employed by Heschong Mahone Group [3] and the content of LM 83-12 [4], with special attention given to the topics presented in the “Discussion” charts. The multidisciplinary group included five architects, a mechanical engineer, and a psychologist and it was subdivided into three groups for the evaluation of the four environments: two offices and two classrooms. The computational stage adhered to that described in LM 83-12 [4].

2.1 Study Sample and Site Selection

The two classroom environments, identified as Ateliê 301 and LabMicro, are located in the Department of Architecture and Urbanism and the two office environments were the research laboratories named Gtec and Gestcon, located in Building B of the Department of Civil Engineering, all situated on the main campus of the Federal University of Santa Catarina (UFSC).

The buildings are less than 500 m from each other, but show divergences regarding the solar position, characteristics of the openings, solar protection elements, optical properties of surfaces, and architectural features, as summarized in Fig. 1.

	ATELIÊ 301	LABMICRO	GTEC	GESTCON
Story	3rd floor	Mezzanine of 3rd floor	2nd floor	2nd floor
Area	60 m²	40,60 m²	33,44 m²	45,22 m²
Openings	Southwest: 2 x (2.2m x 2.6m) Northwest: 2 x (11m x 2.6m) Note: Mezzanine with zenithal lighting.	North: 3 x (1.1m x 1.1m) Zenith: 1 x (4.7m x 1m) Note: horizontal brise-soleil to the south - light shelf.	Southeast: 3 x (1.9m x 1.1m) 3 x (1.9m x 0.6m)	Northwest: 4 x (1.9m x 1.1m) 4 x (1.9m x 0.6m)
Solar protection / obstruction	Concrete brise-soleil on the northwest and southeast openings	Concrete brise-soleil and film on the north openings	Concrete brise-soleil	Concrete brise-soleil
	Plant mass with high canopies on the northwest openings	-	Plant mass and building next to openings	Plant mass next to openings

Fig. 1 General characteristics of the environments selected for the study

The survey of the space conditions was based on the survey forms given in Appendix A of Heschong Mahone Group [3], A-3 Building Survey and A-4 Space Survey in addition to the protocol of daylight measurement established by the Brazilian standard ABNT- NBR 15215-4 [20]. The questionnaires adopted were based on the survey forms of Appendix A given in Heshong [3], that is, A-1 Occupant Survey and A-2 Expert Survey. The first contains 25 questions that aim to characterize the "point-in-time" conditions of daylighting, according to the user perception and personal satisfaction with that space (See Table 1).

The second questionnaire contains 54 questions approaching daylighting from a broader prospect, seeking to identify the annual performance. The original questionnaires of Heschong [3] were modified as follows:

- A question about the reason for the operation of the blinds was included (6);
- In questions 9 and 10, a request to explain the answer given was added;
- Question 19 was removed since the users considered it the same as question 20;
- A question about the user's motivation to work in that environment was included;
- The optional descriptive questions were removed, except question 25 of Heschong [3], where question 24 was adapted to be answered on an agree-disagree scale;
- The scale with nine options from "totally disagree" to "totally agree", including the option "n/a" (also represented by numbers) was reduced to five options and the

Table 1 Questionnaire applied to determine user satisfaction

Section	N	Question	
Characterization of the sample group	01	Today's date (day, month, year) (original Q.01)	Personal characterization, location, operation, and time of use of each environment under study.
	02	Your age (yrs) (original Q.02)	
	03	What are the weather conditions right now? (original Q.03)	
	04	About how close are you to a window with a view? (original Q.04)	
	05	If this room has windows with blinds or curtains, overall right now are they? (original Q.05)	
	06	Why do you operate the blinds or curtains? (additional question added by the authors)	
	07	For about how long have you been using this room? (original Q.06)	
	08	When you come here, how many hours per day do you generally spend in this space? (original Q.07)	
User perception	09	I enjoy being in this room (original Q.08)	Response varies in the range: 1. Totally disagree, 2. Disagree, 3. Neutral, 4. Agree, 5. Totally agree
	10	I find this room visually attractive (original Q.09)	
	11	Temperature in the room is always comfortable (original Q.10)	
	12	Noise level in the room is always comfortable (original Q.11)	
	13	I like the view I have from the window (original Q.12)	
	14	I think the view out the window(s) is big enough (original Q.03)	
	15	I am happy with how the blinds (or curtains) operate (original Q.14)	
	16	The lighting conditions are always comfortable (original Q.15)	
	17	The electric light in this room is always sufficient (original Q.16)	
	18	The electric lights are never too bright (original Q.017)	
	19	I can work happily in this room with SOME of the electric lights turned off (original Q.19)	
	20	The daylight in this room is always sufficient (original Q.20)	
	21	The daylight in this room is never too bright (original Q.21)	
	22	I am able to do my work here without any problems from glare or troubling reflections (original Q.22)	
	23	I feel motivated in this room to do my job (additional question added by the authors)	
Open questions	24	If you could make any changes, how would you improve the visual conditions in this room? (original Q.25)	Discursive response
	25	Draw the daylit area *(additional question added by the authors)*	Draw

Source Adapted from Heschong Mahone Group [3]—Occupant Survey

numbers were replaced by text as follows: "totally disagree", "disagree", "neutral", "agree" and "totally agree".

Minor changes were made to the specialists' questionnaire, implementing just the changes made to the user satisfaction questionnaire. The instructions for the space and building survey were kept when they applied to the place of study. Thus, the environments were kept as found, except for the artificial lighting, which was switched off whenever possible. Visits were arranged to cover different times and days with varying sky conditions.

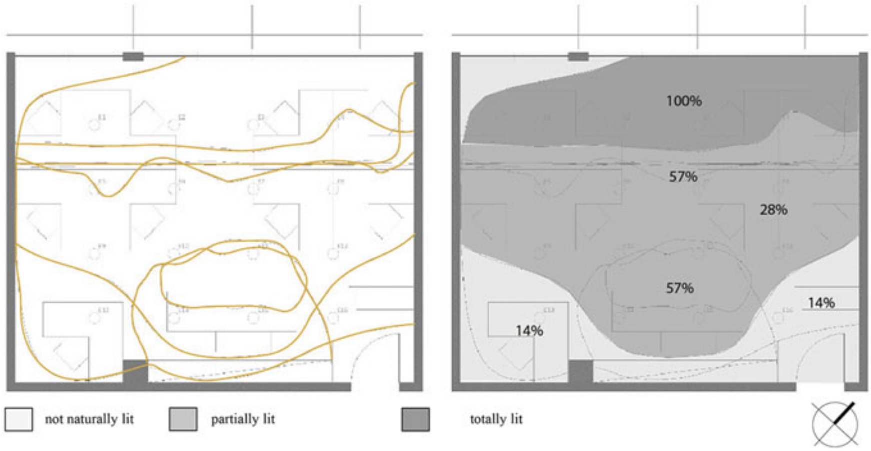

Fig. 2 Example of the drawing synthesis process (Gestcon Nov. 18th—morning)

For question 25, the floor plan of each room was provided so that the user could draw the daylit area according to their perception, as carried out in the studies by Heshong [3], Reinhart et al. [1], Nezamdoost and Wymelenberg [14], and Rizzardi [21]. For each environment, the drawings were digitalized, superimposed, and analyzed as a function of the average of the drawn area, according to the percentage obtained from the evaluations [1]. Thus, the areas were classified as "non-daylit areas" when they represented less than 25% in the drawings, "partially daylit area" for results between 25 and 75%, and "fully daylit area" for over 75%, as shown in Fig. 2.

2.2 Climate-Based Daylight Metrics Simulation

The simulations were carried out in the modeling plug-in DIVA-for-Rhino [22] with the aid of the EnergyPlus Weather file EPW-SWERA [23]. Details on the simulation parameters have been previously reported [24].

The evaluation parameters considered for sDA were the target values proposed in LM 83-12, which considers acceptable a situation where $sDA_{300/50\%}$ is achieved in at least 55% of the floor area and is preferable when it occurs in more than 75% of the area. For $ASE_{1000/250h}$, the value of 10% was employed, as stipulated by the LEED V.4 certification [18], since this adjustment was made after it was identified that the original limit of the LM 83-12 [4] (up to 2% of the floor area) is excessively restrictive. This should be revised in the next version.

3 Occupant Assessments and Daylight Metrics

A total of 132 questionnaires were applied to individuals, mostly between 20 and 30 years of age (86%), with 13% aged over 30, and 1% under 20. The climate conditions were mainly divided into days with cloudy sky and/or rain (46%) or clear sky with or without direct sunlight (47%). The four selected environments have windows with a view outside and it was noted that regardless of the solar direction, people preferred to sit next to the openings, with 60% seated at approximately 1.5 m and 35% between 3.0 and 4.5 m away from the windows. The curtains were reported to be totally open in the Ateliê and Gestcon rooms, 25% closed in Gtec and 75% closed in LabMicro. The main reason given for operating the curtains was related to either an excess or lack of lighting in the rooms (85% of answers). One of the hypotheses raised in this study is related to user behavior in semipublic spaces and attempts to verify whether or not the individuals under study were active. Thus, a correlation between the answers to "Q6—Why do you operate the blinds/curtains?" and "Q22—I can work without glare problems" was sought. The hypothesis would be confirmed if the individuals who reported that glare posed a problem in Q22 operated the curtains due to lighting issues. With the application of the chi-squared test, the association between the variables was confirmed.

In the second part of the questionnaire, the responses "totally agree" and "agree" were considered as positive aspects, and "totally disagree" and "disagree" as negative aspects. Thus, the LabMicro room was associated with the greatest dissatisfaction, with negative evaluations amounting to 60%, followed by the Ateliê (33%), Gestcon (20%), and Gtec (18%), as shown in Fig. 3.

Aspects observed from the drawings provided in response to question 25 included the influence of visual adaptation and the contrast in the representation of the daylit area by the respondents. The adaptation was perceived through both excess and lack of daylighting. In the Ateliê, where the sDA obtained through simulation was 100% of the area, the occupants identified non-daylit areas while the measurements indi-

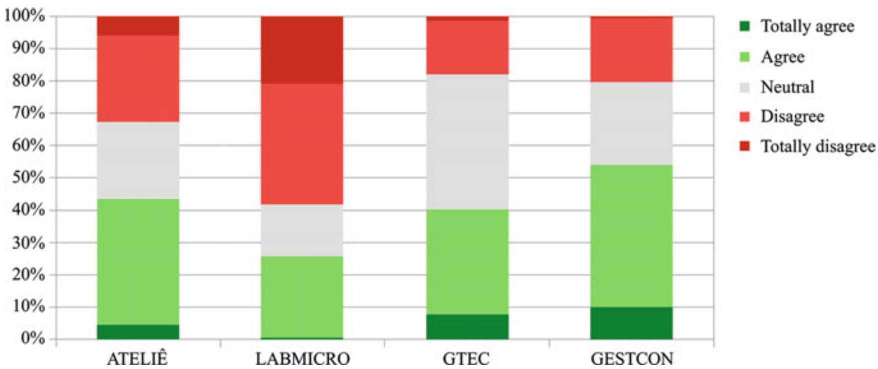

Fig. 3 Summary of responses to questions 9–23

cated illuminances between 400 lx to 2000 lx. Reinhart et al. [1] attributed this to the marking of daylighting by contrast, which occurs for fully daylit spaces. The architectural particularities of the rooms in the building belonging to the Architecture Department should be noted since the reflectance of the surfaces is high and the average illuminance of the environments is usually higher compared with other buildings. Besides Reinhart et al. [1], Rizzardi [21] also carried out a similar study in this building, in addition to an environment in the Integrated Physical Space (Espaço Físico Integrado—EFI) building a little over 500 m away.

As a result, a correlation with $sDA_{500/50\%}$ was found for the room in the Architecture Department while the environment of the EFI building was more closely related to $sDA_{300/50\%}$, analogously to the values proposed by Reinhart et al. [1]. Regarding the results presented herein, the best correlation would be for $sDA_{750/50\%}$.

The Gtec room, for which the simulated sDA was 16%, showed a large variation in the illuminance with maximum values of 400 lx on Nov. 18th, during a sunny afternoon, and 70 lx on Nov. 17th, during cloudy conditions at dusk. This did not interfere with the evaluation of the respondents since, in general, the areas partially and totally daylit covered from 1/3 to 1/2 of the room area. The measurements indicated values close to 100 lx as the limit between partially daylit and non-daylit, corresponding to the value found by Nezamdoost and Wymelenberg [15], who attributed these values to the age of the occupants, being mostly young individuals as in the case of this study. Another aspect that may be related to this tolerance for lower illuminances is the predominant activity conducted in the environment since Labmicro and Gestcon reported similar preferences and the main activity was the use of computers. These environments showed a stronger relation with $sDA_{200/50\%}$ and the Labmicro with $sDA_{500/50\%}$.

As observed in the results reported in Fig. 4, only Gtec did not exceed the limit established in the LEED V.4 [18] for $ASE_{1000/250h}$ (10% of the area). The results for the other rooms, where values were found to be excessive, corroborate the user perception, since the questions related to glare had high percentage scores, indicating discomfort and with most points having results above 1000 lx coinciding with the location of the work plans of the rooms.

Based on the questionnaires, it was also noted that 100% of the respondents in the Ateliê indicated that they were seated up to 4.5 m away from the windows, and for the LabMicro this value was 70% of the sample.

The results for the Gestcon, despite indicating a high probability of glare, do not conform to the user evaluations, because discomfort due to excess glare was not reported. However, the results are consistent with those for sDA, since one of the negative indexes elucidated refers to daylight insufficiency.

The disadvantage observed in the evaluations for Gtec is mostly related to insufficient daylight in the environment, which coincides with the low result for the sDA and the null value for the ASE.

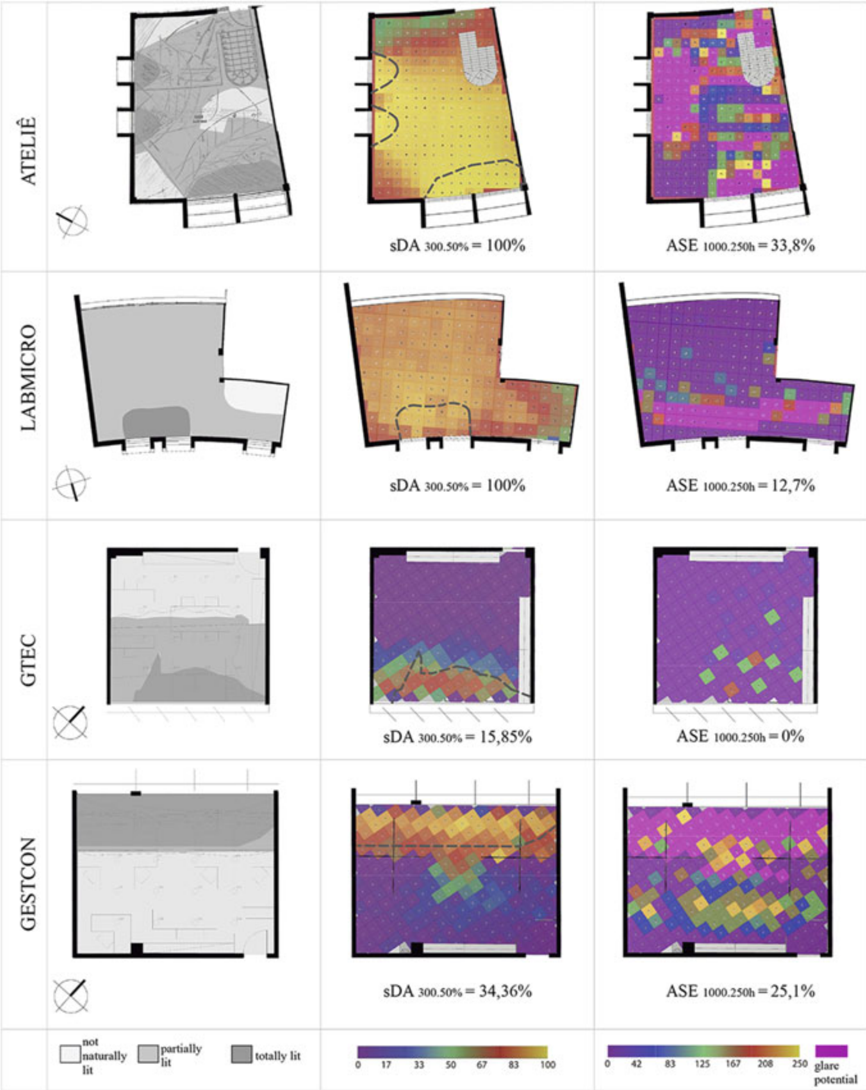

Fig. 4 Summary of drawings and computational simulations

4 Discussion

Barriers to environmental comfort in the Global South, addressed in this chapter, are associated with the adoption of criteria for the evaluation of daylight performance based exclusively on surveys conducted with people from the Northern Hemisphere. The results of this study were not conclusive on the need to restrict this generalization to the criteria of the IES LM-83-12 [4]. However, they indicated a possible cultural influence on the behavior of individuals regarding the operation of blinds in semi-public places. In the former, the results showed that the occupants' preferences appeared to be more strongly related to architectural solutions and their effects on the visual perception of individuals than to sociocultural and climatic aspects. This is because of the different architectural strategies employed in the rooms, combined with the visual adaptation capacity of the occupants that led to the differences since the two buildings are located on the same campus and presented very different responses for daylight sufficiency but more similar responses for glare. Thus, the hypothesis regarding coastal lifestyle could not be proved. In the latter, the question on the adjustment of blinds revealed an association between the operation pattern and visual comfort, indicating that users are active in semipublic places. The hypothesis of a cultural influence on the device activation profile in shared spaces, which is important for post-occupation characterization and to develop algorithms for building systems – operation, therefore needs to be investigated in greater depth.

5 Conclusions

This chapter discussed the daylighting preferences of occupants of buildings situated in socioenvironmental contexts that differ from those that originated the IES LM 83-12 performance metrics. It was concluded that although the sufficiency metric criterion is not representative of the respondents' preference, the discrepancy is not related to the local factor. The fact that the observed disparity is related to the architecture and the observer questions the effectiveness of the metrics.

However, in the absence of more precise references and their worldwide acceptability, such criteria are useful as a starting point to characterize daylighting performance in the Global South, although this does not rule out the need for further studies in this field and even for the reassessment of metrics.

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References

1. Reinhart C, Rakha T, Weissman D (2014) Predicting the daylit area—a comparison of students assessments and simulations at eleven schools of architecture. LEUKOS 10:193–206. https://doi.org/10.1080/15502724.2014.929007
2. Pinheiro DPN (2004) A resiliência em discussão. Psicologia em Estudo 9:67–75. https://doi.org/10.1590/S1413-73722004000100009
3. Heschong Mahone Group (2012) Daylight metrics. Final Project Report. Tech. rep., Gold River, USA
4. IESNA - The Daylight Metric Committee (2012) IES LM-83-12. Approved method: IES spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). New York, USA

5. Moser G, Uzzell D (2012) Environmental psychology. In: Weiner I, Tennen H, Suls J (eds) Handbook of psychology, vol 5, 2nd edn. Wiley, New Jersey, USA, p 608
6. Corral-Verdugo V (2005) Psicologia ambiental: objeto, “realidades” sócio-físicas e visões culturais de interações ambiente-comportamento. Psicologia USP 16:71–87. https://doi.org/10.1590/S0103-65642005000100009
7. Attia S, Carlucci S (2015) Impact of different thermal comfort models on zero energy residential buildings in hot climate. Energy Build 102:117–128. https://doi.org/10.1016/j.enbuild.2015.05.017
8. de Dear RJ, Brager GS (2002) Thermal comfort in naturally ventilated buildings: revisions to ASHRAE standard 55. Energy Build 34:549–561. https://doi.org/10.1016/S0378-7788(02)00005-1
9. Givoni B (1992) Comfort, climate analysis and building design guidelines. Energy Build 18:11–23. https://doi.org/10.1016/0378-7788(92)90047-K
10. Pierson C, Piderit B, Iwata T, Bodart M, Wienold J (2022) Is there a difference in how people from different socio-environmental contexts perceive discomfort due to glare from daylight? Lighting Res Technol 54:5–32. https://doi.org/10.1177/1477153520983530
11. Jones NL, Reinhart CF (2019) Effects of real-time simulation feedback on design for visual comfort. J Build Perform Simul 12:343–361. https://doi.org/10.1080/19401493.2018.1449889
12. Nezamdoost A, Wymelenberg KVD (2015) Daylit area revisited: a comparative sensitivity study of daylit area drawings with daylight results from point-in-time and annual simulations. In: IES conference 2015 Indianapolis, Indianapolis. USA
13. Nezamdoost A, Wymelenberg KVD (2016) Sensitivity study of annual and point-in-time daylight performance metrics: a 24 space multi-year field study. ASHRAE and IBPSA-USA SimBuild (2016) Building performance modeling conference. Salt Lake City, USA, pp 49–56
14. Nezamdoost A, Wymelenberg KVD (2017) A daylighting field study using human feedback and simulations to test and improve recently adopted annual daylight performance metrics. J Build Perform Simul 10:471–483. https://doi.org/10.1080/19401493.2017.1334090
15. Nezamdoost A, Wymelenberg KGVD (2017) Revisiting the daylit area: examining daylighting performance using subjective human evaluations and simulated compliance with the LEED version 4 daylight credit. LEUKOS 13:107–123. https://doi.org/10.1080/15502724.2016.1250011
16. United States Census Bureau (2018) QuickFacts: Los Angeles city, California. https://www.census.gov/quickfacts/losangelescitycalifornia
17. National Institute of Metrology (2021) Instrução normativa inmetro para a classificação de eficiência energética de edificações comerciais, de serviços e públicas. Tech. rep., Ministry of Economy, Brasilia, Brazil
18. US Green Building Council (2013) LEED v4: Daylight. https://www.usgbc.org/credits/healthcare/v4-draft/eqc-0
19. International Well Building Institute (2020) The WELL building standard. Feature 62: daylight modeling. https://standard.wellcertified.com/light/daylight-modeling
20. ABNT (2005) NBR 15215-4. Iluminação natural - Parte 4: Verificação experimental das condições de iluminação interna de edificações - Método de medição. Technical Standards, Brazilian Association, Rio de Janeiro, Brazil
21. Rizzardi AF (2018) Investigação sobre percepção visual e medidas de avaliação da iluminação natural. Master’s thesis, Federal University of Santa Catarina, Florianopolis, Brazil
22. Solemma L (2014) DIVA for Rhino: environmental analysis for buildings
23. Energy Efficiency Laboratory in Buildings (2018) Weather files. https://labeee.ufsc.br/downloads/arquivos-climaticos/inmet2018
24. Kramer ER (2020) Investigação da preferência dos ocupantes frente aos valores alvo das medidas de suficiência de luz e seus respectivos critérios: final research report. Florianópolis

Daylighting Design Strategies for Office Spaces in Different Chilean Climates

Cecilia Palarino-Vico and María Beatriz Piderit-Moreno

Abstract The chapter discusses the optimization of daylighting strategies to achieve visual comfort in side-lit office spaces. Glazed facades are commonly used in the design of office buildings, where direct sunlight causes visual glare, and the prolonged use of dynamic user-operated shading devices reduces daylighting and blocks the view outside. Visual comfort at the use stage depends on early design decisions appropriate to each context to maximize uniform daylight indoors and control glare risk. This may be a challenge in extensive territories with great variability of prevalent skies and daylight availability. The research was carried out in an experimental office space prototype, analyzing daylight strategies in three Chilean cities with different climate conditions. They were evaluated using the climate-based daylight modeling method and validated with the dynamic daylighting metrics in sustainable codes. The chapter provides a selection of daylighting strategies suitable for different climates. It illustrates the daylight performance regarding illumination level and the potential glare control to achieve visual comfort for the occupants.

Keywords Daylighting · Side-lit office · Daylight strategies · Design optimization · Daylight performance

1 Introduction

Office buildings often have glazed facades to capture the maximum daylight in side-lit office spaces with limited daylight potential. For instance, research in Santiago

C. Palarino-Vico (✉) · M. B. Piderit-Moreno
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: arq.ceciliapalarino@gmail.com

M. B. Piderit-Moreno
e-mail: mpiderit@ubiobio.cl

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Table 1 Summary of daylight parameters and target values [7]

Daylight metrics	Acceptance	Preference	Source
sDA 300 lx, 50%	55% of the area	75% of the area	[5]
ASE 1000 lx, 250 h	20% of the area	10% of the area	[5]
UDI-c 100 lx to 3000 lx	80% occurrence	Non-specified	[6]
UDI-e > 3000 lx	Non-specified	Non-specified	[6]

de Chile showed that the fully glazed façade is the city's predominant type of office building [1]. Its use has become widespread in all locations and climates. However, in some contexts, overexposure produces high ranges of illuminance, glare, and contrasts, affecting the occupants' visual comfort. Continued and unplanned use of user-operated dynamic sun shading devices affects daylight illumination levels and the view out. These two parameters help create healthy environments and benefit the productivity of the occupants [2, 3].

Daylighting design strategies optimized for the building context are a valuable opportunity to use available resources effectively. The approach should be balanced to achieve adequate daylighting, around 500 lx for workstations with computer screens [4] while controlling potential visual discomfort and taking advantage of views outside. The objective here is to answer the question, what are the most effective strategies to meet daylighting expectations in side-lit office spaces in different climatic contexts regarding prevailing sky and daylight availability?

The chapter proposes daylighting strategies in three climatic contexts in Chile, representative of conditions with different requirements. The lighting performance of the strategies is analyzed through dynamic daylighting metrics in the sustainable codes, which integrate the evaluation of daylight provision and potential glare prediction into a combined approach, shown in Table 1. Spatial Daylight Autonomy (sDA) measures the minimum requirement of 300 lx, at least 50% of the operating hours, analyzed with Annual Sunlight Exposure (ASE), which measures the maximum requirement of 1000 lx for 250 h over the course of a year to control high illuminances [5]. Furthermore, the Useful Daylight Illuminance (UDI) measures illuminance in a range between 100 lx and 3000 lx, considering autonomous between 300 lx and 3000 lx, and over-lit when it exceeds 3000 lx [6].

The evaluation is made using climate-based daylight simulation (CBDM), with the DIVA plugin for the Rhinoceros 3D NURBS modeler, which uses a Radiance ray tracer to simulate illuminance distributions [8]. The light scene is built with an architectural 3D model and a climate file (energy plus weather) for each location to conclude the effectiveness of the design criteria applied.

2 Daylighting Design Strategies

The research focuses on strategies for catching, transmitting, distributing, and controlling daylight. Table 2 summarizes design recommendations developed by leading entities in advanced daylighting and energy design. The recommendations guide decisions on building shape, openings, and interiors to define the experimental prototype (See Fig. 1) and solar devices for optimizing each climate.

The experimental model is an office prototype of 84 m^2. It is characterized by a square floor plan with 9.15 m sides (maximum distance from the occupant to the façade to provide daylight and views of the exterior). The ceiling has a height of 3.0 m which increases to 3.35 m near the façade to enhance daylight capture and reflections. The opening is north-oriented, with an area of 12 m^2, in the central position of a wall area of 30.6 m^2. It determines a window-to-wall ratio (WWR) of 40%, according to the energy criteria guided by ASHRAE. The opening is 5.0 m wide and divided into two sections: an upper opening for daylighting (Daylight Window) and a lower opening for exterior views (View Window). The opening starts at 0.8 m to provide views outside from the seated position of the occupant.

3 Optimization of Daylighting Strategies in Three Climatic Contexts

Given the wide spectrum of daylight and sky variations, a detailed site analysis of the Chilean climatic context is carried out by looking at the Köppen–Geiger climate classification, average temperatures (T° Avg.), and frequency of skies: overcast, intermediate, and clear using the ASRC-CIE model [12, 13]. The cities of Calama (22°28′0″S, 68°55′60″W), Santiago (33°27′0″S, 70°40′25″W), and Puerto Montt (41°28′18″S, 72°56′23″W) show three different conditions described in Table 3.

3.1 Strategies for CIE Predominant Clear Sky (Calama)

The city of Calama requires solar shading strategies throughout the year. The proposal applies a fixed external shading device of horizontal louvers 10 cm apart, which effectively obstructs solar angles (89° sum., 44° wint.) and provides views of the exterior. The material of the louvers is permeable to daylight transmission, with a 50% perforated surface, distant from the opening to create a ventilated gap to reduce the radiant temperature. Simulation results show a uniform daylight pattern with acceptable visual comfort thresholds in Fig. 2.

Table 2 Design criteria for side-lit office spaces [7]

Building components	Source
Building form	
Geometry/Floor Plan	[1, 3]
- Distance of occupants from façade 9.15 m (max.)	
- Regular occupied areas distance from façade 4.55 m > 40%	
- Occupied areas distance from façade 6.0 m > 75%	
- Maximum floorplan depth without the use of skylight 18.2 m	
Geometry/Height	[1]
- Ceiling height (min.) > 2.75 m and in public spaces >3.10–3.65 m	
Orientation	[1, 3]
- Dominant orientation north–south facades within 15°	
- Prioritize floorplans extension towards the east–west	
Fenestration	
Wall–window ratio	[1, 3]
- WWR (20%–1%)—Preferred north/south	
Window distribution	[9–11]
- View Window (VW) + Daylight Window (DW)	
- VW height: from 0.75 m up to 1.80–2.20 m; from floor overcast sky	
- DW height: up to the ceiling (2.20–3.35 m)	
Glazing (Visible light transmission—VT)	[9–11]
- Windows in general VT −0.6/0.7	
- Daylight Window VT > 0.6/0.7	
- View Window VT < 0.6/0.7 (also east/west façade)	
- Avoid reflective or tinted glass	
Devices	
Daylight	[9–11]
- Light shelves/Reflector devices/Diffuser screens/Light guiding shade	
Fixed shading	[9–11]
- Horizontal: Overhang/Louvers/Multiple blades/Vertical panel	
- Vertical: Façade screens/Brise-soleil/Vertical fins/Slanted vertical fins/in colder climates or overcast sky perforated materials	
Dynamic shading Internal	[9–11]
- Roller blinds/Venetian blinds/Curtains/Vertical louver blinds	
Interiors	
Program zoning	[9–11]
- Open-plan office: north/south prior orientation, primary daylighting area	
- Circulation: Between workstations at the end of daylighting area	
- Private office: east/west prior orientation, glazed walls parallel to the façade	

(continued)

Table 2 (continued)

Building components	Source
Partitions - Workstation partitions $h < 1.2$ m and parallel to the window - Panels perpendicular to window ($h > 1.2$ m), translucent panels ($h > 1.65$ m) - Prior perpendicular orientation of user to window	[10]
Reflectance (LVR) - Light reflectance values (LRV) 80% ceiling—50% walls—20% floors - Avoid the "cave effect" with high LVR in the perimeter zone - Increase LVR of daylight surface devices	[10]

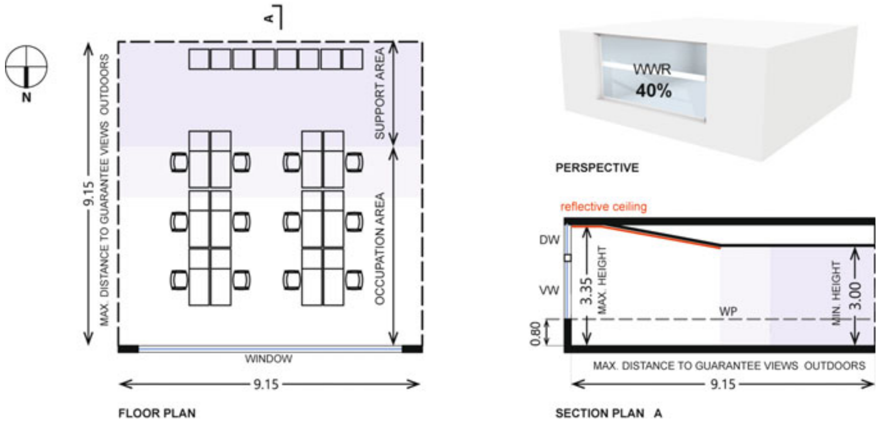
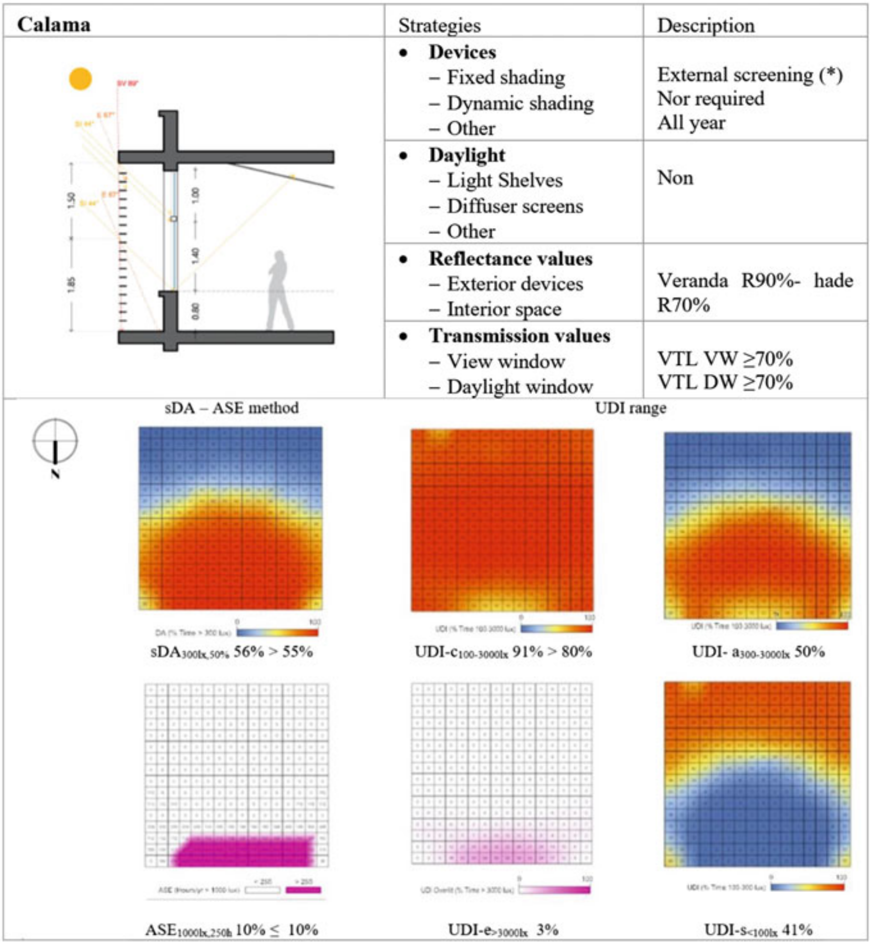


Fig. 1 Prototype office model [7]

Table 3 Characteristics of the case studies

Cities	Köppen Geiger	T°max Avg. (°C)	T°min Avg. (°C)	Frequency (%) of CIE sky			
				Clear (%)	Cl. Turb. (%)	Interm. (%)	Overcast (%)
Calama	BWk	24.1	5.1	50	23	16	11
Santiago	Csb	29.8	11.4	19	22	30	29
Puerto Montt	Cfb	19.6	9.4	10	12	32	46

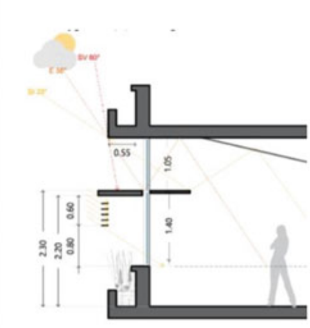


Calama	Strategies	Description
	• **Devices** – Fixed shading – Dynamic shading – Other	External screening (*) Nor required All year
	• **Daylight** – Light Shelves – Diffuser screens – Other	Non
	• **Reflectance values** – Exterior devices – Interior space	Veranda R90%- hade R70%
	• **Transmission values** – View window – Daylight window	VTL VW ≥70% VTL DW ≥70%

Fig. 2 Optimized façade strategies and illuminance distribution in Calama

3.2 *Strategies for CIE Predominant Intermediate Sky (Santiago)*

The city of Santiago requires mixed winter–summer strategies. The aim is to capture passive solar gain in winter when overcast skies predominate and low overheating. Overhangs are applied to the outside of openings to effectively control the sun in summer and at the equinoxes. In addition, the visual window has fixed exterior horizontal slats spaced at 10 cm to protect the desk from direct sunlight in winter. An interior lighting shelf increases and redirects the light to improve reflections and prevents glare at desks. Simulation results show a uniform daylight pattern with acceptable visual comfort thresholds Fig. 3.



Santiago	Strategies	Description
	• **Devices** – Fixed shading – Dynamic shading – Other	Overhang + Brise-so-leil Blinds & curtains (win-ter) Seasonal regulation
	• **Daylight** – Light Shelves – Diffuser screens – Other	External & internal Recommended
	• **Reflectance values** – Exterior devices – Interior space	Light-shelf R90% Wall thickness R70%
	• **Transmission values** – View window – Daylight window	VTL VW ≥70% VTL DW ≥79%

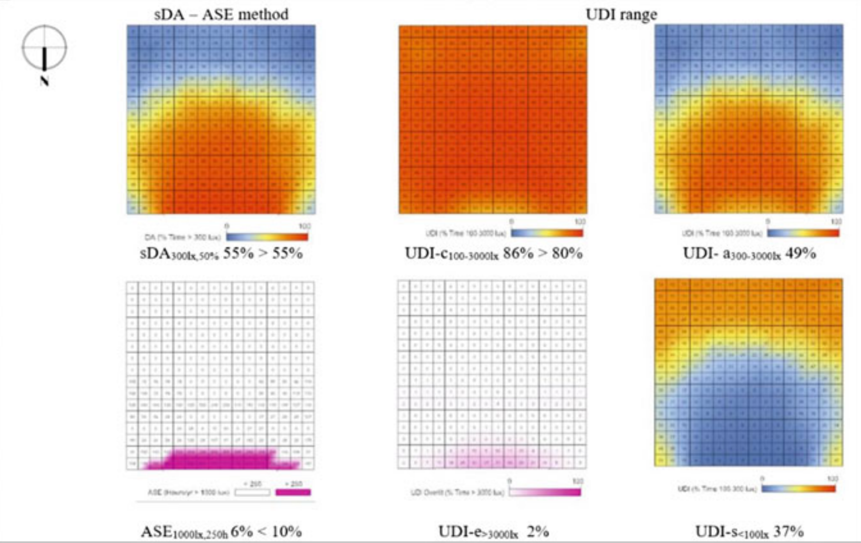


Fig. 3 Optimized façade strategies and illuminance distribution in Santiago

3.3 Strategies for CIE Predominant Overcast Sky (Puerto Montt)

The city of Puerto Montt requires passive solar gain strategies during most of the year due to low temperatures and the frequency of overcast skies in winter and at equinoxes. A horizontal overhang is planned to control solar radiation in summer. However, dynamic devices (translucent curtain type) are also necessary to regulate sunlight on the work plane during short periods of the year. Due to the limited availability of daylight, internal reflections are enhanced by increasing the reflectance

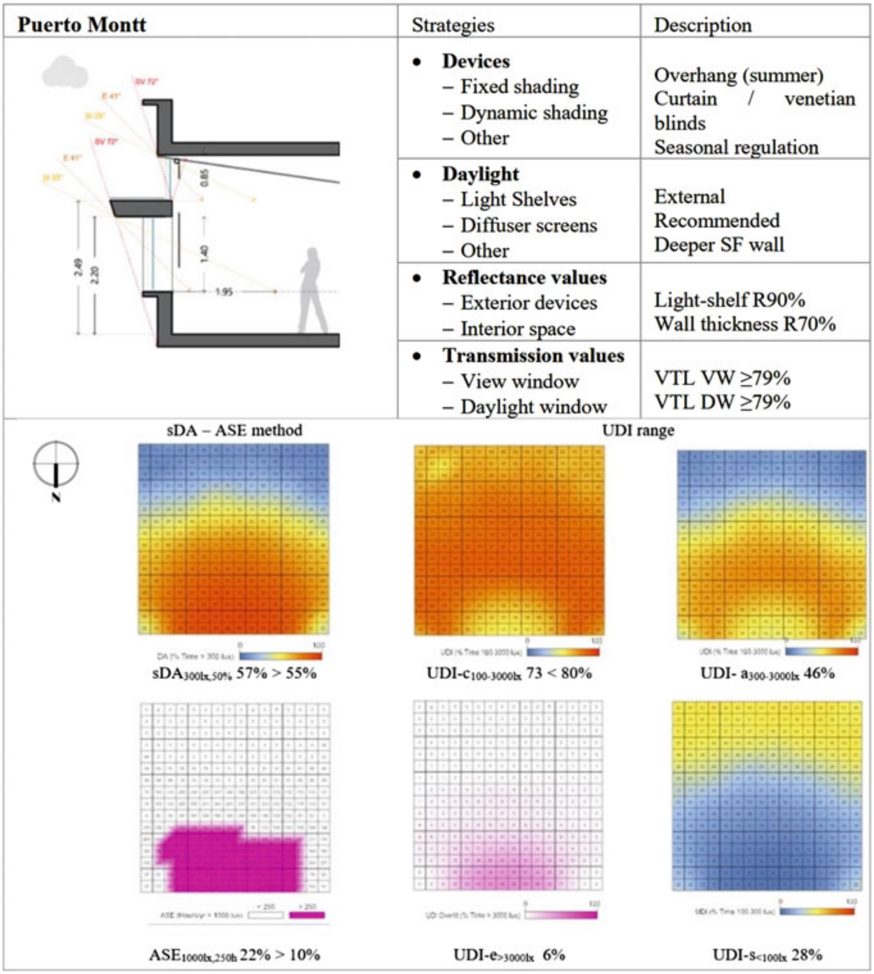


Fig. 4 Optimized façade strategies and illuminance distribution in Puerto Montt

of materials. Simulation results show a uniform daylight pattern with acceptable visual comfort thresholds in Fig. 4.

4 Results

The dynamic simulation analyzes the experimental model to establish the base lighting performance in the three locations, shown in Fig. 5. Daylight availability metrics achieve satisfactory illuminance levels, meeting the thresholds of sustainable codes.

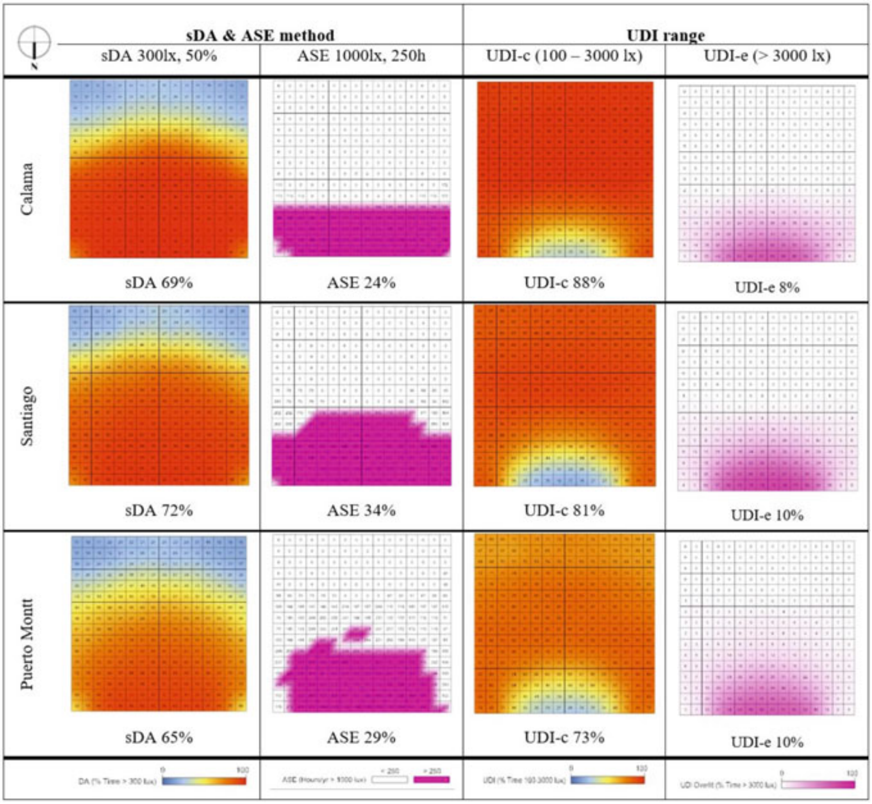


Fig. 5 luminance distribution maps sDA & ASE and UDI range, three climates

However, high illuminance (>1000 lx) for prolonged periods (>250 h) is a constant because the models do not have devices that are appropriate for the climatic contexts. Solar control designs are important to reduce high illuminances, and the results show that the strategies proposed in Section 3 satisfactorily achieve the objectives defined according to the needs of the different contexts.

In Calama, with clear skies and hot temperatures, the daylight performance reaches sDA 69% and ASE 24%. The optimization achieves sDA 56% and ASE 10%, meeting the LM-83 code requirement. In addition, the optimization improves the UDI-c by 91% (base performance UDI-c 88%), meeting the PSBP requirement. Regarding the range segments, it achieves an autonomy UDI-a 50% and over-illumination in the area near the window at 3%. Sunscreens regulate high illuminances and play a fundamental role in climates with high solar presence.

In Santiago, with intermediate sky and temperatures, daylight performance achieved sDA 72% and ASE 34%, and then with the optimization, achieves sDA 55% and ASE 6%, complying with the LM-83 code requirement. The case presented the most accentuated sun exposure. However, sunscreens show effective sunlight regulation. In addition, it increased the UDI-c value to 86% (the base performance was UDI-c 81%), meeting the PSBP requirement. Regarding the range segments, it achieves a UDI-a of 49% and over-lighting in the nearby window area of 2%.

In Puerto Montt, with an overcast sky and cold temperatures, the initial daylight performance was sDA 65% and ASE 29%, decreasing to sDA 57% and ASE 22%. Compliance with LM-83 is conditioned because ASE exceeds 20%. The high illuminances respond to the projected passive gain strategy, designed for a predominantly overcast sky. The values indicate the need for user-operated dynamic shades. On the other hand, UDI-c 73% is below the 80% required by PSBP, which is explained by the low daylight availability from the overcast sky. Regarding the UDI range, it achieves a UDI-a of 46% and over-lighting in the nearby window area of 6%.

5 Discussion

The results demonstrate that integrating passive strategies can balance illuminance levels and high illuminance control. The dynamic metrics used to evaluate daylighting performance show that the results are close to the required thresholds defined by the codes for occupant visual comfort. The evaluation method and daylight metrics applied are widely used. They were developed in the Northern Hemisphere, established in sustainable standards, and are the reference for developing standards applied in the Southern Hemisphere. The results show that compliance with the lighting performance of the optimized designs is achieved in two of the three climates. In latitudes and overcast climates such as Puerto Montt, the illuminance values do not meet the illuminance range or threshold requirements.

Studies have concluded that the lighting environment of a location influences people's tolerance to illuminance levels [14]. This suggests that matching thresholds to sky conditions would be more useful for users than the standard. And there is research such as that of Marins et al. [15] that shows that light levels traditionally considered low are perceived as sufficient by people between 150 and 300 lx [16, 17] and that there is no consensus among researchers about which metric and which illuminance and time ranges, limits, or thresholds, best describes people's perception of light sufficiency [18]. Therefore, the authors assume that the strategies applied in this climate are valid and effectively optimize the model.

6 Conclusions

The review of three cities in Chile with different sky conditions shows that the requirements vary in each location depending on the availability of daylight and the incidence of sunlight. Regarding design criteria for climate optimization, there are enough works focused on passive strategies. This work allowed testing their application in different sky conditions in Chile, selecting the most important strategies, classifying them, and organizing them in a checklist for easy application by designers. The key aspect to optimize the criteria was observing how the strategies impact the amount and distribution of daylight in the space through the CBDM methods, and the UDI, SDA, and ASE metrics. It puts into perspective the need to reflect on the most appropriate thresholds to evaluate such large and variable territories concerning daylight availability for validating the designs.

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References

1. Bodart M, Bustamante W, Encinas F (2010) Iluminación natural de edificios de oficina. ARQ (Santiago). https://doi.org/10.4067/S0717-69962010000300007
2. Leung TC, Rajagopalan P, Fuller R (2013) Performance of a daylight guiding system in an office building. Solar Energy 94:253–265. https://doi.org/10.1016/j.solener.2013.05.004
3. Mardaljevic J, Andersen M, Roy N (2012) Daylighting metrics: is there a relation between useful daylight illuminance and daylight glare probability? In: Proceedings of the building simulation and optimization conference BSO12
4. UNE-EN (2012) UNE-EN 12464-1: Iluminación de los lugares e trabajo. Parte 1: Lugares de trabajo en interiores
5. IESNA - The Daylight Metric Committee (2012) IES LM-83-12. Approved method: IES spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). New York, USA
6. EFA (2015) Priority school building programme (PSBP). PSBP 2: documents and overview
7. Palarino-Vico C, Piderit-Moreno MB (2020) Optimisation of passive solar design strategies in side-lit offices: maximising daylight penetration while reducing the risk of glare in different Chilean climate contexts. J Daylighting 7:107–121. https://doi.org/10.15627/jd.2020.9
8. Reinhart CF, Mardaljevic J, Rogers Z (2006) Dynamic daylight performance metrics for sustainable building design. LEUKOS 3:7–31. https://doi.org/10.1582/LEUKOS.2006.03.01.001
9. ANSI/ASHRAE/IESNA (2011) Advanced energy design guide for small office buildings
10. AEO/NBI/IDL/IA (2011) Daylighting guide for the commercial office
11. IC/CITEC (2012) Manual de Diseño Pasivo y Eficiencia Energética en Edificios Públicos
12. Piderit MB, Cauwerts C, Diaz M (2014) Definition of the cie standard skies and application of high dynamic range imaging technique to characterize the spatial distribution of daylight in Chile. Revista de la construcción 13:22–30. https://doi.org/10.4067/S0718-915X2014000200003
13. Perez R, Michalshy J, Seals R (1992) Modeling sky luminance angular distribution for real sky conditions: experimental evaluation of existing algorithms. J Illum Eng Soc 21:84–92. https://doi.org/10.1080/00994480.1992.10748005
14. Trudeau M, Li C, Frisque A (2016) Modelling for daylight autonomy for LEED v4 – implications for cities in northern latitudes. In: eSIM building performance simulation conference, pp 715–721
15. Marins DP, Alvarez CE, Piderit B, Segatto M (2019) Below useful daylight illuminance (budi): a new useful range measurement parameter. In: 2019 SBFoton international optics and photonics conference (SBFoton IOPC), IEEE, pp 1–5. https://doi.org/10.1109/SBFoton-IOPC.2019.8910193
16. Shafavi NS, Zomorodian ZS, Tahsildoost M, Javadi M (2020) Occupants visual comfort assessments: a review of field studies and lab experiments. Solar Energy 208:249–274. https://doi.org/10.1016/j.solener.2020.07.058

17. Nezamdoost A, Van Den Wymelenberg K (2017) A daylighting field study using human feedback and simulations to test and improve recently adopted annual daylight performance metrics. J Build Perform Simul 10:471–483. https://doi.org/10.1080/19401493.2017.1334090
18. Nezamdoost A, Van Den Wymelenberg KG (2017) Revisiting the daylit area: examining daylighting performance using subjective human evaluations and simulated compliance with the LEED version 4 daylight credit. LEUKOS 13:107–123. https://doi.org/10.1080/15502724.2016.1250011

Circadian Stimulus Potential in Offices with Artificial Lighting

María Beatriz Piderit-Moreno and Cecilia Palarino-Vico

Abstract Several research projects have revealed the importance of circadian light in the health and well-being of people. Most of these studies have been carried out in extreme regions, with a lack of daylight. However, this has led to greater awareness of the non-visual effects of light and the importance of lighting designs that consider principles that generate circadian activation in all contexts, including the Global South. The main objective of this chapter is to analyze the lighting conditions and to know the circadian stimulation potential for offices that lack windows for daylight and are only illuminated with artificial lighting, where a low circadian impact is assumed. The results indicate that in offices that were not intentionally planned to comply with the characteristics of the circadian stimulus, it is not possible to achieve it just by having lamps with a color temperature between 3000 to 6500 K, but it is necessary to have horizontal illuminance levels above 300 lx and evaluate the vertical illuminance that the occupant has, when designing. It is necessary to move towards a more integrated design, focusing on workplaces without access to daylight.

Keywords Circadian stimulus · Artificial lighting · Office spaces

1 Introduction

Light plays a fundamental role in our visual, physiological, and behavioral health. Science has shown that illumination perceived in the retina, positively affects human physiological cycles and allows maintaining the synchronization of the circadian cycle. The circadian system is responsible for regulating internal biological rhythms, controlling significant functional and behavioral aspects of the human being such

M. B. Piderit-Moreno (✉) · C. Palarino-Vico
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mpiderit@ubiobio.cl

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as the sleep–wake cycle, beats per minute, core body temperature, and hormonal secretion and suppression, that affect the state of awareness, mood, and melatonin. These aspects are part of what is known as the non-visual effects of light and are affected by the amount of light we are exposed to in our lives, demonstrating that when there are insufficient levels of light, there are adverse effects on people's health and performance.

Knowledge about the circadian stimulus and health has meant a greater level of awareness in lighting design, mainly because it implies different design goals than those traditionally considered. While the traditional approach sees visibility, glare, contrast, and the appearance of a space, the circadian stimulus affects factors like exposure time, illumination level, and the light spectrum a person is exposed to. Likewise, the circadian stimulus involves different assessment methods and metrics that consider other factors, like the vertical illuminance measured from the point of view of the observer, to analyze the amount of incident light on the retina which activates internal physiological processes to suppress melatonin. However, even though interest in the circadian stimulus is growing within the plane of knowledge, in practice, design continues to work on meeting minimum lighting levels through horizontal illuminance on the work plane, without considering a global analysis that includes parameters to cover both the visual and non-visual effects. Facing this, it is felt that in indoor spaces, there are no suitable lighting conditions to guarantee a circadian stimulus for occupants, especially in spaces that do not have windows that provide sufficient daylight on the retina.

The main goal of this work is to analyze the lighting conditions of offices that do not have windows to provide daylight, and that are solely lit by artificial lighting, and to get to know their circadian stimulus potential, assuming as a hypothesis that the occupants of these spaces have a low circadian stimulus. The research highlights aspects of effective lighting for people's health and well-being in indoor spaces, through circadian stimulus.

2 Circadian Lighting in Office Spaces

Daylit indoor spaces provide greater benefits for users in regulating their circadian rhythm, leading to better health, mood, and sleep cycles [1]. According to a study made by Boubekri et al. [2], occupants of windowless indoor spaces state having shorter and lower quality sleep compared to occupants of naturally lit spaces. Other research shows that the increase in daily light exposure [3, 4], and at levels above 1000 and 2500 lx, improve the quality of sleep the following night, benefitting circadian synchronism [5]. Apart from suppressing melatonin, daylight is responsible for the production of serotonin (the happiness hormone), which regulates mood, pleasure, and well-being [6], and for the production of cortisol (stress hormone).

In the work setting, exposure to daylight (>10000 lx) for at least 3 hours can reduce job stress and dissatisfaction [7, 8]. A direct impact on mood and depression has also been shown [6, 9].

Despite these benefits, it is not always possible to have daylighting, and workplaces without daylight are common. In lengthy shifts, the lack of exposure to daylight can be significant, leading to circadian desynchrony. Therefore, artificial lighting should have similar characteristics to daylight, to simulate the physiological effects of circadian stimulation for office occupants. Factors such as intensity, light spectrum, and color temperature (CCT) of the lamp have a great impact. In addition, where possible, dynamic (or circadian) lighting should be preferred over traditional static lighting.

However, often there is neither the technology nor the means to have it. Research has shown that considering a light source with cold white CCT (4000 K), where there is high illuminance (1000 lx), a state of greater awareness and physiological excitation is created compared to one with low illumination (200 lx), and therefore, a better performance [10]. In addition, the color temperature also has an impact. Both Boyce [11] and Chellappa et al. [12] found that light sources with a high blue light content, around 6500 K, increase the state of awareness and the cognitive performance of occupants compared to ones with lower values.

2.1 *Quantifying Circadian Stimulus Potential*

Three metrics quantify the non-visual effects of light on humans: the Circadian Action Factor, the Circadian Stimulus (CS), and the Equivalent Melanopic Lux (EML). In this research, the circadian stimulus model provided by the Lighting Research Center (LRC) is used. The latter has taken on a key role in the field of lighting design for buildings [13]. The CS metric represents the effectiveness of light in suppressing melatonin and is based on the human circadian phototransduction scientific model, which combines melatonin suppression with an estimation of photoreceptor responses (of the eye's cones and rods), to change the light signals into neural signals for the circadian system [14]. Thus, to estimate whether a lighting system will provide a suitable CS, the distribution of the spectral irradiance of the light on the cornea is estimated, by the so-called Circadian Light (CLA).

Figure 1 shows the absolute sensitivity of the human circadian system, represented as an irradiance spectral distribution, which shows that on facing a higher illuminance level (lx), melatonin suppression increases and the circadian stimulus (CS) is proportionally higher [15]. CS is a measure of the effectiveness of retinal light stimulus for the human circadian system, which ranges from the CS threshold = 0.1 (unmeasurable suppression) to CS saturation = 0.7 (70% suppression). Research has shown that exposure to CS of 0.3 or more for the eye, for at least 1 hour at the start of the day, is effective to stimulate the circadian system; and at least 2 hours to improve sleep quality, mood, and state of awareness, as well as to reduce worker stress [5, 15].

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute, developed a tool for calculation, the "CS calculator" [17], which is applied in this study. This allows determining CS and CLA values and selecting the illumination levels

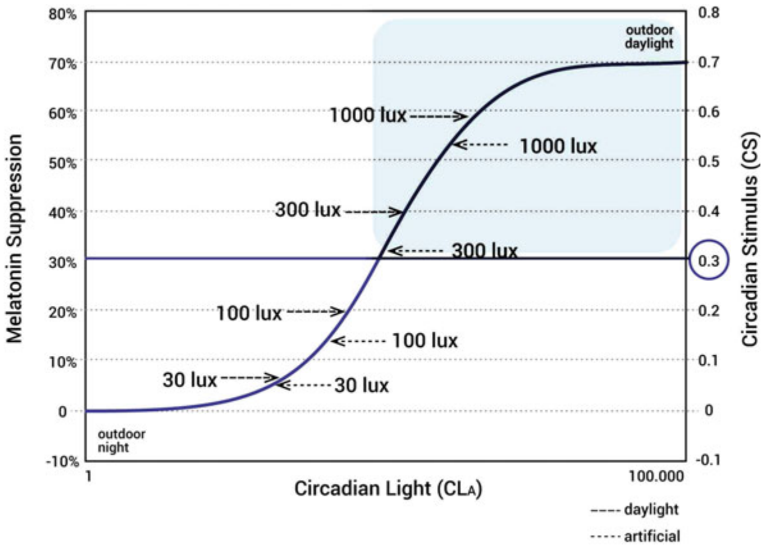

Fig. 1 Human Circadian System Sensitivity. Adapted from [16]

Table 1 Calculation tool entry variables

Sources	Lamp and CCT to select the available sources in the CS calculator
Illuminance	Vertical illuminance value in lux
Biological Input Variables (Optical Density)	The human retina differs quite substantially in the optical density of its muscular pigment, which can range from 0.3 to 0.7, but the original model assumes a single optical density of 0.5 for all individuals

and light sources to increase the efficiency of circadian light exposure in buildings. The calculator provides values for different light sources, calculating CS values for light source spectrums supplied by the user. The entry data for the calculation is presented in Table 1.

3 Evaluation of Circadian Stimulus in Artificially Lit Offices

For the study, the workspaces in the offices of Universidad del Bio-Bío were analyzed, selecting a part of the administrative building in Concepción, Chile. The general lighting conditions of the offices in the building considering the floor plan, determine that 52.95% of the office surface has access to daylight. Thus, 47.05% is lit just by artificial light. From this area, 9 offices were evaluated.

There are 39 workstations, as can be seen in Fig. 2. The lighting conditions with a lack of windows and with artificial lighting imply assuming that these premises fit the hypothesis of having low circadian potential.

The analysis methodology consisted of making a photographic survey with a fish eye lens while making horizontal illuminance (Eh) measurements on the work plane, as well as vertical illuminance (Ev) measurements at the height of the observer. The types of lighting are characterized by the correlated color temperature (CCT).

4 Results

Table 2 shows the data and CS calculation of 30 workstations, as the most representative ones, although the results were analyzed based on 39 workstations. Overall, it

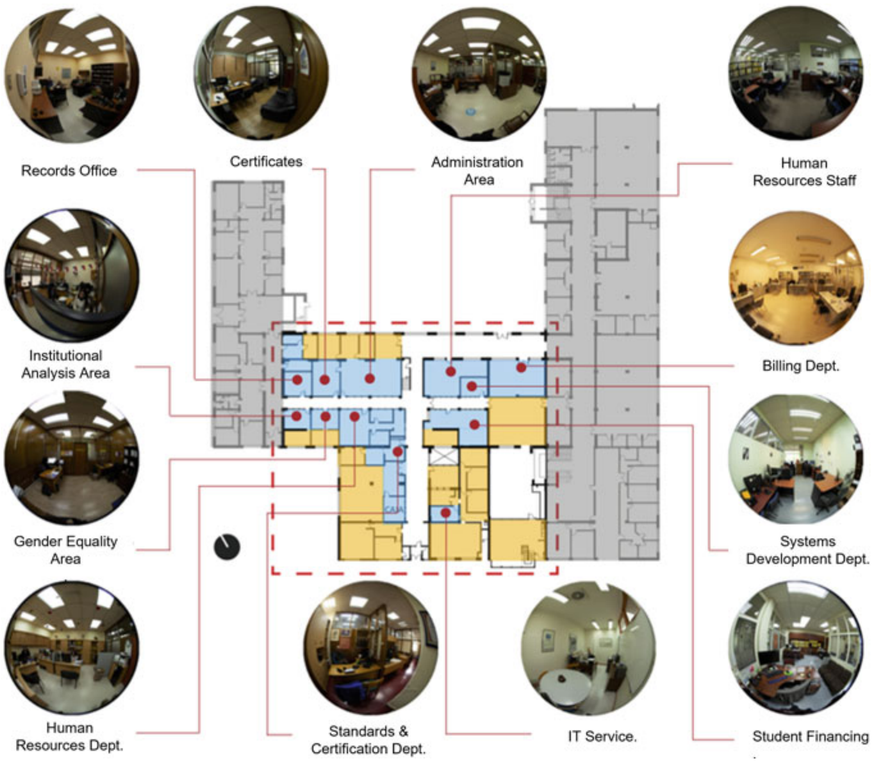

Fig. 2 Workspace distribution, UBB administration building

Fig. 3 Lighting conditions of the Systems Development and Billing Departments of Universidad del Bio-Bio Administration area

is seen that just 15% of them (6 workstations) reach a CS > 0.3, which is why 85% of the people face lighting conditions that do not favor circadian stimulus.

For color temperature, the CCT of the lights in all the workstations is between the extremes typically considered for office environments (3000 and 65000 K). As for the illumination levels, 72% of the workstations do not reach horizontal illuminance levels, Eh > 300 lx, required in offices as per the recommendations of EN 12464-1 [18]. The vertical illuminance is variable, with higher levels at the workstations, where Eh > 300 lx. On the other hand, a relationship between Ev and EH is seen, finding that when Ev:Eh is relatively high (0.65:1, according to [19]), the CS values are higher, although this does not mean that target values are reached.

In this sense, in workstations located in the same office, and thus under the same CCT condition (6500K), a higher CS is perceived where the horizontal illuminance (Eh) is higher. This is the case of the Systems Development Department, which has values of CS 0.366 with Eh 455 lx, and CS 0.321 with Eh 370 lx.

It is also seen that in some stations, despite having Eh 230 lx < 300 lx, the Ev is 215 lx and there is an Ev:Eh ratio of 0.93 < 0.65 m, and with this, a circadian stimulation of CS 0.308. In the Billing Department, circadian stimulation is not reached in any of the five workstations, and the results vary between CS 0.072 and CS 0.195. Although in two of the five stations, the Eh is 460 lx and 447 lx, and the CCT is 3000 K (of warm type light), this is not enough to reach circadian stimulation. However, it is seen that at the workstation where the Ev:Eh ratio is 0.94 (i.e., >0.65:1), the CS value is higher than on the others, although it is still a long way below the target value of CS > 0.3.

Figure 3 shows the visualization of lighting in the Systems Development and Billing Departments, showing that the latter, which has the most deficient lighting, also has only part of the lighting because the premises are in a poor condition.

Table 2 Circadian stimulation measurements considering the illuminance of each workstation

Type of premises	Type of lamp	Color Temp. Kelvin (K)	Desktop	Eh (lx)	Ev (lx)	Ev/Eh	CS
Billing Dept.	Fluorescent Tube T8 36 W	3000 K (WW)	1	295	115	0.39	0.13
			2	181	170	0.94	0.19
			3	194	60	0.31	0.07
			4	447	140	0.31	0.15
			5	460	135	0.29	0.15
Human Resources Staff	Led Tube T8 18 W	6000 K (DW)	1	317	150	0.47	0.24
			2	463	110	0. 24	0.18
			3	440	290	0.66	0.33
			4	270	163	0.60	0.25
			5	250	135	0.54	0.22
Student Financing	Led Tube T8	6500 K (DW)	1	556	365	0.65	0.37
			2	600	345	0.66	0.35
			3	345	220	0.64	0.29
Administration Area	Fluorescent Tube T8 36W	4000 K (DW)	1	162	80	0.49	0.07
			2	190	100	0.53	0.08
			3	209	75	0.36	0.06
			4	198	107	0.54	0.09
Systems Development Dept.	Fluorescent Tube T8 36 W	6500 K (DW)	1	370	240	0.65	0.32
			2	185	173	0.94	0.26
			3	440	290	0.66	0.36
			4	230	215	0.93	0.30
Human Resources Dept.	Fluorescent Tube T8 36 W	6500 K (DW)	1	230	90	0.39	0.16
			2	200	80	0.40	0.14
			3	220	97	0.44	0.17
			4	160	90	0.56	0.16
			1*	245	120	0.49	0.20
			2*	190	105	0.55	0.18
Standards and Certification Dept.	Fluorescent Tube T8 36 W	6500 K (DW)	1	279	140	0.50	0.22
			2	253	144	0.57	0.22
			3	160	140	0.88	0.23

*Individual offices within the same unit

In addition, it is seen that for lighting with CCT of 6500 K, an Ev:Eh ratio higher than or equal to 0.65 is seen in 13% of the workstations, but there is no circadian stimulation, given that the horizontal and vertical illuminance is less than 300 lx. Figure 4 shows two offices with a CCT of 6500 K, the Student Financing office with LED lamps, and the Human Resources office with fluorescent lamps, resulting in lighting with greater contrast. The first image shows the office lit with LED lamps, which have Eh $>$ 300 lx levels (560 lx, 520 lx and 345 lx), and Ev $>$ 200 lx, where all the workstations reach a circadian stimulus of CS $>$ 0.3. On the contrary, the office

Fig. 4 Lighting conditions of the Student Financial and Human Resources offices in the Universidad del Bio-Bio Administration area

lit with fluorescent lamps has a circadian stimulation of CS < 0.2 m, the result of low illuminance on both the work plane and the vertical plane at eye level.

5 Discussion

Providing circadian stimulus for occupants implies achieving several lighting design variables. First of all, providing suitable illuminance levels for visual comfort of between 300 lx to 500 lx perceiving, at eye level, enough light to suppress melatonin (mainly in the morning), and providing neutral to cold environments that are similar to daylight (with CCT > 4000 K). And although the recommendations estimate considering an Ev:Eh ratio of 0.65:1, the results show that reaching this is not enough to have a circadian stimulus.

The analysis presented shows that most workspaces do not provide a circadian stimulus for occupants, and even have difficulties in reaching the horizontal illuminance recommended for comfortably performing visual tasks. As a result, there is deficient lighting with short- and long-term consequences for the occupants, due to the impact this can have on circadian disruptions and the associated physiological processes.

This means facing the great challenge of improving lighting conditions in workspaces. First, and associated with lighting design criteria, the intended inclusion of variables that quantify the non-visual effects of light as a key factor for well-being. Second, and associated with mitigation measures for a lack of circadian stimulus, supplementing the general lighting with light sources at eye level (such as desk lamps), preferably dynamic light to adjust its intensity, CCT, and/or establishing photosensitive regulation systems. However, this solution is regulated by the occupant (there is no guarantee that the stimulus perceived is sufficient or suitable), and in contexts with less technological development, as in the Global South, these solutions can entail a high investment, making them unviable. In addition, and associated with compensatory measures, it is important that the occupants estimate exposure to daylight for 1–2 hours a day, to offset the lack of daylight, especially for workers in windowless offices.

6 Conclusions

This research implements the use of a simple calculation method to predict circadian stimulus, which can be applied by architects and designers to make design decisions that try to favor characteristics of the lit setting that have an impact on the circadian stimulus and better physiological well-being for occupants of naturally and artificially lit spaces.

At the same time, it has been shown that artificial lighting design must move towards an integrated design. That is to say, apart from providing suitable lighting levels for visual tasks with an adequate light distribution, estimating characteristics of the light source, considering the color temperature with a high blue spectrum, and managing to obtain vertical illuminance considering the observer, to include circadian light as a design principle.

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References

1. Boyce PR (2003) Human factors in lighting, 2nd edn. CRC Press. https://doi.org/10.1201/9780203426340
2. Boubekri M, Cheung IN, Reid KJ, Wang CH, Zee PC (2014) Impact of windows and daylight exposure on overall health and sleep quality of office workers: a case-control pilot study. J Clin Sleep Med 10:603–611. https://doi.org/10.5664/jcsm.3780
3. Hubalek S, Brink M, Schierz C (2010) Office workers' daily exposure to light and its influence on sleep quality and mood. Lighting Res Technol 42:33–50. https://doi.org/10.1177/1477153509355632
4. Rea M, Figueiro M (2018) Light as a circadian stimulus for architectural lighting. Lighting Res Technol 50:497–510. https://doi.org/10.1177/1477153516682368
5. Ticleanu C (2017) Report describing initial literature review on circadian lighting. Tech. rep., BRE Client Report B137170-1001, Garston
6. Beute F, de Kort Y (2013) Let the sun shine! measuring explicit and implicit preference for environments differing in naturalness, weather type and brightness. J Environ Psychol 36:162–178. https://doi.org/10.1016/j.jenvp.2013.07.016
7. Alimoglu MK, Donmez L (2005) Daylight exposure and the other predictors of burnout among nurses in a university hospital. Int J Nurs Stud 42:549–555. https://doi.org/10.1016/j.ijnurstu.2004.09.001
8. Jung CM, Khalsa SBS, Scheer FAJL, Cajochen C, Lockley SW, Czeisler CA, Wright KP (2010) Acute effects of bright light exposure on cortisol levels. J Biol Rhythms 25:208–216. https://doi.org/10.1177/0748730410368413

9. Kaida K, Takahashi M, Otsuka Y (2007) A short nap and natural bright light exposure improve positive mood status. Ind Health 45:301–308. https://doi.org/10.2486/indhealth.45.301
10. Smolders K, de Kort Y, Cluitmans P (2012) A higher illuminance induces alertness even during office hours: findings on subjective measures, task performance and heart rate measures. Physiol Behav 107:7–16. https://doi.org/10.1016/j.physbeh.2012.04.028
11. Boyce PR (2010) Review: the impact of light in buildings on human health. Indoor Built Environ 19:8–20. https://doi.org/10.1177/1420326X09358028
12. Chellappa SL, Steiner R, Blattner P, Oelhafen P, Götz T, Cajochen C (2011) Non-visual effects of light on melatonin, alertness and cognitive performance: Can blue-enriched light keep us alert? PLoS ONE 6:e16429. https://doi.org/10.1371/journal.pone.0016429
13. Figueiro MG, Gonzales K, Pedler D (2016) Designing with circadian stimulus. LD+A Mag 8:30–34
14. Rea MS, Figueiro MG, Bierman A, Bullough JD (2010) Circadian light. J Circadian Rhythms 8:2. https://doi.org/10.1186/1740-3391-8-2
15. Figueiro M, Kalsher M, Steverson B, Heerwagen J, Kampschroer K, Rea M (2019) Circadian-effective light and its impact on alertness in office workers. Lighting Res Technol 51:171–183. https://doi.org/10.1177/1477153517750006
16. Figueiro M, Steverson B, Heerwagen J, Rea M (2017) Circadian light and its impact on alertness in office workers: a field study. In: Proceedings of the 2017 illuminating engineering society annual conference, Portland, Oregon. https://www.lrc.rpi.edu/programs/lighthealth/pdf/figueiro_iesconference_aug2017.pdf
17. Lighting Research Center (2019) Lighting research center cs calculator. https://www.lrc.rpi.edu/cscalculator/. Accessed 10 Oct 2022
18. EN (2021) EN 12464-1. Light and lighting - lighting of work places - Part 1: indoor work places
19. Jarboe C (2020) Strategies for delivering circadian stimulus in an office space while minimizing energy use. LD+A Mag. https://www.ies.org/lda-magazine/featured-content/strategies-for-delivering-circadian-stimulus-in-an-office-space-while-minimizing-energy-use/. Accessed 10 Oct 2022

Acoustic Comfort

Acoustic Comfort and Noise Control in the Design of Multi-residential Buildings in the Tropics

Giancarlo Gutiérrez and Laura Marín-Restrepo

Abstract Noise exposure significantly affects health and well-being. However, today's cities are becoming increasingly noisier. Furthermore, in the tropics, on one hand, the use of natural ventilation as a passive conditioning strategy increases the exposure of spaces to ambient noise. On the other hand, housing projects concentrate a high number of housing units per area, adding interior noise from people. Moreover, multi-residential building projects in the tropics have little or no consideration of design, material, or construction practices to mitigate noise inside spaces and regarding the relationship that each dwelling has with the environment, both inside and outside the building. An acoustical approach, in the first stages of residential projects, can help the design and the designer to improve noise control and acoustic comfort, in particular to avoid sleep disturbances. This chapter reviews the most common architectural design conditions and decisions for the distribution of spaces in multi-residential buildings, which negatively impact the performance of noise control in them, identifying the situations and decisions to be avoided, those which must be fostered, and the mitigation and control activities to implement when these emerge.

Keywords Noise control · Design strategies · Residential buildings · Acoustic comfort · Sleep disturbances

G. Gutiérrez
Acoustics Consultant, Medellín, Colombia

L. Marín-Restrepo (✉)
Architecture et Climat, Louvain Research Institute for Landscape, Architecture, Built Environment, Université catholique de Louvain, Louvain-la-Neuve, Belgium
e-mail: laura.marinrestrepo@uclouvain.be

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1 Introduction

Noise has been recognized as one of the environmental pollutants most frequently found in spaces where there is human activity. Noise exposure significantly affects the quality of life of large swathes of the population [1], with physical and mental impacts such as hearing impairment and tinnitus, cardiovascular and metabolic disorders, cognitive impairment, and sleep disturbance, among others [2].

However, today's cities are becoming increasingly noisier, surpassing the WHO's recommended noise exposure thresholds to avoid adverse health effects [3]. In fact, the Environmental Noise Report states that in Europe, at least one person in five is exposed to noise levels that are considered harmful to their health [1]. This number may be much higher in contexts such as those of the Global South, and in particular in South America, if the differences in the population's cultural behavior [4], and the limited regulation of commercial-, industrial-, and transport-related activities in industrial development areas, are considered, where noise is an unwanted by-product that a large part of the population endures [1, 5].

In this regard, it is important to note that Environmental noise is defined as any unwanted or harmful outdoor sound produced by human activity, such as noise emitted by transport and industrial activity [6]. It is an environmental pollutant that leads to annoyance, can be perceived as stressful [7], and is associated with an increased risk of negative physiological and psychological health outcomes [8]. On the other hand, acoustic comfort is defined as "the perceived state of well-being and satisfaction with the acoustical conditions of a given environment" [9]. This involves the occupant's perception regarding their acoustic environment (transport, urban equipment, activities, noise-producing neighborhoods).

In this way, providing acoustic comfort could be understood as minimizing intrusive noise and maintaining satisfaction among building users [10]. It has been concluded that "the overall perception of both comfort and the quality of the space can be profoundly influenced by noise and the stress it causes" [11]. Hence, an acoustically comfortable environment is one where desired sound is encouraged, while the undesired, namely noise, is absent.

This is a challenge in today's cities, where environmental noise is ever higher, and where people are exposed to different sources of noise [3]. In this vein, homes are where people seek shelter, look to rest, and, therefore, where they least tolerate noise. However, growth in demand for housing units, an increased need for mobility in our cities, and the trend toward re-densification and maximizing land use are leading to a high-rise city model with multi-residential buildings. These also pose a challenge for noise control, as they are a source of noise themselves [12].

Thus, it is worth clarifying that buildings are exposed to noises from multiple sources. From outside, through industrial, commercial, or leisure activities, land or air-based means of transport, but also from inside, produced in the building or the technical space, from other housing units, or by the housing units themselves. Although another field of acoustics applied to buildings focuses on the indoor conditioning of the spaces, to provide a better sound quality, this chapter focuses on the control and mitigation of indoor and outdoor noise.

This is particularly relevant in the Global South because apart from the environmental noise conditions a building is exposed to due to its geographical location, there are a series of characteristics in these contexts that can produce yet more noise and affect the inhabited space further still:

- Designs for natural ventilation—In countries of the tropics with non-extreme weather conditions, buildings are designed to take advantage of airflows for natural ventilation. These air renewal and passive conditioning strategies expose spaces to environmental noise.
- Housing density—Mass-scale housing projects in the Global South concentrate a large number of housing units per area, typically with a high occupation per unit. This leads to a significant amount of noise from human behavior.
- Technical service units of the building that use equipment with obsolete and noisy technology. These units, just through their operation, produce noise that is perceived in the private spaces of the home and can cause sleep disturbances (elevators, pumping equipment, hydraulic networks, etc.). They also tend to be installed without all their accessories or with lower labor/material quality.

Thus, considering that noise affectation of sleep is one of the critical issues and the major health problems it entails [13], and the challenges that living in multi-residential buildings involves, especially in the Global South and the Tropics, in this chapter acoustic comfort in multi-residential buildings is related with the mitigation of noise-related sleep disturbances.

With this goal in mind, noise control and acoustic comfort in multi-residential buildings become especially salient, concepts that can, and should, be addressed from the conception of projects, and not as a problem to solve when already built. In this sense, architecture can play an important role, given that it is from the design stage where decisions can be made that have a greater impact on the building's end performance. However, acoustic factors are typically given little consideration during the project's planning and design stages [14], hence the need to include a noise protection and control approach in their design.

For this, it is important to understand how sound behaves. Sound is defined as the sensation perceived in the ear when a body vibrates in an elastic medium, which can be a gas, such as air, or solids and liquids. With this in mind, when studying sound and noise in buildings, two types of sound propagation are acknowledged, airborne noise, and structure-borne noise, which are responsible for how the environment is perceived inside housing units (See Fig. 1).

Sound, with noise sources in the same housing unit and/or on the same floor of the building, is most often heard as airborne noise. In the case of noise from equipment, machinery, and services, as well as the noise found in the mezzanines, this is mainly perceived as structure-borne noise.

On the other hand, noise sources with a fixed emission point, such as industrial, commercial, or leisure facilities, are known as fixed sources, as their emission position

Fig. 1 Noise sources in multi-residential buildings. Based on [10]

Table 1 Maximum permissible noise levels by land use. Typical structure of the requirements of Latin American standards

Type of zone by land use	Equivalent sound pressure limits NPS eq [dBA]	
	Daytime	Nighttime
Hospital and Education Zone	55	45
Residential Zone	60	50
Commercial Zone	65	55
Industrial Zone	75	65

does not vary in time. Meanwhile, traffic noise is identified because its generation is due to multiple mobile sources that circulate in a preset direction along the route of the roads they follow.

In this line, it is important to emphasize that most regulations in South America just focus on defining the amount of noise that can be emitted by fixed sources into the environment, seeking to control the exposure of areas defined as protected. In areas meant for residential, hospital, educational, or rest purposes, the standard imposes more restrictive levels, separating these into day and nighttime schedules, looking to avoid sleep disturbances. As an example, Table 1 presents the highest permissible noise levels by land use, which is repeated without any major variations across South American regulations (See [15]).

However, it has been acknowledged that the greatest source of environmental noise affecting inhabited settings, is caused by air and land-based transport [16], i.e., noise from moving sources, which is unregulated. On the other hand, local standards are seen as confusing or difficult to apply when facing vacuums created by urban sprawl, where multiple sectors coexist, along with the weakness in the regulation and control of noise sources. In particular, it must be considered that it is from the design of housing units and residential complexes where the decisions are made that lead to rooms being exposed to different sources of noise, such as outdoor noise, that is generated by others, or from rooms of different housing units.

In this aspect, in Europe, legislations such as those of the United Kingdom [17] have developed regulations and technical standards and recommended practices to apply in the planning of a residential project, which consider the evaluation of the noise found onsite before implementing the project, and how to act accordingly to protect indoor environments from the architectural design and construction activities [18].

However, in South America, only a few legislations, such as the Chilean NCh352 [19], address the planning of acoustic behavior of inhabitable spaces from the architectural design of the space, of its relationship with the surroundings, with the outside, and particularly with the rest of the residential units of the same building.

Facing the lack of regulations, technical standards, or building regulations that include noise control solutions in the region's residential building projects, it becomes necessary, from the architectural conception of the project, to have noise control and acoustic technical revisions that help support decision-making in terms of function, use, and materiality, which have the suitable performance to mitigate outdoor environmental noise, control noise from the service units of the building itself, and to mitigate noise issues related to the rest of the residential units.

In this sense, this chapter addresses the revision of the most common architectural design conditions and decisions on the distribution of spaces in multi-residential buildings, which negatively impact the performance of noise control in them, identifying the situations and decisions to be avoided, those which must be fostered, and the mitigation and control activities to implement when these emerge.

2 Architectural Design for Acoustic Comfort

The design of a dwelling, from an acoustic criteria approach, can be broken down into different areas considering the following:

1. The nature of the acoustic requirement of the space, how private these must be, and how protected they have to be against outside noise.
2. The amount of noise that is produced from the space.

Starting from this identification, the relationship that each space has with adjoining ones within the same housing unit and with other external residential spaces must be validated since, in terms of noise control, the basic minimum premise in housing is to favor the protection of private areas to avoid sleep disturbances, which means moving them away or protecting them from other areas that produce high noise levels.

Thus, the areas of a dwelling can be identified as:

1. Private (bedrooms): Areas destined for sleeping.
2. Social and circulation (living room, dining room, hallways, dens, and studies): Spaces for the generation of moderate noise, with medium to short stays, with equipment that can emit noise that can be controlled by the user (TV/audio equipment).

3. Services (kitchen, bathrooms, and laundry room): spaces with high levels of activity and noise generation from using the hydraulic and electrical systems, etc., where it is not usually possible to control the noise emission from the source (flushing toilets, washing machines, household appliances, etc.).

The design decisions that are commonly used are reviewed and validated regarding their usefulness to maintain acoustic comfort and noise control, with an emphasis on private areas, differentiating between airborne noise (Sect. 2.1) and structure-borne noise (Sect. 2.2).

2.1 Airborne Noise

2.1.1 Outside Noise

The development of a housing project should consider the noise conditions of the location beforehand, so that the design, location, orientation, and material of the building provide control strategies. When possible, urbanism, site conditions, and the distance of the building's façade from the street can play a relevant role in the mitigation of the amount of street noise that reaches the housing units (See Fig. 2).

In a project located in a sector with high environmental noise levels, private areas should have less exposure to sources of noise. If lighting and natural ventilation through windows must be used, it must be clear that these are the more fragile point of the façade, and that they have the greatest noise filtration.

In most projects, sliding windows are used to not take space from rooms with casement windows. However, most commercial sliding window solutions have poor noise isolation performance as a result of the system's operation. In critical noise sector conditions, private areas should be designed and built with casement windows that have a better isolation performance, and that allow the user to decide against ventilation, but gain efficient control of the noise filtering inside.

Different window installation options can offer, depending on the materials, operation system, and glazing profiles, isolation levels that may be useful for noise control (See Fig. 3). The use of overhangs or other design elements can be coupled with windows to shield from noise while allowing the windows to open for ventilation. This topic has been addressed in research such as that of Tang [21], Torresin et al. [22].

- PROMOTE: Window solutions with hinged or swinging operation systems in rooms exposed to noisy environments.
- AVOID: Plenum window systems, with fixed latticework or grids.
- SOLVE: plenum or casement window systems, with high air resistance, perimetral elastic appearance, rigid assembly, and multiple laminated glazing.

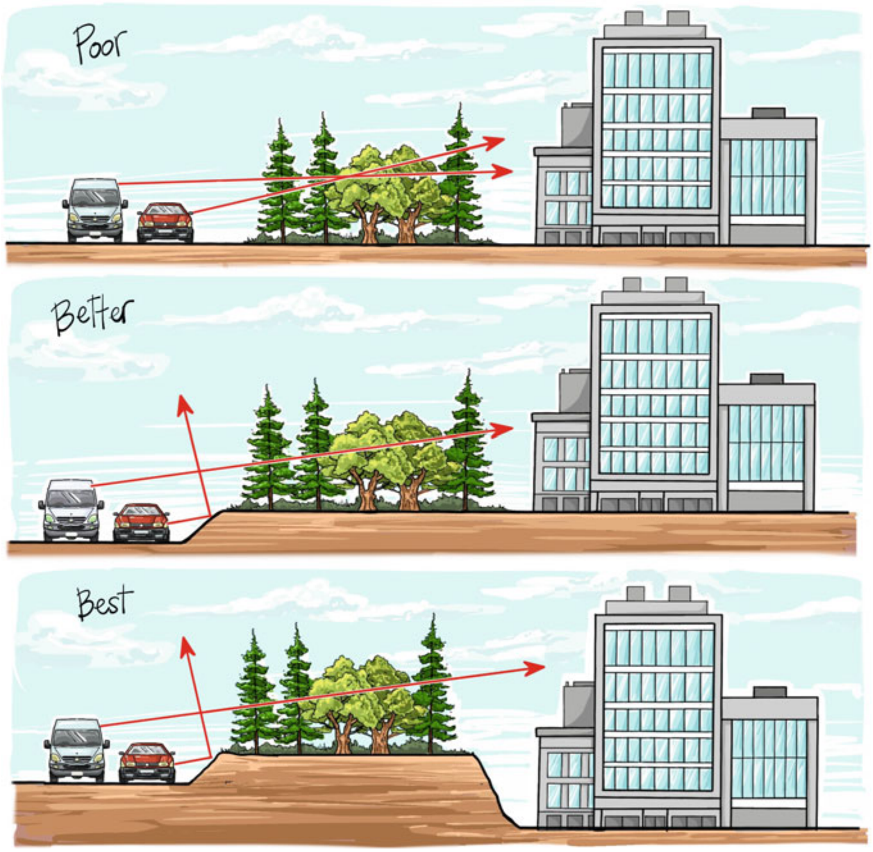

Fig. 2 Traffic noise barriers, strategies for noise control from the urbanism. Based on [20]

2.1.2 Indoor Noise

The layout of the home's service units next to private areas produces noise issues that can disturb people. This is why the design can use the social areas for circulation or short stays to offset the appearance of these phenomena (See Fig. 4).

En-suite bathrooms do not entail noise issues and sleep disturbances for the users of the bedrooms they are in. However, it must be avoided that, by design and distribution, these units are in contact with other private areas in the same apartment, or private areas of adjoining housing units (See Fig. 5).

- PROMOTE: Powder rooms in contact with circulation areas or service areas such as kitchens, closets, living rooms, etc.), or other bathrooms.
- AVOID: Powder rooms or main bathrooms alongside rooms they are not directly part of.

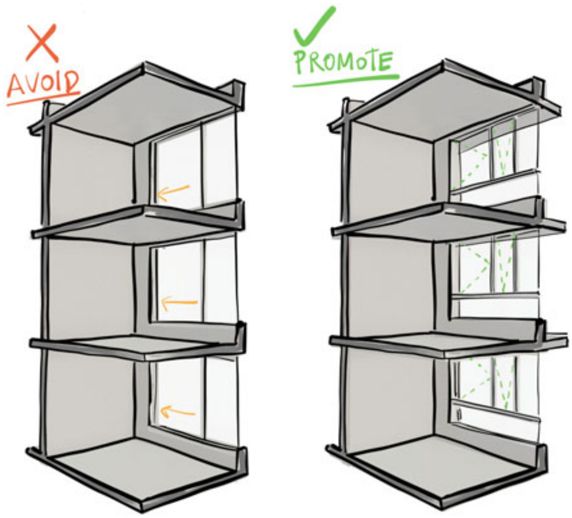

Fig. 3 Window strategies for noise control and natural ventilation

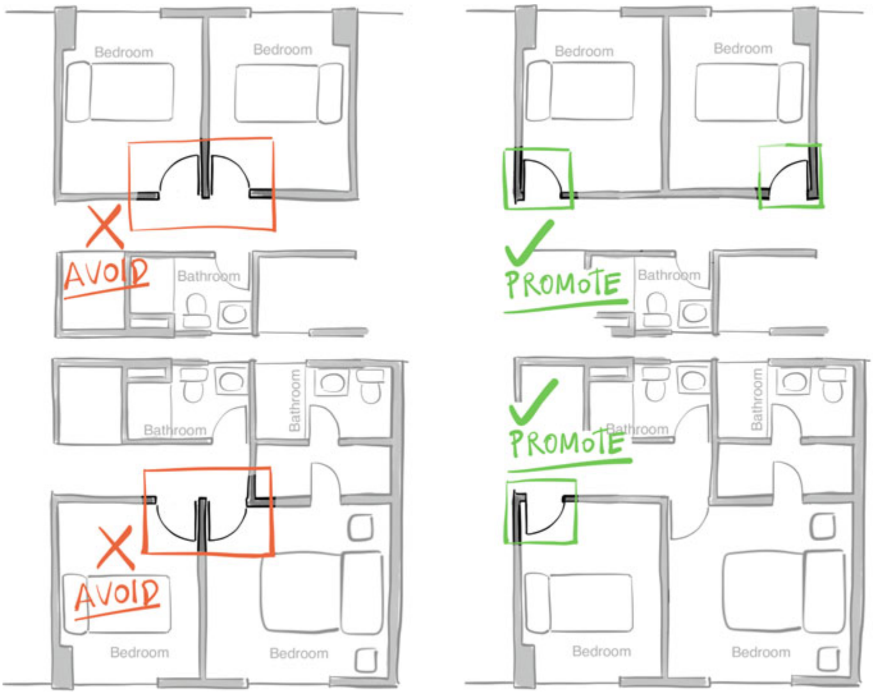

Fig. 4 Strategies to control indoor noise

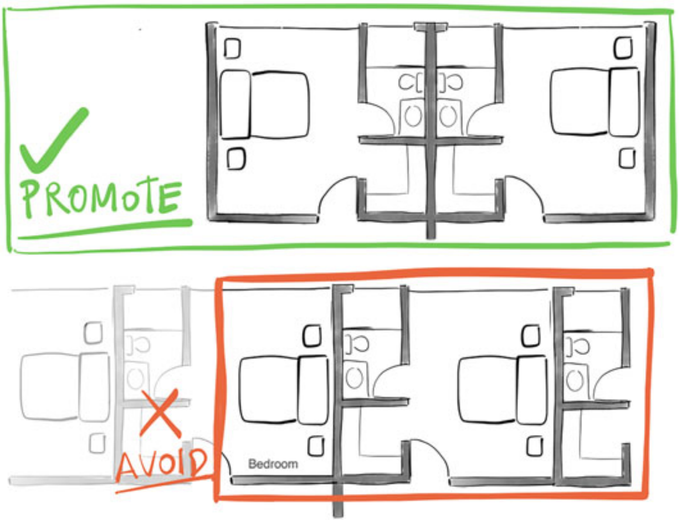

Fig. 5 Incorrect location of bathrooms in the same residential unit

- SOLVE: The main noise produced in bathrooms comes from the hydraulic flow of the supply and drainpipes. To mitigate noise spreading between spaces from the piping, these must be covered with fibrous insulation materials when the networks are installed to avoid rigid contact with the wall, and if it were the case, use a second wall or lining.

2.1.3 Other Housing Units

In multi-residential buildings, each housing unit is in contact with one or more units. Here, it is necessary to design so that the shared surfaces do not include bedrooms to avoid noise issues, and that shared surfaces are spaces with similar use behaviors.

Often, the home's main room lines up with the wall of the adjoining housing unit and shares this with a social area that tends to produce noise at night. In the case of one home's bedroom sharing the wall with the bedroom of the other dwelling, and due to the design and size of the room, has the headboard resting against this wall, the likelihood of disturbance is greater due to the low noise level in both spaces, which means that daily noise can be perceived (See Fig. 6).

- PROMOTE: Adjoining spaces between units must be service areas such as kitchens, hallways, bathrooms, and living rooms.
- AVOID: Matching bedrooms of one residential unit with spaces of the adjoining residential unit.
- SOLVE: When adjoining surfaces of the housing units are bedroom walls, these must be built with high-performance acoustic insulation using techniques such

Fig. 6 Locations to be avoided between adjoining housing units

as a double wall with internal fibrous insulation, or walls coated with insulating layers on both faces.

2.2 *Structure-Borne Noise*

The most characteristic noise issue of multi-residential buildings is the vertical spread of structural noise between occupied spaces through the mezzanine slabs.

This type of noise is caused by the impacts the floor of a housing unit receives, which are structurally transmitted through this to the space immediately below. The more rigid and dense the floor structure is, the greater speed and intensity the noise will have, disrupting the peace of the spaces below.

- PROMOTE: Designs with the same distribution, so they match the spaces above and below with the same use dynamics so that the activity is the same at the same time. To avoid sleep disturbances, bedrooms must be designed on top of bedrooms.
- AVOID: Designing service spaces or social areas that can have nighttime activity above the bedrooms of the dwelling immediately below.
- SOLVE: The noise control on floor slabs. This can be done using 1. Unattached mortar installed on insulating elastic materials, or 2. using slab-mortar-finish solutions with density variations, and on being solutions that work by avoiding the vibration or impact reaches the main structure, their efficiency is limited to these being applied when the floor is built, as solutions under ceilings are less efficient (See Fig. 7). In both cases, these are specific construction solutions for noise control that affect the project's budget, so they are rarely used onsite.

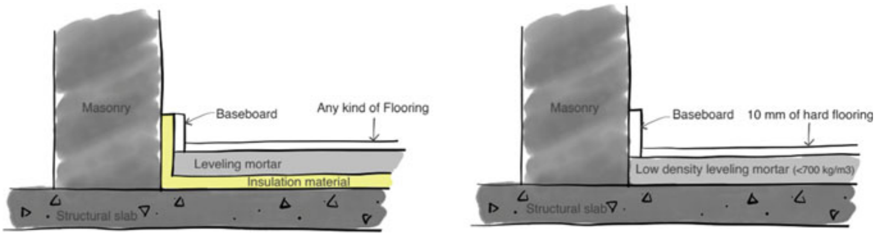

Fig. 7 Floating concrete slabs

2.2.1 The Building's Technical Services

All equipment, machinery, or systems that provide services to a building produce movement, impacts, and vibrations that are transmitted to the construction, and can be perceived in inhabited areas, leading to annoyance from noise, and in some cases, to sleep disturbances. In serving the building, these systems are irreplaceable, so measures in the system's design, the choice of suitable technology, and the interaction with the building's architecture must be taken to control, mitigate, and reduce noise production.

In the context of the Global South, it is common that due to budgetary decisions, there is no access to equipment with state-of-the-art technology and lower operational noise levels, or to accessories recommended by the manufacturer for their installation. In fact, assembly practices that compromise the construction with structure-borne transmissions are commonplace, making the problem even more evident and affecting more areas.

Elevators: Elevators produce noise that is spread as vibration through the concrete walls and slabs that the equipment's system is in contact with. As such, it must be avoided that a wall is shared between a bedroom and any of the shafts (See Fig. 8).

Elevators should be installed with all their anti-vibration and elastic mounts that minimize the transmission of vibrations to adjoining spaces.

- PROMOTE: The use of silent-running equipment technology installed with anti-vibration elastic supports, following the supplier's recommendations.
- AVOID: That the elevator shaft is alongside bedroom areas inside the dwellings.
- SOLVE: Elevator noise is spread to bedrooms as vibrations of the dividing wall. Covering the wall with fibrous acoustic absorption materials and lightweight finishes is the only mitigation option.

Water Pumps: The pumping equipment of the water networks produces noise and vibrations that are transmitted through the structures where they are installed, and also through the pipes. Their installation in basements minimizes the possibility of causing bother in the private areas of housing units on higher floors.

If they are installed on the terrace, it must be avoided that they are located above the bedrooms of the lower floor and, in any case, this equipment should be installed on

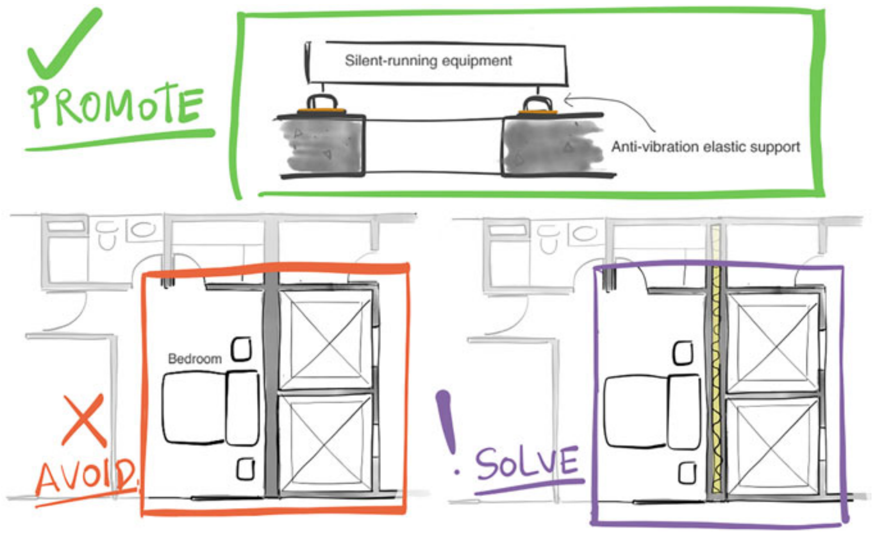

Fig. 8 Recommendations when locating elevators right by housing units

insulated bases, with elastic or spring-based anti-vibration mechanisms, and should be connected to the pipes by flexible couplings and joints, avoiding all rigid contact with the building's structure.

- PROMOTE: The use of silent-running technology and the installation of noise and vibration control accessories suggested by the manufacturer. Use foundations with an inertia bench installed on rigid insulation plates of a suitable thickness for the equipment's weight.
- AVOID: Installing the equipment close to, on the same concrete slab as, directly above, or below housing units.
- SOLVE: Apart from the assembly of equipment to avoid noise transmissions to the building's structure, the pump rooms must be confined and with acoustically insulated access doors.

Shafts: The routes of the shafts for water services, downpipes, etc., should not go through bedrooms, to avoid the noise from the flow along with vibrations.

It is commonplace that shaft walls are built with the same configurations as the project's other walls, disregarding that the routes of the networks can cause noise from flow, impact, or vibrations, that can be transmitted to the private areas of the home.

With the introduction of lightweight construction systems, the need to protect against fires has combined designs that also provide high performance in controlling the noise emitted from the shaft.

In the USG document, Shaft Wall System Catalog-SA 926 [23], the company producing the USG lightweight construction system provides guidelines for shaft wall construction typologies considering fire resistance, which ends up providing an acoustic performance rated with the STC (Sound Transmission Class) indicator.

- PROMOTE: routes of the shaft through social or service areas.
- AVOID: shaft routes through bedrooms.
- SOLVE: In the case of shaft routes through bedrooms, the pipes must be covered with fibrous insulation materials, and the walls must be enclosed with a high-performance insulated wall solution, double masonry with internal insulation, masonry covered with insulation, and a lightweight or multi-layer lightweight construction finish.

3 Conclusions

In the context of the Global South and its developing cities, environmental noise sources are growing and are difficult to control which is why, in the future, local legislation will have to work with a greater scope, considering noise as a contaminant that must be avoided, and against which residential constructions have no greater protection.

When the pandemic in 2020 shut down all activities and the cities were silenced, the world spent more time at home, doing more activities in these spaces. It was then discovered that buildings, especially multi-residential ones, do not have sufficient acoustic performance to be comfortable. In communities for which there are statistics, major increases in the number of noise complaints compared to before were recorded, with a different dynamic. The complaints about environmental noise from noise sources such as transport, construction works, and industrial activity fell, while complaints for cohabitation noise issues, rose [24, 25].

Even though the residents of multi-residential buildings must accept and tolerate living with an inevitable amount of noise, as a result of the occupation of housing with different density levels, the building's performance regarding the transmission of noise between spaces is a decision made before the project is occupied. In many cases, the control of noise between floors has been applied administratively, fostering cohabitation agreements that commit residents in these buildings to minimize potentially noise-producing activities, at least at nighttime, to avoid sleep disturbances caused by noise in a lower housing unit.

Most of the architectural design decisions of a residential building can eliminate an important number of potential noise situations that could produce sleep disturbances, and deciding to protect private spaces can have an impact on how the space is used, and determine the amount of noise this use can generate.

In comparison to the thermal and lighting aspects, the acoustic environment has been overlooked during the education of building engineers and architects [14], a trend that is also present in academic research [22]. In the specialized technical literature, there are many assembly designs to control noise between spaces, that can be used depending on the building practices and the availability of local materials.

However, these solutions look to solve existing problems and entail additional work for the site's construction, with an impact on material consumption, sacrificing the project's available space, and limited results that could be avoided with an architectural design that is aware of the need to think how the space will be heard.

Regulations and policies must also move forward along this line, including requirements for noise control and acoustic comfort from the project's conception, going beyond the protection of fixed sources toward mobile ones, and for multi-residential buildings, the noise caused inside the buildings themselves.

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References

1. European Environment Agency (2020) Environmental noise in Europe - 2020. Luxembourg. https://doi.org/10.2800/686249
2. World Health Organization (2011) Burden of disease from environmental noise quantification of healthy life years lost in Europe. Copenhaguen, Denmark
3. Aletta F (2022) Listening to cities: from noisy environments to positive soundscapes. In: Programme UNE (ed) Noise, blazes and mismatches - emerging issues of environmental concern, United Nations Environment Programme, London, UK, p 56
4. Casas-García O, Betancur-Vargas CM, Montaño-Erazo JS (2015) Revisión de la normatividad para el ruido acústico en Colombia y su aplicación. ENTRAMADO 11:264–286. https://doi.org/10.18041/entramado.2015v11n1.21106
5. Gamero Motta HG (2020) Comparación de los niveles de ruido, normativa y gestión de ruido ambiental en Lima y Callao respecto a otras ciudades de latinoamérica. Revista Kawsaypacha: sociedad y medio ambiente, pp 107–142. https://doi.org/10.18800/kawsaypacha.202001.004
6. EU (2002) Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise
7. Stansfeld S, Clark C (2019) Mental health effects of noise. In: Encyclopedia of environmental health. Elsevier, pp 287–294. https://doi.org/10.1016/B978-0-12-409548-9.11814-7
8. Jarosińska D, Ève Héroux M, Wilkhu P, Creswick J, Verbeek J, Wothge J, Paunović E (2018) Development of the WHO environmental noise guidelines for the European region: an introduction. Int J Environ Res Public Health 15:813. https://doi.org/10.3390/ijerph15040813
9. Azar E, O'Brien W, Carlucci S, Hong T, Sonta A, Kim J, Andargie MS, Abuimara T, Asmar ME, Jain RK, Ouf MM, Tahmasebi F, Zhou J (2020) Simulation-aided occupant-centric building design: a critical review of tools, methods, and applications. Energy Build 224:110292. https://doi.org/10.1016/j.enbuild.2020.110292
10. Building Science (2016) Ambiente en Interiores y Bienestar. El comic de Saint-Gobain sobre Multi-Confort, Saint-Gobain
11. Arnau Kuri J (2019) El ruido, la percepción de confort acústico y la percepción del entorno urbano arquitectónico. De los métodos y las maneras 4:9–14. http://cyadposgrados.azc.uam.mx/
12. Vardaxis NG, Bard D, Waye KP (2018) Review of acoustic comfort evaluation in dwellings-part i: associations of acoustic field data to subjective responses from building surveys. Build Acoust 25:151–170. https://doi.org/10.1177/1351010X18762687

13. Basner M, McGuire S (2018) WHO environmental noise guidelines for the European region: a systematic review on environmental noise and effects on sleep. Int J Environ Res Public Health 15:519. https://doi.org/10.3390/ijerph15030519
14. Wang C, Si Y, Abdul-Rahman H, Wood LC (2015) Noise annoyance and loudness: acoustic performance of residential buildings in tropics. Build Serv Eng Res Technol 36:680–700. https://doi.org/10.1177/0143624415580444. http://journals.sagepub.com/doi/10.1177/0143624415580444
15. Gutiérrez G, Marín-Restrepo L (2022). Regulación suramericana sobre ruido - fuentes fijas. https://doi.org/10.6084/m9.figshare.21395571.v2. https://figshare.com/articles/online_resource/Regulaci_n_Suramericana_sobre_Ruido_-_Fuentes_fijas/21395571
16. World Health Organization (2018) Environmental noise guidelines for European region
17. Goverment HM (2015) Approved document E: Resistance to the passage of sound. NBS, UK
18. Alonso A, Suárez R, Patricio J, Escandón R, Sendra JJ (2021) Acoustic retrofit strategies of windows in facades of residential buildings: requirements and recommendations to reduce exposure to environmental noise. J Build Eng 41:102773. https://doi.org/10.1016/j.jobe.2021.102773
19. INN (2000) NCh352.Of2000 Aislación acústica -Parte 1: Construcciones de uso habitacional - Requisitos mínimos y ensayos. Instituto Nacional de Normalizacion, Chile
20. IOA, Anc, (2015) Acoustics of Schools: a design guide. Institute of Acoustics and the Association of Noise Consultants, UK
21. Tang SK (2017) A review on natural ventilation-enabling façade noise control devices for congested high-rise cities. Appl Sci 7:175. https://doi.org/10.3390/app7020175
22. Torresin S, Albatici R, Aletta F, Babich F, Oberman T, Kang J (2019) Acoustic design criteria in naturally ventilated residential buildings: new research perspectives by applying the indoor soundscape approach. Appl Sci 9:5401(9):5401. https://doi.org/10.3390/APP9245401
23. USG (2017) USG SHAFT WALL SYSTEMS USG interior panel & finishing solutions. https://www.usg.com/content/dam/USG_Marketing_Communications/united_states/product_promotional_materials/finished_assets/usg-shaft-wall-systems-catalog-en-SA926.pdf
24. Tovell J, Steeves A (2020) Noise complaints in Ottawa surge to seven-year high during COVID-19 - capital current. https://capitalcurrent.ca/noise-complaints-in-ottawa-surge-to-seven-year-high-during-covid-19/. Accessed 01 Oct 2022
25. Yildirim Y, Arefi M (2021) Noise complaints during a pandemic: a longitudinal analysis. Noise Mapp 8:108–115. https://doi.org/10.1515/noise-2021-0008. https://www.degruyter.com/document/doi/10.1515/noise-2021-0008/html

Barriers and Challenges of Acoustic Design in Flexible Learning Spaces for Schools in Chile

Constanza Ipinza, Maureen Trebilcock-Kelly, and María Beatriz Piderit-Moreno

Abstract This chapter addresses the regulatory barriers and acoustic design challenges for skills development in the twenty-first century in the Global South, within new flexible learning spaces. Nowadays, the diversity of teaching methodologies and approaches has made the ambient sound more complex due to the noise caused by group learning activities. Therefore, the objective of this article was to make an international review of acoustic design regulations and recommendations for flexible learning spaces. Currently, the limited acoustic design criteria for these new spaces differ from one another, evidencing impressions when defining which parameters would be optimal to characterize their acoustics. Understanding the operationalization of architectural design and pedagogical use will be essential to provide adequate verbal communication using variable acoustics, which involves the use of acoustic control elements and devices to cover the current gaps in existing standards.

Keywords School infrastructure · Flexible space · Intrusive noise · Acoustic design

C. Ipinza (✉)
School of Architecture, University of Santiago de Chile, Santiago, Chile
e-mail: constanza.ipinza@usach.cl

C. Ipinza · M. Trebilcock-Kelly · M. B. Piderit-Moreno
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mtrebilc@ubiobio.cl

M. B. Piderit-Moreno
e-mail: mpiderit@ubiobio.cl

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1 Introduction

Since the beginning of the twenty-first century, the way of teaching and conceiving educational spaces has evolved from teacher-centered teaching, with the frontal organization of furniture for instructional teaching organized in rows, to student-centered learning, whose different learning modalities [1] (See Fig. 1) have involved rethinking the design of spaces, seeking to personalize the ways boys and girls learn based on the educational plans of [2].

Making a learning space more flexible has meant providing multiple pedagogical alternatives by adapting school furniture and transforming the limitations of the built environment by opening and closing walls to varying degrees (See Fig. 2). For [1] and other authors [3, 4], the first step to making an educational space more flexible, and respond to contemporary needs, is to convert traditional classrooms into learning workshops and increase the number of learning modalities by five to seven, on incorporating adaptable furniture. After this, by setting up adjoining spaces, semi-connected by a common space, it is possible to facilitate collaborative work between rooms and cover 10 learning modalities, while, a greater degree of flexibility emerges when a space traditionally occupied by a group of classrooms and a hallway are united, forming a small educational community that favors around fifteen learning modalities.

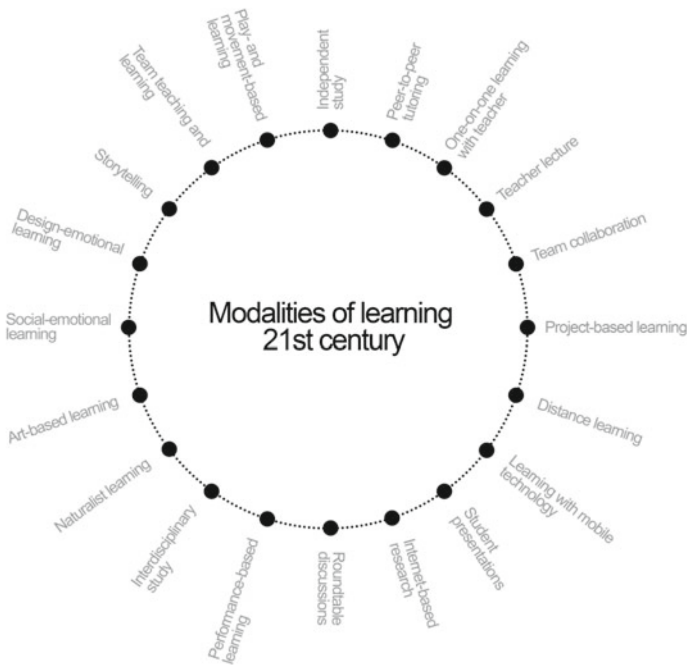

Fig. 1 Learning modalities for twenty-first century according to [1]

Fig. 2 Representation of degrees of flexibility of the learning space according to [4], adapted by [3] and redrawn by the authors

Following this, although the design of the space should be flexible and adaptable, it should be considered that it is the teachers who define the configuration and use alternatives [5, 6], depending on the teaching and learning approaches they look to put into practice (See Fig. 3). The fundamental purpose of making the space more flexible is to provide a variety of educational experiences, promote greater commitment and autonomy in students, and increase the levels of reflection, collaboration, and motivation [7–9].

Although there are multiple benefits of flexible learning spaces [10–12], it has also been shown that, by promoting collective practice and group interaction, the space is prone to generating high levels of noise inside [13] and can induce a lack of privacy and distraction [9, 14–17], generating stress for the students and teachers [18, 19]. Likewise, intrusive noise from other classes or work groups can affect speech intelligibility and cause discomfort from the noise generated by conversation [20–23]. Considering that activities involving group work and movement will take place at least 50% of the time in schools [6, 24], excessive noise may significantly affect people's well-being [20, 25, 26], both in communication, attention, and memory and in academic performance and cognitive development [15, 27–31]. It should also be considered that the most vulnerable population, such as children with autism spectrum disorder, hearing impairment, or language disorders, are greatly affected by interior noise levels [32]. Thus, safeguarding an acoustic comfort, understood as the perceived state of well-being with acoustical conditions, is essential to achieve the development of student-centered learning modalities.

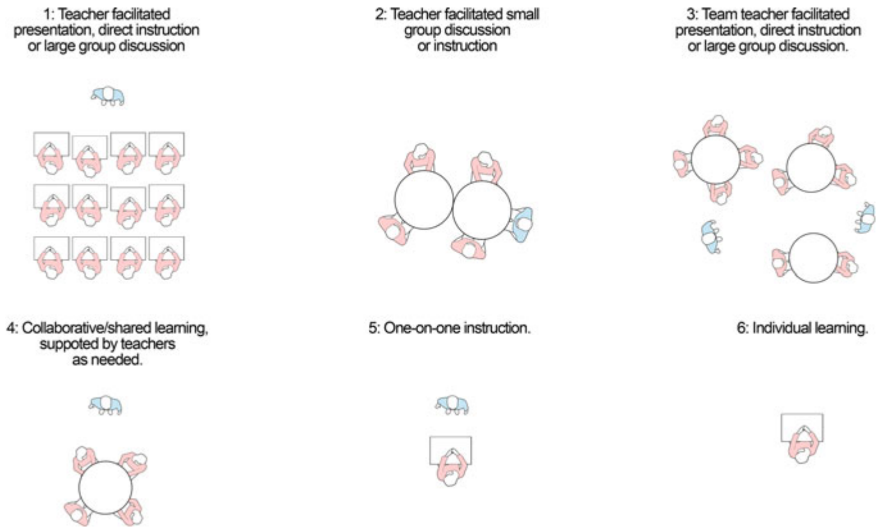

Fig. 3 Teaching and learning approaches, according to [4], adapted by [3] and redrawn by the authors

In the Global South, great efforts have been made to improve the conditions of educational infrastructure and support the demands that this new era entails. An example of this has been the work carried out in recent years by the Education Division of the Inter-American Development Bank (IDB) and the local agencies of the region's countries,[1] where they have sought, through projects and public policies, to promote and guarantee access for students to resilient, sustainable, and accessible infrastructures, to improve the installed capacity for learning and skills of the twenty-first century in Latin America and the Caribbean [33]. However, although there is still an important gap regarding the progress of the Global North and no evidence has been found yet on acoustic quality in this context, flexibility in educational spaces is being incorporated into the design of spaces in the region,[2] and therefore, environmental acoustic challenges are an extremely relevant area to consider, especially based on the foreign experience of the northern countries.

[1] In 2010, Argentina, Barbados, Chile, Colombia, Costa Rica, Guatemala, Honduras, Jamaica, Mexico, Dominican Republic, and Trinidad and Tobago, presented the "Learning in Schools of the twenty-first century" proposal and obtained funding from IDB's Regional Public Assets program, whereby they have found design alternatives to create spaces that are conducive to new learning, along with planning tools, sustainable construction methods, and financing alternatives, with varying achievements in the field of school infrastructure.

[2] In 2018, the IDB-led architecture competition, "Schools of the twenty-first century in Latin America and the Caribbean" was launched. The call received 115 innovation applications from 17 countries in diverse fields of design, construction, management, and use. These buildings can be reviewed in the catalog of infrastructures selected by the "Schools of the twenty-first century in Latin America and the Caribbean" contest, where 80 buildings that facilitate twenty-first century learning and skill development have been recognized [33].

2 Acoustic Parameters for the Design of Educational Spaces

Acoustic design has not been fully integrated into the vast majority of educational spaces in the southern hemisphere and the interior conditioning of classrooms has recently been considered within some public policies and design guidelines to safeguard user well-being [34]. However, at a global level, learning spaces have traditionally been acoustically conditioned by the Reverberation Time (RT) and Background Noise Level (L_{eqAS}) parameters, and occasionally, some standards have integrated the Speech Transmission Index (STI) and Signal-to-Noise Ratio (SNR). These parameters are normally applied in both traditional and flexible spaces, despite the great differences in spatial terms and pedagogical use.

Reverberation Time (RT) Reverberation time is defined as the persistence time of the sound, in seconds, once a sound source has stopped emitting inside a room. Its duration depends mainly on the volume and absorption of the space since it is the travel time of successive reflections of sound waves on the surfaces of the inner envelope. Although reverberation time is measured over a spectrum of frequency bands, most standards define a unique number (RTmid), corresponding to the arithmetic average of the 500 Hz, 1 kHz, and 2 kHz frequency bands. In educational spaces, the maximum reverberation time commonly used is 0.6 s [34–40], although depending on the standard, the requirements vary considering the volume of the space, where the lower the volume, the longer the requested reverberation time is.

Noise Level (L_{eqAS}) Ambient noise levels in unoccupied learning spaces are generated by different sources from inside and outside. While the noises from outside are usually produced by traffic or other adjacent spaces such as classrooms, yards, and circulation spaces, noises from ventilation equipment, lighting, or projectors are found inside the premises. Generally, the noise inside the spaces is characterized as an equivalent continuous weighted sound pressure level A (L_{eqAS}) and is measured at a given time. Depending on the standard, the background noise level requirement in furnished spaces and without the presence of students and teachers varies with a maximum of between 30 dBA and 35 dBA [36–38, 40, 41]. Likewise, this parameter generally defines or is associated with the acoustic insulation that the different constructive elements of the space's envelope must provide.

Speech Transmission Index (STI) Speech intelligibility represents the degree of understanding of a speech considering ambient noise levels, reverberation time, and the location of the speaker and the listener. Classifying speech intelligibility by using STI, allows evaluating the comprehension of the spoken voice from 0 to 1, quantifying the percentage of the message that is understood correctly. When an STI is greater than 0.6, the intelligibility is considered good to excellent (greater than 0.75), while between 0.45 and 0.6, it is regular, and less than that number would have a subjective assessment of deficient or bad. In educational spaces, an STI of 0.6 is mostly accepted.

Signal-to-Noise Ratio (SNR) This ratio identifies the difference between the levels of the spoken voice and the noise level of the learning environment under occupation conditions. Some authors recommend providing a signal-to-noise ratio of between +15 dB [40] and +20 dB [42], especially for primary school students, to ensure optimal speech intelligibility. However, considering that the weighted sound pressure level of the voice at a distance of one meter is 57.4 dBA for normal voices, and 66.5 dBA for raised voices [40], this ratio is difficult to achieve when there are group and collaborative learning activities, due to the noise level associated with these.

3 Acoustic Design Barriers

To analyze the situation and the challenges of school infrastructure in Latin America and the Caribbean, in 2010, the Inter-American Development Bank project "Learning in Schools of the twenty-first century", was created [43]. Starting from this project, an environmental and energy audit of 117 representative classrooms was carried out in six countries, among them Chile, where it was shown that, in most unoccupied spaces, the noise levels did not comply with the limits established by the international standard, demonstrating a problem both with the sound insulation of envelope elements and with internal acoustic conditioning [44].

Following on from this project, acoustic design criteria were included in the Strategic School Infrastructure of the Ministry of Education [45] and the Design Guide for New Educational Spaces [34], which has recently been updated [35]. Since then, compliance with the acoustic performance parameters of reverberation time, speech intelligibility, and acoustic insulation of the façade and between premises has been requested in the country's new public primary and secondary schools. However, the guide does not require a maximum background noise level. A study in Santiago de Chile [46] has concluded that, with current urban noise levels, it would not be possible to apply the acoustic criteria of the guide in 70% of schools.

Moreover, when analyzing the recommended values for background noise (L_{eqAS}), reverberation time (RT), and the speech transmission index (STI) for closed and open spaces in different countries (See Table 1), the absence of acoustic conditioning requirements for occupied learning spaces is seen, even when learning methodologies have changed and the sound environment has become more complex.

It should be noted that Table 1 considers closed spaces, as those traditional four-walled classrooms with a single class group, and open spaces, as those learning spaces connected by semi-open mobile divisions, or that in open plan, form a learning community integrating parallel class groups. In this regard, it should be noted that the New Zealand regulations welcome the change of educational paradigm, assuming that every school incorporates active and innovative learning, and therefore, does not differentiate between open and closed space. In addition, although only the United

Table 1 Summary of acoustic criteria for educational spaces in countries

Standard	Country	Closed space			Open space		
		L_{eqAS} (dBA)	RT (s)	STI	L_{eqAS} (dBA)	RT (s)	STI
MINEDUC	Chile	–	0.6–0.7	0.6	–	–	–
BB93	UK	30–35	0.6–0.8	–	40–45	0.5	0.6[b]–0.3[c]
ANSI S12.60	USA	35	0.6–0.7	0.6	–	–	–
DQLS	New Zealand	–	–	–	40–45	0.4–0.5 1.2[a]	–
BR15	Denmark	30	0.6	0.6	30	0.3–0.4	0.6[b]–0.2[c]
SS025268	Sweden	26–40	0.6	–	30	0.4	–
NBN 01-400-2	Belgium	35	0.35log (1.25 V)	–	–	–	–
Mode		35	0.6	0.6	30	–	0.6

[a]Break spaces or resource rooms
[b]Instruction or critical listening activity–within the group
[c]Between groups (during critical listening activities)
L_{eqAS}: background noise level in an unoccupied classroom
RT: average reverberation time
STI: speech transmission index

Kingdom, Sweden, and Denmark define specific acoustic criteria for open spaces, only Danish and UK regulations differentiate STI values between instructional and critical listening areas and intermediate spaces to protect acoustic privacy between learning groups.[3] In the case of New Zealand, this distinction is made using the reverberation time differentiated by area.

Likewise, among the aforementioned countries, there is a variation in the standards recommended for open spaces, evidencing impressions when defining which parameters would be optimal to characterise the acoustics of a flexible learning space. On the other hand, the ANSI and BB93 standards do not encourage designing partially closed or fully open learning spaces for critical listening activities because adequate acoustic isolation between parallel groups cannot be guaranteed.

It could be pointed out that, although most countries of the Global South and North promote spatial flexibility in school design to meet contemporary educational challenges, in acoustic terms, a large part of the standards have not changed profoundly in the last 20 years [22] and the acoustics of closed space continues to be addressed to achieve optimal intelligibility conditions, especially for instructional-type teaching. In this regard, although the acoustic criteria summary table reflects an optimal reverberation time of 0.6 s, with the exception of some countries, it has been shown that, in active learning spaces, a maximum acceptable

[3] With STI, it is possible to identify privacy and speech distraction distances [47] to evaluate whether tasks that require cognitive resources are being affected by parallel conversations. The speech distraction distance is evaluated when the STI falls below 0.5 with regard to the speaker, while the privacy distance is evaluated when an STI falls below 0.2.

reverberation time should reach between 0.35 and 0.5 s, to achieve an adequate SNR [15, 48].

Likewise, it has been concluded that, for open-plan spaces with dynamic activities and variable levels of intrusive noise, it is more appropriate to use a design criterion such as the STI, since it combines SNR and reverberation in a single parameter [15]. However, although several studies in the Global North have measured noise levels between 58 and 77 dB during group learning activities [24, 48–50], and in Chile, noise levels between 63 and 79 dB have been found in unoccupied classrooms [51]; it has been recommended indoor noise levels between 55 dBA [14, 52] and 60 dBA [53] under occupied conditions, which involves both the acoustic conditioning of the project and the educational itinerary of the learning center.

4 Acoustic Design Challenges

From an acoustic design perspective, it is relatively simple to ensure a comfortable acoustic environment in closed spaces for teacher-centered learning. In Fig. 4, it can be seen that when the teaching approach is only instructional and the indoor noise levels do not exceed 45 dB, the acoustic conditioning should only be responsible for achieving an adequate reverberation time, distributing the absorbent materials considering the amplification of the speech at the front part of the space.

Nevertheless, by making the space more flexible, and providing a variety of learning modalities, new challenges emerge to achieve adequate environmental acoustic comfort, since the organization of furniture and space changes depending on the teaching approach and activities. However, regardless of the variety of learning experiences provided, it will be essential to safeguard adequate verbal communication, reducing the distraction associated with the dynamic noises of conversation and movement in the environment.

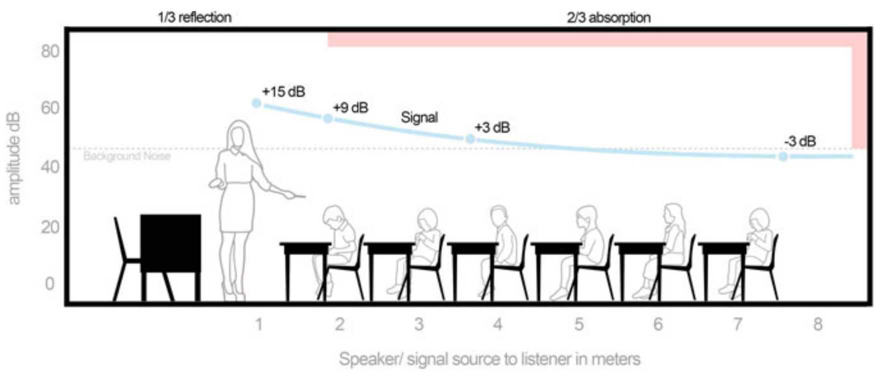

Fig. 4 Relationships between SNR and distance absorbing surfaces for instructional teaching

As a result, learning from the past will be key. Although spatial flexibility in learning environments was explored between the 1950s and 60s through open and semi-open floor plan typologies in North America, the UK, and other countries [54], many of these spaces reverted to the traditional system in the late 1970s, due to a disconnect between the educational project and architectural intentions, and problems of environmental acoustic comfort related with interior noise levels [15, 27, 55–58].

One of the most significant impacts of acoustic conditioning on students is when group learning activities take place, and the simultaneous conversations of groups cause students to raise their voices, triggering a chain reaction that increases noise levels inside the space (Lombard effect). Previous studies have shown that this phenomenon, accompanied by a high reverberation, can be deleteriously critical to speech intelligibility and even more so in elementary school students who are developing their communication skills [59].

In a study of 13 Schools in the United Kingdom, [24] observed a significant positive correlation between noise levels for learning activities and reverberation time and identified factors that affect the acoustic conditions of learning spaces. On one hand, they suggested controlling the volume of the space using a maximum height of 2.4 m when sufficient acoustic absorption is not incorporated into the premise's surfaces and, on the other, proposed limiting the amount of reflective glass surface to 16% of the surfaces. Other authors have promoted incorporating absorbent material in at least 90% of the ceiling surface, limiting the height of the acoustic ceiling to 3.5 m, using carpets to reduce the impact of footsteps and the movement of tables [15, 60], and developing a homogeneous distribution of the absorbent surfaces on the walls, to avoid unwanted reflection effects, such as floating echo or sound deviation [36].

Nowadays, with the paradigm shift in education, some authors have recommended that research develops new ways to approach the acoustic design of educational spaces, considering the operationalization of space following the diversity of pedagogical use scenarios [61, 62]. In turn, due to the limited evidence on noise control strategies, for [63], there is an outstanding challenge in developing new noise control strategies and systems that customize acoustic environments to learning needs.

Mealings et al. [14], for example, demonstrated in a comparative case study between closed, open, and semi-open classrooms, that a flexible space with more than 90 students is not appropriate due to the high levels of intrusive noise that occur in the environment. In addition, although closed classrooms presented the best acoustic condition against the intrusive noise of other activities, they suggested that spaces with sliding walls can provide acoustic and pedagogical flexibility in the spaces.

However, with the use of acoustic barriers, such as furniture that blocks the line of sight between activities and at the same time generates micro spatialities to house small learning groups, it would be possible to have classes that involve critical listening activities in open spaces, since this type of strategies interrupt reflection routes, dispersing and reducing sound energy even with the presence of intrusive noise.

To achieve these challenges in open spaces, [15], in a systematic review of the effects of noise in open-plan spaces, have recommended that the mobile divisions

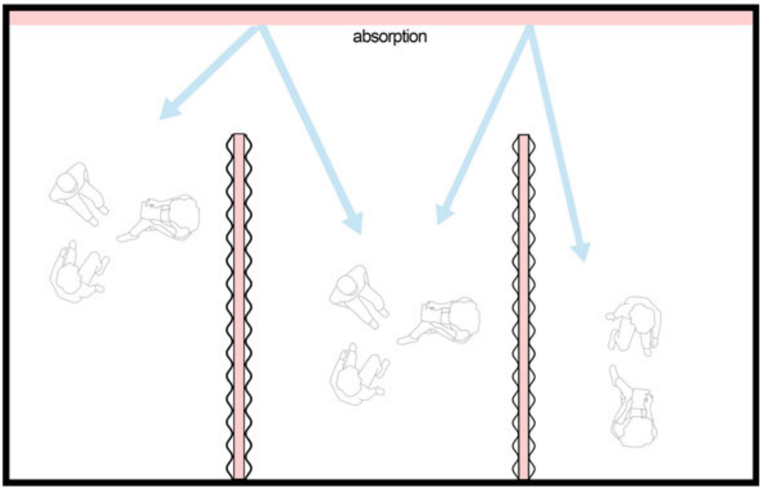

Fig. 5 Effect of surfaces on the use of acoustic partition screens in group work

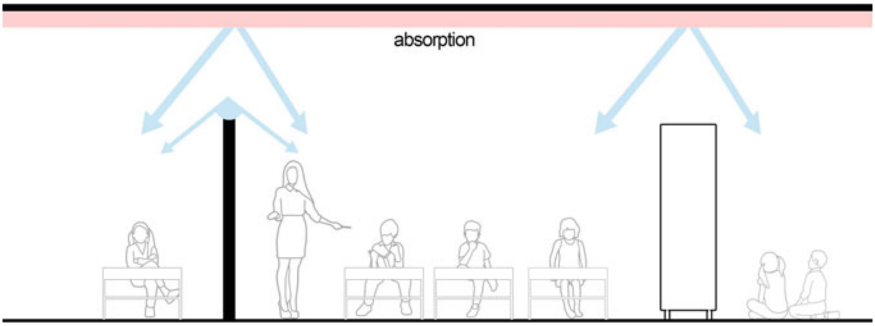

Fig. 6 Effect of height on acoustic screens and dividing furniture in group work

between learning groups have heights of at least 1.6 to 2.0 m and absorbent material incorporated in the ceiling and wall surfaces to avoid sound reflection (See Figs. 5 and 6). Also, separations between classes would have to be at least 6.5 m, and an ideal surface per child should be between 4 and 5 m^2, which is quite distant from the current conditions in Chile, where an area of 2 m^2 per student is considered in each class.

6

Regarding the speech intelligibility parameter, for [48], if a reverberation of 0.4 s is assumed in the furnished space, when there is noise during critical listening activities, students should meet within 3 m of the speaker and the estimated STI values, to achieve satisfactory intelligibility, should be 0.61, with a minimum SNR of 8.5 dB, for 11-year-old students, 0.69 with an SNR of 12.5 for 8-year-old students, and 0.75,

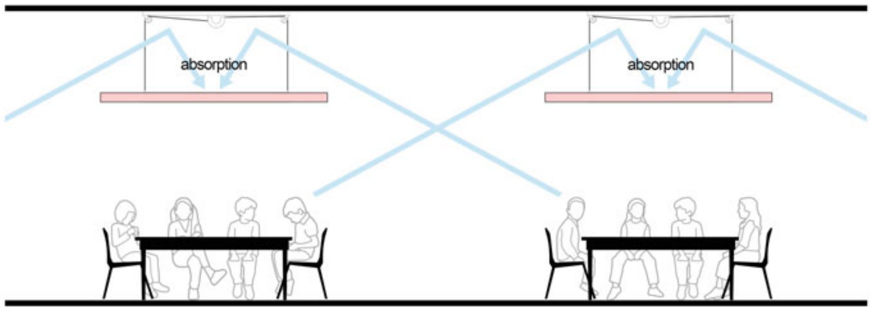

Fig. 7 Effect of dropped ceilings during group work

with an SNR of 15.5 dB, for 6-year-old boys and girls, since cognitive and auditory processing is still developing.

On the other hand, [64], through a simulation of the acoustic performance of 5 configurations of a closed learning space, with two variants of an individual acoustic control device for two types of activity (individual study and conference), confirmed that by incorporating a variable acoustics device, the reverberation and sound pressure levels (SPL) of voices in the space could be increased or reduced, depending on the learning situations sought. Based on this innovation, the results suggest that thinking about lower ceiling areas in some work areas could contribute to acoustic comfort by reducing or amplifying sound energy and the possible reflections generated on the ceiling within specific areas of a room (See Fig. 7).

If the function and pedagogical use of the learning space change, it seems insufficient to assume that all learning situations can be remedied with static acoustic design criteria that respond mainly to critical listening activities of instructional-type teaching. Considering other types of active and group learning activities also demands reducing or redirecting noise sources, and therefore, incorporating acoustic design strategies through furniture or other control devices, to improve teaching and learning situations, following the needs of each school community, and seeking the integration of variable acoustics that reinforces existing standards.

5 Conclusions

Based on the new challenges posed by the twenty-first century, for approximately 10 years, the Global South has begun to rethink the design of learning spaces as a catalyst for pedagogical change. The incorporation of flexibility and versatility of use from a declared approach of comfort and environmental sustainability has allowed providing a wider variety of educational experiences and encouraged collaboration between teachers and students. However, guaranteeing student-centered learning and safeguarding the quality of the indoor environment and communication as a fundamental motor of the educational process, has been a little addressed aspect in the region, although, given the evidence of the northern countries, it will probably present great challenges in the coming years.

It is known that the values recommended for indoor acoustic conditioning are insufficient to ensure environmental comfort, especially considering contemporary principles in education. First, because mainly acoustic conditioning in unoccupied spaces has been considered, and second, because they generally solve instructional-type critical listening, except for New Zealand, Denmark, Sweden, and the United Kingdom, which contemplate some criteria for open or semi-open plan spaces, although with a broad difference between their descriptors. In Chile, although insulation is required on walls, recommendations for background noise levels are not contemplated, which makes it even more difficult to safeguard good acoustic quality against noise sources that may come from outside.

Considering that group and collaborative work are learning approaches that generate high levels of noise, affecting speech intelligibility between students and teachers, the literature would seem to suggest that the first condition to acoustically manage the flexible space would be to achieve a reverberation time of 0.4 s, to homogeneously distribute absorbent elements on the surfaces, and not exceed heights of 3.5 m. However, incorporating other acoustic strategies that allow interrupting, dispersing, and reducing the sound energy between learning groups, by using vertical or horizontal elements, could provide greater acoustic versatility to the space, although this aspect lacks study.

To rethink the acoustics of space based on the well-being, needs, and health of all the people who inhabit a school community, it will be essential to understand the degrees of flexibility in architecture and pedagogy, addressing the different sound scenarios educational experiences have. Once that is understood, incorporating variable acoustics strategies that improve current barriers and update interior acoustic conditioning designs in the different learning modalities, perhaps it can guarantee, together with adequate management of the educational center, compliance with appropriate acoustic comfort.

Finally, due to the poor acoustics of the current infrastructure in the Global South, the consequences that hybrid online learning systems will have during the Covid-19 pandemic are still unknown. Primary education, which provides the basics for reading and communication, will probably have to compensate for the literacy gap as soon as possible. Thus, acoustic comfort and speech intelligibility will be an urgent challenge.

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References

1. Nair P (2014) Blueprint for tomorrow: Redesigning schools for student-centered learning. Harvard Education Press
2. Barrett P, Davies F, Zhang Y, Barrett L (2017) The holistic impact of classroom spaces on learning in specific subjects. Environ Behav 49:425–451. https://doi.org/10.1177/0013916516648735
3. Cleveland B, Soccio P, Love P (2016) Learning environment evaluation and the development of school facility design guidelines. In: Baguley M (ed) Australian association for research in education (AARE) conference 2016, Australian association for research in education (AARE), Melbourne, Victoria, http://hdl.handle.net/11343/191239
4. Dovey K, Fisher K (2014) Designing for adaptation: The school as socio-spatial assemblage. J Archit 19:43–63. https://doi.org/10.1080/13602365.2014.882376
5. Starkey L, Leggett V, Anslow C, Ackley A (2021) The use of furniture in a student-centred primary school learning environment. NZ J Educ Stud 56:61–79. https://doi.org/10.1007/s40841-020-00187-9
6. Imms W, Mahat M, Byers T, Murphy D (2017) Type and use of innovative learning environments in australasian schools ILETC survey 1
7. Attai SL, Reyes JC, Davis JL, York J, Ranney K, Hyde TW (2021) Investigating the impact of flexible furniture in the elementary classroom. Learn Environ Res 24:153–167. https://doi.org/10.1007/s10984-020-09322-1
8. Clinton V, Wilson N (2019) More than chalkboards: Classroom spaces and collaborative learning attitudes. Learn Environ Res 22:325–344. https://doi.org/10.1007/s10984-019-09287-w
9. Kariippanon KE, Cliff DP, Lancaster SL, Okely AD, Parrish AM (2018) Perceived interplay between flexible learning spaces and teaching, learning and student wellbeing. Learn Environ Res 21:301–320. https://doi.org/10.1007/s10984-017-9254-9
10. Barrett P, Treves A, Shmis T (2019) The impact of school infrastructure on learning: A synthesis of the evidence. World Bank Group, Washington, DC
11. Kariippanon KE, Cliff DP, Lancaster SJ, Okely AD, Parrish AM (2019) Flexible learning spaces facilitate interaction, collaboration and behavioural engagement in secondary school. PLOS ONE 14:e0223607. https://doi.org/10.1371/journal.pone.0223607
12. Manca S, Cerina V, Tobia V, Sacchi S, Fornara F (2020) The effect of school design on users' responses: A systematic review (2008–2017). Sustainability 12:3453. https://doi.org/10.3390/su12083453
13. Sala E, Rantala L (2016) Acoustics and activity noise in school classrooms in Finland. Appl Acoust 114:252–259. https://doi.org/10.1016/j.apacoust.2016.08.009
14. Mealings KT, Buchholz JM, Demuth K, Dillon H (2015) Investigating the acoustics of a sample of open plan and enclosed kindergarten classrooms in Australia. Appl Acoust 100:95–105. https://doi.org/10.1016/j.apacoust.2015.07.009
15. Shield B, Greenland E, Dockrell J (2010) Noise in open plan classrooms in primary schools: A review. Noise Health 12:225–234. https://doi.org/10.4103/1463-1741.70501
16. Vijapur D, Candido C, Özgür G, Wyver S (2021) A ten-year review of primary school flexible learning environments: Interior design and IEQ performance. Buildings 11:183. https://doi.org/10.3390/buildings11050183
17. Mealings KT, Demuth K, Buchholz JM, Dillon H (2015) An assessment of open plan and enclosed classroom listening environments for young children: Part 2-teacher's questionnaires. J Educ Pediatr (Re)Habilitat Audiol 21:20–38
18. Mogas-Recalde J, Palau R, Márquez M (2021) How classroom acoustics influence students and teachers: A systematic literature review. J Technol Sci Educ 11:245. https://doi.org/10.3926/jotse.1098
19. Alterator S, Deed C (2013) Teacher adaptation to open learning spaces. Issues Educ Res 23:315–330

20. Bluyssen PM, Zhang D, Kurvers S, Overtoom M, Ortiz-Sanchez M (2018) Self-reported health and comfort of school children in 54 classrooms of 21 dutch school thuildings. Build Environ 138:106–123. https://doi.org/10.1016/j.buildenv.2018.04.032
21. Zhang D, Ortiz MA, Bluyssen PM (2019) Clustering of dutch school children based on their preferences and needs of the IEQ in classrooms. Build Environ 147:258–266. https://doi.org/10.1016/j.buildenv.2018.10.014
22. Robinson A, Bellert A (2020) Co-teaching in (refurbished) flexible learning spaces: Promoting quality acoustics for learning and collaboration. In: Acoustics 2019, sound decisions: Moving forward with acoustics–proceedings of the annual conference of the Australian acoustical society, Cape Schanck, Victoria, Australia
23. Chiang CM, Lai CM (2008) Acoustical environment evaluation of joint classrooms for elementary schools in Taiwan. Build Environ 43:1619–1632. https://doi.org/10.1016/j.buildenv.2007.10.014
24. Shield B, Conetta R, Dockrell J, Connolly D, Cox T, Mydlarz C (2015) A survey of acoustic conditions and noise levels in secondary school classrooms in England. J Acoust Soc Am 137:177–188. https://doi.org/10.1121/1.4904528
25. Karjalainen S, Brännström JK, Christensson J, Sahlén B, Lyberg-Åhlander V (2020) A pilot study on the relationship between primary-school teachers' well-being and the acoustics of their classrooms. Int J Environ Res Pub Health 17:2083. https://doi.org/10.3390/ijerph17062083
26. Klatte M, Hellbrück J, Seidel J, Leistner P (2010) Effects of classroom acoustics on performance and well-being in elementary school children: A field study. Environ Behav 42:659–692. https://doi.org/10.1177/0013916509336813
27. Shield BM, Dockrell JE (2003) The effects of noise on children at school: A review. Build Acoust 10:97–116. https://doi.org/10.1260/135101003768965960
28. Shield BM, Dockrell JE (2008) The effects of environmental and classroom noise on the academic attainments of primary school children. J Acoust Soc Am 123:133–144. https://doi.org/10.1121/1.2812596
29. Klatte M, Bergström K, Lachmann T (2013) Does noise affect learning? A short review on noise effects on cognitive performance in children. Front Psychol 4:578. https://doi.org/10.3389/fpsyg.2013.00578
30. Zhang D, Tenpierik M, Bluyssen PM (2019a) The effect of acoustical treatment on primary school children's performance, sound perception, and influence assessment. E3S Web Conf 111:02046. https://doi.org/10.1051/e3sconf/201911102046
31. Zhang D, Tenpierik M, Bluyssen PM (2019) Interaction effect of background sound type and sound pressure level on children of primary schools in the Netherlands. Appl Acoust 154:161–169. https://doi.org/10.1016/j.apacoust.2019.05.007
32. Nelson PB, Soli S (2000) Acoustical barriers to learning. Lang Speech Hear Serv Schools 31:356–361. https://doi.org/10.1044/0161-1461.3104.356
33. Bos MS, Schwartz L, Licheri M (2018) Escuelas del Siglo XXI en América Latina y el Caribe. Washington D.C., https://doi.org/10.18235/0001450
34. Ministerio de Educación (2016) Criterios de diseño para los nuevos espacios educativos. Santiago, Chile
35. Ministerio de Educación (2020) Guía Criterios de Diseño para Proyectos de Ampliación. Reposición y Construcción Nueva, Santiago, Chile
36. Ministry of Education (2020) Designing quality learning spaces (DQLS) acoustics. New Zealand
37. Education and Skills Funding Agency (2014) BB93: Acoustic design of schools–performance standards. UK. https://www.gov.uk/government/publications/bb93-acoustic-design-of-schools-performance-standards
38. SBi-anvisning 258 (2015) Anvisning om bygningsreglement 2015 (Guidelines on building regulations 2015). Denmark
39. SIS–Bygg och anläggning (2007) SS 25268:2007 Acoustics–Sound classification of spaces in buildings–Institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels. Sweden

40. ANSI/ASA (2010) S12.60-2010/Part1 acoustical performance criteria, design requirements, and guidelines for schools, Part 1: Permanent schools. USA
41. NBN (2012) NBN S 01-400-2 acoustic criteria for school buildings. Belgium
42. Bradley JS, Sato H (2008) The intelligibility of speech in elementary school classrooms. J Acoust Soc Am 123:2078–2086. https://doi.org/10.1121/1.2839285
43. Gargiulo C (2014) Aprendizajes en las escuelas del siglo XXI: Nota 1: Introducción a la serie de notas. https://publications.iadb.org/en/learning-twenty-first-century-schools-note-1-series-introduction
44. SanJuan G, Hoses S, Martini I (2014) Aprendizaje en las escuelas del siglo XXI: Nota 5: Auditoría ambiental y condiciones de confort en establecimientos escolares. https://publications.iadb.org/es/publicacion/17002/aprendizaje-en-las-escuelas-del-siglo-xxi-nota-5-auditoria-ambiental-y
45. Ministerio de Educación (2014) Plan Estratégico de Infraestructura Escolar: Fortaleciendo la Educación Pública. Santiago, Chile
46. Aguilar JR (2019) Una mirada a los criterios de diseño acústico de la infraestructura educacional en Chile. Revista ingeniería de construcción 34:115–123. https://doi.org/10.4067/S0718-50732019000200115
47. ISO (2012) ISO 3382-3:2012 acoustics—measurement of room acoustic parameters—part 3: Open plan offices
48. Greenland EE, Shield BM (2011) A survey of acoustic conditions in semi-open plan classrooms in the united kingdom. J Acoust Soc Am 130:1399–1410. https://doi.org/10.1121/1.3613932
49. Sarantopoulos G, Lykoudis S, Kassomenos P (2014) Noise levels in primary schools of medium sized city in Greece. Sci Total Environ 482–483:493–500. https://doi.org/10.1016/j.scitotenv.2013.09.010
50. Lundquist P, Holmberg K, Landstrom U (2000) Annoyance and effects on work from environmental noise at school. Noise Health 2:39–46
51. Armijo G, Whitman CJ, Casals R (2011) Post-occupancy evaluation of state schools in 5 climatic zones of chile. Gazi Univ J Sci 24:365–374. https://orca.cardiff.ac.uk/id/eprint/69707/
52. Mealings KT (2016) Classroom acoustic conditions: Understanding what is suitable through a review of national and international standards, recommendations, and live classroom measurements. In: Proceedings of acoustics2016: the second Australasian acoustical societies conference, Australian acoustical society, vol 2, pp 1047–1056
53. Kristiansen J, Lund SP, Persson R, Challi R, Lindskov JM, Nielsen PM, Larsen PK, Toftum J (2016) The effects of acoustical refurbishment of classrooms on teachers' perceived noise exposure and noise-related health symptoms. Int Arch Occup Environ Health 89:341–350. https://doi.org/10.1007/s00420-015-1077-3
54. Bennett N, Andreae J, Hegarty P, Wade B (1980) Open plan schools
55. Lewis PT (1977) Noise in primary schools: implications for design. J Architect Res 6:34–37
56. Kingsbury HF, Taylor DW (1970) Acoustical conditions in open-plan classrooms. J Acoust Soc Am 47:79–79. https://doi.org/10.1121/1.1974729
57. Brogden M (1983) Open plan primary schools: Rhetoric and reality. School Organ 3:27–41. https://doi.org/10.1080/0260136830030104
58. Atkin J, Chester M, Cleveland B, Culkin M, Calzini J, Davies M, Featherston M, Goddard T, Hes D, Jamieson P, Leonard R, London G, Salagaras S, Stewart P, Sutton L, Wilks S, Woodman K (2009) TAKE 8 learning spaces: The transformation of educational spaces for the 21st century. Australian Institute of Architects
59. Whitlock J, Dodd G (2006) Classroom acoustics–controlling the cafe effect...is the lombard effect the key? In: Acoustics 2006., Christchurch, New Zealand, pp 423–426
60. IOA/ANC (2015) Acoustics of schools: a design guide. UK
61. Pääkkönen R, Vehviläinen T, Jokitulppo J, Niemi O, Nenonen S, Vinha J (2015) Acoustics and new learning environment-a case study. Appl Acoust 100:74–78. https://doi.org/10.1016/j.apacoust.2015.07.001
62. Bluyssen PM (2017) Health, comfort and performance of children in classrooms-new directions for research. Indoor Built Environ 26:1040–1050. https://doi.org/10.1177/1420326X16661866

63. Mogas-Recalde J, Palau R, Galés NL, Gallon R (2020) Developments for smart classrooms. Int J Mobile Blend Learn 12:34–50. https://doi.org/10.4018/IJMBL.2020100103
64. Zhang D, Tenpierik M, Bluyssen PM (2021) Individual control as a new way to improve classroom acoustics: A simulation-based study. Appl Acoust 179:108066. https://doi.org/10.1016/j.apacoust.2021.108066

Energy Use and Energy Efficiency

Impact of Urban Re-Densification on Light Consumption and Energy Poverty: On the Equator—in the City of Quito

Estefanía Montes-Villalva, María Beatriz Piderit-Moreno, and Alexis Pérez-Fargallo

Abstract The high-rise re-densification of cities is jeopardizing sunlight access for housing, with the ensuing repercussions on the quality of life and welfare of their inhabitants, as well as the energy and light benefits of solar radiation. This article evaluates the impact of urban re-densification on the lighting energy demand in high-rise dwellings in Ecuador. Thus, the urban and building characteristics of the city of Quito were analyzed, using simulation tools to explore the reduction of solar irradiance on the facade, and the increase in lighting demand while determining boundary conditions vis-a-vis the increase in energy demand, the average wage, and the ten percent rule. The results show that solar obstructions and shadows cast between buildings reduce solar radiation by between 40 and 80%, increasing lighting consumption compared to an unobstructed scenario, by between 2 and 498%. These re-densification scenarios can lead to relevant social issues associated with energy poverty. Concluding that, to avoid energy poverty, the possible building height must be limited considering the street width. This research seeks to help public policy developers in their future decision-making, as it opens up the debate between high-rise re-densification and energy poverty, presenting risks that are currently not considered in urban planning.

Keywords Solar access · Urban densification · Solar obstruction · Lighting consumption · Energy poverty

E. Montes-Villalva · A. Pérez-Fargallo (✉)
Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: aperezf@ubiobio.cl

M. B. Piderit-Moreno
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mpiderit@ubiobio.cl

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1 Introduction

The construction sector is facing major problems such as energy consumption (EC), energy poverty (EP), and climate change [1]. This phenomenon has attracted the attention of the scientific community and society, in general, due to its political and social implications [2, 3].

Some research has linked solar access and urban geometry to a higher or lower likelihood of EP [4]. EP is related to the inability of homes to maintain minimum temperatures, have energy services available, or ones that are affordable [2, 5]. There is a broad consensus that EP emerges as a result of the high energy prices, low family incomes, buildings with low energy efficiency (EE), inefficient household appliances [6, 7], and the needs and practices of the occupants [8], discarding the influence of the urban setting on the increase or reduction of EP. However, the energy performance of buildings and, therefore, energy expenses for air-conditioning depend on the climate, the building design, efficient systems, and occupant behavior [9]. Some authors also introduce the concept of "Inter-Building Effects", highlighting the importance of fully understanding the energy issues when considering the complex interactions that are produced by spatial proximity [10, 11]. Within the urban morphology, the orientation, urban density, building height ratio, and street width play a determining role in their performance [12], and also for a greater or lesser risk of suffering from EP [4].

City densification is a determining indicator for their planning, an aspect that is directly linked with the energy use of the buildings [13]. Previous research has shown that, in latitudes close to the equator, re-densification heights of 200 m to 240 m represent a winter sunlight reduction of between 40 and 70% in a radius of 150 m [14]. On the other hand, in a densification scenario of 60%—the ratio between the built area and the total area of analysis—the heating demand increases by up to 20%, while in densification scenarios of 30%, it does so by 3% [15]. Under the same conditions, it has been seen that the lighting demand increases by up to 42% [16], with the main issue being that the urban canyons considering the highest aspect have lower potential daylight, and possibly a higher dependence on artificial lighting, hence the higher energy demand [17].

The city of Quito, under its current growth model, has issues with mobility, services, inequality, etc. [18]. The issue of urban city growth has been considered in territorial organization proposals, but since 1984, it has been acknowledged that peripheral settlements are a pending problem [19]. Urban sprawl, especially informal, the result of unplanned occupation or invasion, is the main urban problem in Quito [20], generating an urban segregation phenomenon and marginalization of low-income users [21], that increases inequality in the city [22], even generating labor exclusion patterns linked to residential location and mobility [23].

For this reason, urban planning has sought to re-density urban areas, develop a compact city model, and contain the sprawl and porosity of the current city. This urban process falls within the Increased Constructability Ordinance, in areas close to the city's first metro line and the Bus Rapid Transit (BRT) system, looking to reduce the aforementioned issues.

Although this high-rise growth is not obligatory, it is felt that in the future, these consolidated areas are transformed and re-densify the current height two-fold, just as has been seen in Bogotá, Montevideo, Santiago, and Sao Paulo, among others. This re-densification within a consolidated and irregular sector, such as that of Quito, can cause solar obstructions that affect both the urban and living space [24].

Currently, lighting covers 28% of the total energy consumption in the residential sector of the Ecuadorian Highlands [25], an aspect that will increase if solar access is considerably reduced, which may also entail an increase in Energy Poverty in the city [26].

There is a lack of research on the impact of urban re-densification regarding the increase of lighting consumption, and, therefore, EP situations on the equator. For this reason, the purpose of this article is to assess how the increased constructability associated with orientation and a number of stories affects solar access, lighting consumption, and energy poverty in Quito dwellings, to finally establish maximum height recommendations considering the distance between buildings that limits the increase of lighting-related energy poverty. To establish this link, the Ten Percent Rule of Boardman [7] has been used.

This research looks to help public policy developers in future decision-making, about risks that are currently not considered in urban planning, and that may go against sustainable development goals linked to the reduction of social inequality, and the reduction of energy consumption.

2 Methodology

2.1 Urban Reference System

Solar-morphological analysis is circumscribed to the concept of an urban canyon. For this reason, the first stage of the research comprised establishing the prevailing urban features of the city of Quito. Concerning the morphological features, a survey was made of the current high-rise buildings, street widths, and orientations, while to establish the geometry and orientation of the scenarios, the Land Occupation and Use Plan (PUOS, in Spanish) and the cadaster of Quito were used. Different scenarios were defined with this information: one without solar obstruction, and five with the most typical distances of the urban setting. These scenarios were combined with the orientations, which were made using the ArcGIS© tool.

2.2 Case Study

The case study, based on the current regulations, was set up on a lot of 400 m^2, with a 20 m face. From this minimum location condition, a floor area of 340 m^2 was proposed, with a floor-to-floor height of 4 m, and an 18 m by 2.2 m high sliding window.

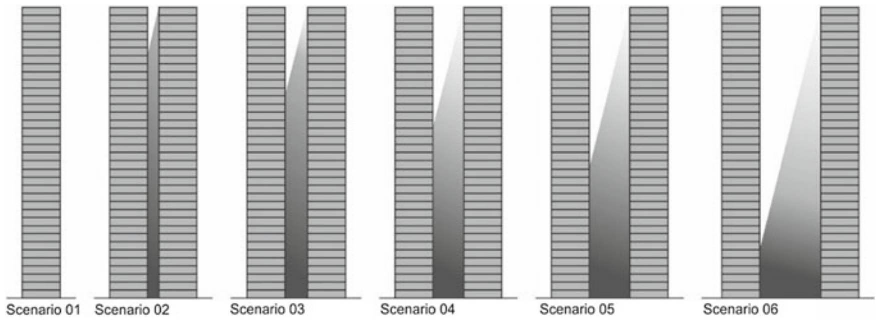

Fig. 1 Analysis scenarios. Critical densification of 36 floors and spacing variations

To characterize the urban canyon, fourteen buildings were randomly chosen in the study area, with different heights and building features. From these, the material of the façade, color, texture, and opaque and translucent area percentage were collected to define the Wall-to-Window Ratio (WWR) and the characteristics associated with the emissivity and reflectance index of the opaque area, for the solar factor. Their averages were then applied to both the theoretical building and the solar obstructions, eliminating the reflection incidence bias in the urban canyon. The window of analysis was the façade affected by the urban canyon to link the results to the obstruction and avoid distortions.

The urban canyon comprised five buildings of the same constructive features and area, varying the distance between the theoretical building and the solar obstruction, with the different orientations, establishing a total of six distancing scenarios that were analyzed in the predominant orientations (see Fig. 1). For this document, the analyses of Scenario 1 (obstruction-free), 2 (minimum distance between theoretical building-obstruction), and 6 (maximum distance between theoretical building-obstruction) are shown since these have the most extreme differences.

2.3 Assessment of Solar Access and Lighting Demand

The quantification of the annual incident solar radiation (SR) $\mathrm{kW\,h/m^2}$ was simulated using Autodesk FormIt 360®, considering the levels captured at the midpoint of the window on all the floors of the different scenarios and orientations (60 models). Dynamic simulations of the LD were made using Design Builder®, in an occupation schedule from 6 am to 6 pm, with an average of 300 lx on the work plane, 85 cm from the ground. The amount of energy required to cover this lighting need was analyzed to quantitatively demonstrate, in this way, the impact of the canyon on the energy behavior of the consolidated environment.

2.4 Definition of Minimum Conditions

The last stage consisted in establishing the maximum admissible height considering the impact on the increase in lighting consumption. This analysis was made based on the EP criterion established by Boardman [7], the ten percent rule, which establishes that a family will be in a situation of EP if they allocate more than 10% of their income to cover energy costs (air conditioning, domestic hot water, cooking, appliances, etc.). In the study location, lighting is 28% of the total consumption, and with the minimum wage of a family group being 700 dollars per month [27], the maximum expenditure on lighting will be $19.60. Additionally, the energy cost that was used is a value of 9.51 cents per kWh [28]. The lighting consumption was determined in dollars with this data, considering theoretical lighting where the demand is equal to the consumption, to establish the urban geometry conditions where this consumption threshold would be exceeded and, therefore, could entail a situation of energy poverty.

3 Results

The research results have been organized into three sections. The first one is related to the collection of urban information, findings that make it possible to form the model of the building and the theoretical urban canyon. The second one shows the variations in solar radiation and lighting for the different analysis scenarios. The third section translates the impacts of the radiation and lighting variation in economic terms to propose recommendations in this regard associated with EP situations.

3.1 Characterization of the Urban and Building Context

The characterization of the urban system has been made based on the heights, street widths, orientations, and constructive characteristics of the envelopes. First of all, it is obtained that the building heights allowed in the PUOS have great variability, where 63% of the analysis area is allocated to 2 and 4 floors, 29% to 6 and 8 floors, 7% to buildings between 10 and 12 floors, and the rest to buildings are over 14 floors (1%). This showed that the current building height of the city is medium-low. However, according to the regulation to increase constructability, four scales are defined: small scale that includes buildings from1 to 6 floors (4–24 m), medium scale from7 to 12 floors (28–48 m), intermediate scale from 13 to 18 floors (52–72 m), and critical scale from 19 to 36 floors (76–144 m). Taking into account that the maximum height allowed by the Eco-Efficiency Ordinance is 36 floors, this height is defined for the solar obstruction and the case study. Regarding the width of streets, about 40% are from 6 to 10 m, 35% from 10 to 14 m, and 9% from 14 to 18 m. For the case study, the 6, 12, 16, 33, and 30 m widths are used, the same ones

Table 1 Analysis scenarios

Scenario	Building height (H) (m)	Street width (m)	Ratio H/W	Orientation °N
Scenario 1		–	–	15°, 30°, 45°,
Scenario 2		6	24	120°, 150°,
Scenario 3	144	12	12	165°, −30°
Scenario 4		16	9	−60°, −135°,
Scenario 5		22	6.5	and −150°
Scenario 6		30	4.8	

as the minimum street widths for increased constructability. As for the orientations, it is observed that the blocks have a rotation every 15° with respect to north, with the prevailing orientations being 15, 30, 45, 120, 150, and 165°, and their complements, since they already have 71% of representativeness in the increased constructability area. Based on this, it was decided to establish 6 distancing scenarios in the ten most representative orientations of the urban sector with the maximum height allowed by the new regulations (see Table 1).

The information collected on the façades shows that the opaque surface ranges between 21.43 and 79.80%, with an average value of 51.27%, while the translucent surface has percentages between 20.20 and 78.56%, with an average of 48.73%. Regarding the materials, the façades with brick, mortar (white, brown, and gray), plaster, exposed concrete, and aluminum predominate; materials with emissivities that are between 0.42 and 0.95 and with reflectance indices between 41 and 90%. On the translucent surfaces, hermetic single- and double-glazed windows with conventional features were observed. Therefore, the facade of the building was characterized by an opaque percentage of 51.27%, with white textured mortar, and a reflectance index of 54%, while 48.73% of the facade has a window area with a 12.15% reflectance index, and a luminous transmission coefficient of 39.2% for the glazing.

3.2 Irradiance on Facades and Lighting Demands

3.2.1 Scenario 1: Building Without Solar Obstruction

Scenario 1 determines annual SR values for a 36-story building (144 m) without solar obstruction in the different orientations. This scenario will be considered the basis for establishing the SR reduction that the study's façade receives as a result of the obstructions.

As can be seen in Tables 2 and 3, the LD is between 7.46 and 7.75 kW h/m^2, with an average value of 7.58 kW h/m^2, and the SR, with a greater difference, ranges from 377 kW to 815 kW h/m^2 depending on the orientation, with the façade with

Table 2 Solar radiation and lighting demand without solar obstruction by orientation

Orientation	Solar radiation (kW h/m^2year)	Lighting demand (kW h/m^2year)
15°	568	7.62
30°	660	7.68
45°	773	7.73
120°	815	7.75
150°	578	7.72
−165°	374	7.68
−150°	377	7.60
−135°	421	7.55
−60°	514	7.46
−30°	458	7.47

Table 3 Solar radiation on façade (kW h/m^2 year) for Scenario 2 and reduction compared to Scenario 1 (%)

Ori.[a]	Floor									
	25		31		34		35		36	
15°	145	74%	191	66%	330	42%	440	23%	521	8%
30°	155	77%	184	72%	324	51%	451	32%	599	9%
45°	148	81%	183	76%	319	59%	478	38%	689	11%
120°	150	82%	167	80%	163	80%	175	79%	196	76%
150°	156	73%	178	69%	279	52%	384	34%	526	9%
−165°	145	61%	181	52%	254	32%	295	21%	336	10%
−150°	151	60%	174	54%	221	41%	262	31%	335	11%
−135°	147	65%	168	60%	271	36%	279	34%	375	11%
−60°	148	71%	163	68%	219	57%	298	42%	467	9%
−30°	156	66%	181	60%	245	47%	308	33%	419	9%

[a] Orientation

the highest SR, having an orientation of 120° with respect to north, and the lowest SR, −165°.

3.2.2 Scenario 2: Urban Canyon Ratio 24

In Fig. 2, the SR reduction due to solar obstruction at 6 m is shown, with this being between 8 and 11% on the 36th floor and increasing as the number of floors decreases until reaching the maximum reduction on the 25th floor, where a reduction occurs between 60% (Orientation −150°) and 82% (Orientation 120°), with an average value of 71%. The highest differences are found on the 33rd and 34th floors, with an orientation difference reaching 33 and 34%.

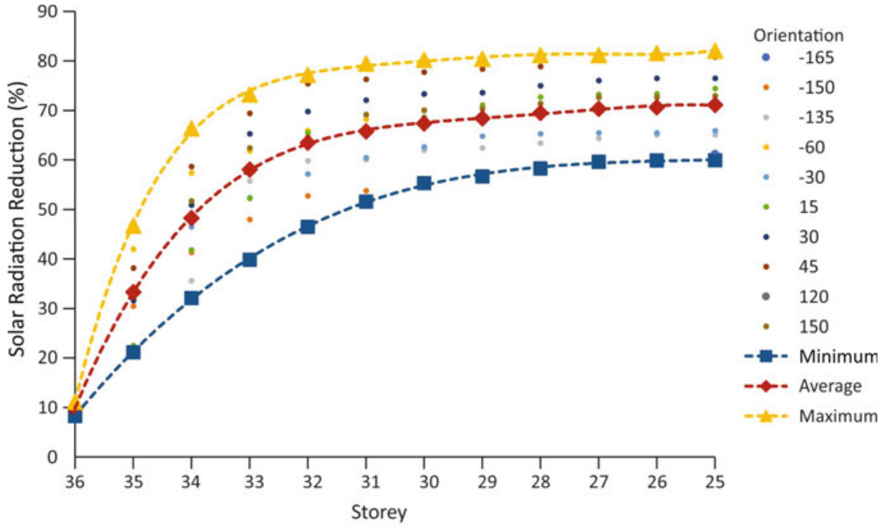

Fig. 2 Percentage of radiation reduction in façade by orientation for an obstruction at 6 m (Ratio 24)

The SR reduction entails an increase in the LD with respect to Scenario 1 (Without obstruction) of between 5.1 kW h/m^2 (36th floor) and 37.1 kW h/m^2 (25th floor) depending on the orientation. The result is a difference by orientation on the 36th floor of 4.0 kW h/m^2 at most, and on the 25th floor of 1.9 kW h/m^2 (see Table 4). The LD increase on the 25th floor is between 457 and 498% with an average value of 480% compared to Scenario 1, a condition that is similar for all floors below this. On the other hand, the top floor (36) has an average LD increase of 84% (see Table 4). Scenario 2 requires on average 42.3 kW h/m^2 to cover the LD generated by solar energy which means 504,188.5 kWh h/m^2 annually.

3.2.3 Scenario 6: Urban Canyon Ratio 4.8

The obstruction at 30 m of distance (Scenario 6) shows that the SR reduction stabilizes around the 5th floor, where a reduction of between 38% (Orientation −165°) and 76% (Orientation 120°) occurs, with an average value of 57% (see Fig. 3 and Table 5). The highest differences are found on the 13th and 24th floors, with a difference by an orientation that reaches 39 and 42%.

6

This scenario generates an average increase in the LD compared to Scenario 1 (Without obstruction) of 0.4 kW h/m^2 (36th floor) and 20.2 kW h/m^2 (5th floor). The result is a difference by orientation on the 36th floor of 0.3 kW h/m^2 at most, and on the 5th floor of 2 kW h/m^2 (see Table 6). The increase in the LD on the 5th floor is between 253 and 286% with an average value of 265% compared to the base

Table 4 Lighting demand (kW h/m^2 year) for Scenario 2 and increase over Scenario 1 (%)

Ori.[a]	Floor									
	25		31		34		35		36	
15°	42.9	463%	41.4	443%	32.6	328%	24.7	224%	16.1	111%
30°	42.8	457%	41.2	437%	34.0	342%	25.8	236%	16.8	119%
45°	44.3	473%	41.9	442%	34.0	340%	24.9	222%	12.8	66%
120°	44.7	476%	42.8	452%	33.9	338%	23.3	200%	13.0	68%
150°	44.4	475%	42.4	449%	33.7	336%	23.5	204%	13.3	73%
−165°	44.5	480%	42.7	455%	33.6	338%	24.0	213%	14.0	83%
−150°	44.5	485%	42.7	461%	34.1	349%	24.0	216%	13.8	82%
−135°	44.7	492%	43.0	470%	34.1	352%	23.5	211%	13.5	79%
−60°	44.6	498%	42.9	476%	34.1	358%	23.6	216%	13.5	80%
−30°	44.2	492%	42.3	466%	33.6	350%	23.5	215%	13.3	77%

[a] Orientation

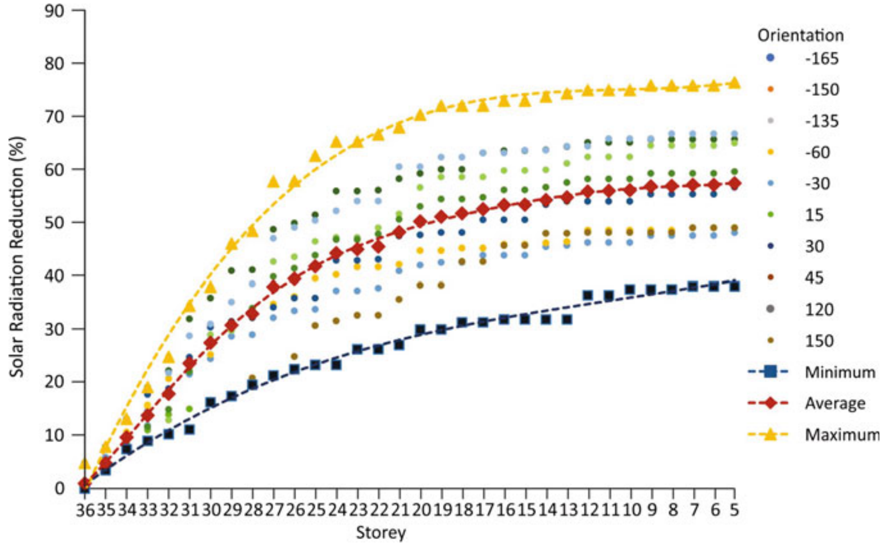

Fig. 3 Percentage of radiation reduction on façade by orientation for an obstruction at 6 m (Ratio 4.8)

scenario, a condition that is similar for all floors below this. On the other hand, the top floor (36) has an average LD increase of 6%, which entails a difference of 78% from Scenario 2. In this scenario, the theoretical building requires 23.3 kW h/m^2 on average to cover the lighting demand generated by the solar obstruction, which means 276,971.3 kWh a year for the entire building.

Table 5 Solar radiation on façade (kW h/m^2 year) for Scenario 6 and reduction from Scenario 1 (%)

Ori.[a]	Floor							
	5		20		30		36	
15°	290	49%	351	38%	476	16%	566	0%
30°	232	65%	287	57%	469	29%	655	1%
45°	258	67%	306	60%	534	31%	770	0%
120°	193	76%	243	70%	506	38%	809	1%
150°	234	60%	272	53%	417	28%	574	1%
−165°	232	38%	262	30%	312	17%	374	0%
−150°	196	48%	219	42%	285	24%	376	0%
−135°	215	49%	233	45%	315	25%	420	0%
−60°	177	66%	210	59%	330	36%	508	1%
−30°	199	57%	240	48%	345	25%	311	32%

[a] Orientation

Table 6 Lighting demand (kW h/m^2 year) for Scenario 6 and increase over Scenario 1 (%)

Ori.[a]	Floor							
	5		20		30		36	
15°	26.9	253%	24.0	215%	17.5	130%	8.1	6%
30°	27.8	261%	25.2	229%	18.1	135%	8.1	6%
45°	28.5	269%	25.7	233%	17.7	129%	7.9	2%
120°	29.1	275%	26.2	238%	18.0	133%	8.2	6%
150°	27.3	254%	25.0	223%	17.9	132%	8.2	6%
−165°	27.6	260%	24.7	221%	17.8	131%	8.1	6%
−150°	27.4	260%	24.9	228%	17.9	135%	8.1	6%
−135°	27.4	263%	24.7	228%	17.1	127%	8.0	6%
−60°	28.8	286%	25.9	247%	17.7	137%	7.9	6%
−30°	27.6	270%	25.1	236%	17.9	140%	8.0	6%

[a] Orientation

3.3 Minimum Site Conditions

Considering that the increase in lighting consumption associated with urban densification may lead to an increase in EP situations, it has been established that the maximum consumption that a family should allocate monthly to lighting is US$19.60. This value has been taken as a reference to determine the maximum number of floors to guarantee solar access based on the distance between buildings. As can be seen in Table 7, the difference in energy expenditure between floor 1 of Scenario 2 and Scenario 6 is between $9.19 and $ 10.99, with an average value of $10.28, with there being no major differences associated with orientation. Within each scenario, there

Table 7 Monthly lighting cost (USD) by scenario, floor, and orientation

	Floor	Orientation (°N)									
		–165	–150	–135	–60	–30	15	30	45	120	150
Scenario 2	1	28.54	28.50	28.64	28.58	28.35	27.37	26.95	28.61	28.62	28.51
Ratio 24	25	28.24	28.19	28.31	28.26	28.05	27.21	27.10	28.06	28.31	28.13
	31	27.04	27.04	27.26	27.22	26.80	26.22	26.13	26.54	27.12	26.86
	34	21.32	21.62	21.64	21.65	21.29	20.66	21.54	21.54	21.50	21.35
	35	15.23	15.20	14.90	14.95	14.92	15.66	16.36	15.77	14.74	14.89
	36	8.89	8.75	8.55	8.53	8.40	10.18	10.67	8.11	8.26	8.45
Scenario 6	1	18.08	17.54	17.84	18.79	17.66	17.30	17.76	18.50	18.87	17.52
Ratio 4.8	5	17.52	17.35	17.37	18.25	17.51	17.07	17.59	18.07	18.42	17.34
	20	15.63	15.81	15.69	16.40	15.93	15.21	15.99	16.32	16.61	15.83
	30	11.27	11.32	10.86	11.21	11.36	11.12	11.44	11.22	11.44	11.35
	36	5.15	5.13	5.08	5.02	5.04	5.13	5.14	5.02	5.20	5.19

are important differences in the monthly energy cost, with the average difference between floors 1 and 36 of Scenario 2 being \$19.39 and for Scenario 6, \$12.88, which shows that solar obstructions can generate important energy inequalities.

In Fig. 4, it is observed that for Scenario 2 (distance of 6 m), the maximum building height must be 8 m to be under the established consumption limit, that is, 2 floors or a ratio of 1.33, while for Scenario 6 (distance of 30 m) it is feasible to project 36 floors (144 m) or a ratio of 4.8. Based on these results and those obtained for scenarios 2, 3, 4, and 5, a distance of 12 m between buildings was determined. The maximum building height will be 20 m, namely 5 floors or a ratio of 1.66; for a distance of 16 m, the maximum building height will be 32 m, namely 8 floors or a ratio of 2; and for a distance of 22 m, the maximum building height will be 48 m, namely 12 floors or a ratio of 2.18.

Therefore, according to the results of Sect. 3.1 for the urban fabric of Quito, high-rise re-densification should be limited based on the current distance between buildings or street widths, establishing 4 floors for 50% of streets that have a width of less than 10 m, between 4 and 6 floors for 33% of streets that have a width between 10 and 14 m, and between 6 and 9 floors for 9% of streets that have a width between 14 and 18 m.

4 Discussion

Many Latin American cities are facing the problem of urban sprawl, which generates problems of segregation, marginalization, and exclusion linked to residential location and mobility [21–23]. In this sense, re-densification policies are being generated that can affect the energy consumption of both public and domestic grid systems [26].

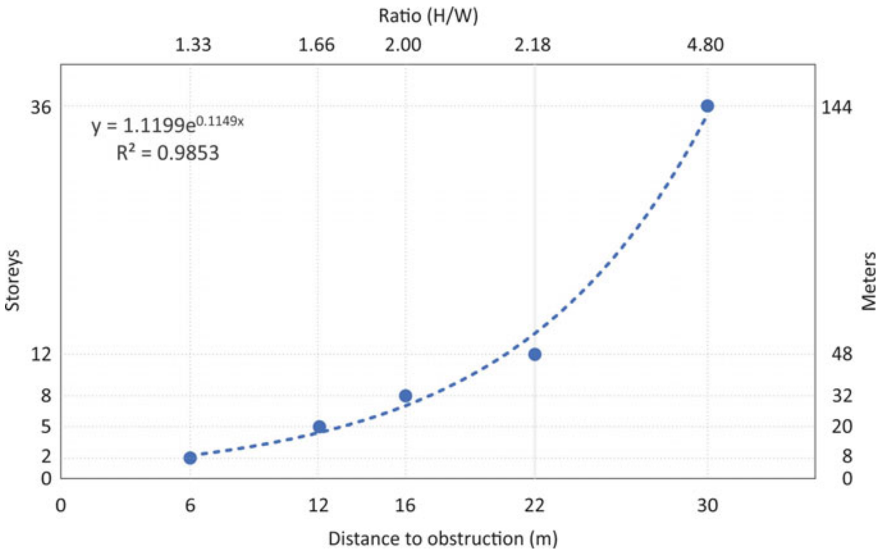

Fig. 4 Maximum number of floors recommended considering the distance from solar obstruction

In Quito, street widths and the morphological orientation of the city respond to the adaptation to the interstices between ravines and hillsides, the result of a complex socio-spatial process and several late urban development plans regarding urban growth control where the minimum conditions for a height re-densification model may conflict with one another.

Some authors indicate that the urban orientation in the east-west direction is more favorable in terms of solar access [29], decreasing as it moves away from the equator [30]. However, the results of Scenario 1 show that the greatest solar radiation occurs in the southeast orientation (120°N). On the other hand, it was found that the reduction of incident solar radiation on the building is mainly related to the distance from the obstruction and its height, with orientation passing to the second plane. This was previously studied by Bournas and Dubois [31] and Bournas et al. (2021) in Sweden, where 54 buildings were evaluated, and it was shown that the performance for each typology is significantly dependent on the surrounding obstructions [31]. However, for the set of orientations evaluated, the average incident radiation ranges from 145 to 809 kW h/m^2, with the most unfavorable orientation (−165°N) being between 145 and 336 kW h/m^2. Therefore, the east-west orientation is not the most favorable for all urban sectors, despite being on the equator.

The results show that the shade generated under a high-rise re-densification scenario reduces the SR by between 40 and 80%, findings that differ from the study carried out in Bogotá where the reduction found was between 30 and 50% [32]. This variation in SR causes an LD associated with solar obstructions, which ranges from 7.90 to 44.70 kW h/m^2, entailing an increase from the unobstructed scenario of between 2 and 498% for the most unfavorable case. This increase decreases as the distance from the solar obstruction increases, with the average difference between Scenario 2 (obstruction at 6 m) and Scenario 6 (obstruction at 30 m) for the most unfavorable floor being 214%.

This coincides with the research carried out by Strømann-Andersen and Sattrup [33] in Copenhagen, who indicated that with respect to unobstructed surroundings, an urban canyon with a ratio of 3.0 could multiply energy consumption by sixfold [33]. Although it can be indicated that the findings regarding the increase or decrease in the use of energy in buildings are quite diverse, some authors indicate that an increase in urban density may imply a reduction in energy consumption associated with a reduction in energy gains and losses [34, 35], and others consider that there is a trade-off between the reduction of heat losses, solar radiation, and natural lighting that implies an increase in energy consumption [36–38]. In the case of Quito, where the consumption associated with air conditioning is very low, this is, without a doubt, the second situation.

On the other hand, the increase in lighting demand means an increase of up to about 30 dollars per month, per housing unit, exceeding the maximum admissible 10% of the monthly salary, destined for lighting. Therefore, according to the results obtained, the building height should be limited considering the lighting consumption to reduce an increase in energy poverty. The needs for additional research regarding solar access planning are significant, and the available literature is scarce, which points to a knowledge gap, just as Kanters et al. [38] pointed out.

These findings should be evaluated with caution due to two methodological limitations that may compromise their external validity. The first limitation is due to the materiality characteristics of the urban canyon both in terms of reflectance and the material of the envelope since these variables have a great impact on the results. The second limitation corresponds to that this study has not analyzed the effects of the urban canyon on the demand for air-conditioning, so it would be interesting to investigate the behavior of theoretical models with another mode of location (detached) to compare these against these results.

5 Conclusions

Solar energy has the potential to reduce consumption in certain climates, helping to address the problems associated with energy consumption and poverty. Research on urban morphology and its relationship with daylighting has been studied for a long time, generating regulations and laws in some cases. In the city of Quito, urban growth is taking place that can cause solar obstructions that affect both urban and residential space.

This research has focused on assessing how the rise of constructability affects solar access, and its impact on lighting consumption in high-rise homes in the city of Quito to establish maximum heights considering the distance between buildings, which reduces energy poverty associated with lighting.

The characterization of the urban system of Quito has allowed showing that the current building height of the city is medium-low, with 63% of the area devoted to buildings between 2 and 4 floors, and 29% to buildings between 6 and 8. 40% of the streets have a width between 6 and 10 m, and 35% between 10 and 14 m, while the prevailing orientations are 15, 30, 45, 120, 150, and 165° and complements, with respect to the north (71% of representativeness).

The re-densification scenarios studied have allowed observing that the reduction in average solar radiation can be between 71% (Scenario 2) and 57% (Scenario 6), and has a determining influence on the orientation and the floor where the dwelling is located. These reductions can mean an average increase in lighting consumption of between 480% (Scenario 2) and 265%, being able to rise from a lighting consumption of 7.58 $kW\ h/m^2$ without obstruction, to an average of 42.3 $kW\ h/m^2$ in the most unfavorable case.

The results recommend that to avoid an increase in EP in the city of Quito, the height should be limited to 4 floors for streets with a width of less than 10 m, between 4 and 6 floors for those with a width between 10 and 14 m, and between 6 and 9 floors for streets with a width between 14 and 18 m, where those cases with a greater height should be studied in detail.

Re-densification is an opportunity to stop the deterioration of the natural landscape and the decline of productive areas or agricultural land. Currently, planning policies are being developed which seek that the city centers with their services, amenities, transport, etc. handle the largest number of people, promoting an increase in housing density. These processes have a strong impact on the solar access of buildings, as has been shown in the results, therefore, urban development plans at the equator should consider the proportionality of the building height and the distancing from the surroundings, and to a lesser extent, the location's orientations.

Ultimately, this research seeks to help public policy developers in their future decision-making about risks that are currently not considered in urban planning by opening the debate on the relationship between urban re-densification and energy poverty, showing that increased height may result in an increase in energy poverty, or less light comfort for the families, something that can certainly be inconsistent with the sustainable development objectives linked to a reduction in social inequality. Therefore, these aspects should be incorporated into urban planning updates in the near future.

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References

1. Santamouris M (2016) Innovating to zero the building sector in europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. Solar Energy 128:61–94. https://doi.org/10.1016/j.solener.2016.01.021
2. Bouzarovski S, Petrova S (2015) A global perspective on domestic energy deprivation: Overcoming the energy poverty-fuel poverty binary. Energy Res Soc Sci 10:31–40. https://doi.org/10.1016/j.erss.2015.06.007
3. González-Eguino M (2015) Energy poverty: An overview. Renew Sustain Energy Rev 47:377–385. https://doi.org/10.1016/j.rser.2015.03.013
4. Pérez-Fargallo A, Rubio-Bellido C, Pulido-Arcas JA, Trebilcock M (2017) Development policy in social housing allocation: Fuel poverty potential risk index. Indoor Built Environ 26:980–998. https://doi.org/10.1177/1420326X17713071
5. Pérez-Fargallo A, Rubio-Bellido C, Pulido-Arcas JA, Guevara-García FJ (2018) Fuel poverty potential risk index in the context of climate change in Chile. Energy Policy 113:157–170. https://doi.org/10.1016/j.enpol.2017.10.054
6. Ambrose AR (2015) Improving energy efficiency in private rented housing: Why don't landlords act? Indoor Built Environ 24:913–924. https://doi.org/10.1177/1420326X15598821
7. Boardman B (2009) Fixing fuel poverty. Routledge, London. https://doi.org/10.4324/9781849774482
8. Love J, Cooper AC (2015) From social and technical to socio-technical: Designing integrated research on domestic energy use. Indoor Built Environ 24:986–998. https://doi.org/10.1177/1420326X15601722
9. Baker N, Steemers K (2003) Energy and environment in architecture: A technical design guide. Taylor & Francis Group
10. Curreli A (2016) El acceso solar a la escala del tejido urbano. El enfoque morfológico y el método de análisis comparativo aplicados al caso de Barcelona. PhD thesis, Universitat Politècnica de Catalunya, Barcelona, Spain. http://hdl.handle.net/10803/392707
11. Wang P, Liu Z, Zhang L (2021) Sustainability of compact cities: A review of inter-building effect on building energy and solar energy use. Sustain Cities Soc 72:103035. https://doi.org/10.1016/j.scs.2021.103035
12. Sanaieian H, Tenpierik M, van den Linden K, Seraj FM, Shemrani SMM (2014) Review of the impact of urban block form on thermal performance, solar access and ventilation. Renew Sustain Energy Rev 38:551–560. https://doi.org/10.1016/j.rser.2014.06.007
13. Quan SJ, Li C (2021) Urban form and building energy use: A systematic review of measures, mechanisms, and methodologies. Renew Sustain Energy Rev 139:110662. https://doi.org/10.1016/j.rser.2020.110662
14. Franco-Medina R, Bright-Samper PJ (2016) Acceso solar en la arquitectura y la ciudad. aproximación histórica. Revista de Arquitectura 18:95–106. https://doi.org/10.14718/RevArq.2016.18.2.9
15. Tereci A, Ozkan STE, Eicker U (2013) Energy benchmarking for residential buildings. Energy Build 60:92–99. https://doi.org/10.1016/j.enbuild.2012.12.004
16. Han Y, Taylor JE, Pisello AL (2017) Exploring mutual shading and mutual reflection inter-building effects on building energy performance. Appl Energy 185:1556–1564. https://doi.org/10.1016/j.apenergy.2015.10.170
17. Krüger E, Suga M (2009) Recommendations of height restrictions for urban canyons in Curitiba, Brazil. J Asian Architect Build Eng 8:447–452. https://doi.org/10.3130/jaabe.8.447
18. Carrión F, Espinosa JE (2012) La forma urbana de Quito: una historia de centros y periferias*. Bulletin de l'Institut français d'études andines 41:503–522. https://doi.org/10.4000/bifea.361
19. Peralta Arias J, Higueras García E (2016) Sustainable urban evaluation of Quito's master plans. Period 1942–2012. Estoa 005:21–34. https://doi.org/10.18537/est.v005.n009.03
20. Cuvi N (2016) Un análisis de la resiliencia en Quito, 1980–2015. Bitácora Urbano Territorial 25:35. https://doi.org/10.15446/bitacora.v2n25.52036

21. Durán G, Martí M, Mérida J (2016) Crecimiento, segregación y mecanismos de desplazamiento en el periurbano de Quito. Íconos–Revista de Ciencias Sociales, pp 123–146. https://doi.org/10.17141/iconos.56.2016.2150
22. Carrión F, Pinto JP (2019) Producción y organización espacial de viejas y 'nuevas" desigualdades en Quito. Andamios Revista de Investigación Social 16:101. https://doi.org/10.29092/uacm.v16i39.676
23. Herrero Olarte S (2021) Identifying patterns of labor exclusion by residencial causes in south america: The case of Quito. J Urban Reg Anal 13. https://doi.org/10.37043/JURA.2021.13.2.11
24. Cárdenas Jirón LA, Vásquez Palau JP, Zamorano JC, Acevedo C (2016) Explorando luz solar en modelos de desarrollo inmobiliario. Aplicaciones en cinco ciudades chilenas. Revista de Urbanismo 158–173. https://doi.org/10.5354/0717-5051.2016.40394
25. Baquero M, Quesada F (2016) Eficiencia energética en el sector residencial de la ciudad de Cuenca, Ecuador. MASKANA 7:147–165. https://doi.org/10.18537/mskn.07.02.11
26. Poruschi L, Ambrey CL (2018) Densification, what does it mean for fuel poverty and energy justice? An empirical analysis. Energy Policy 117:208–217. https://doi.org/10.1016/j.enpol.2018.03.003
27. Comercio EL (2017) INEC: El ingreso de la familia típica en ecuador es USD 700 mensuales, en promedio | El Comercio. https://www.elcomercio.com/actualidad/inec-ingreso-familia-ecuador-sueldo.html
28. ARCONEL (2018) Estadísticas Anuales y Multianual del Sector Eléctrico Ecuatoriano. Ecuador. https://www.controlrecursosyenergia.gob.ec/wp-content/uploads/downloads/2020/08/EstadC3ADsticaAnualMultianual2018.pdf
29. Knowles RL (2003) The solar envelope: its meaning for energy and buildings. Energy Build 35:15–25. https://doi.org/10.1016/S0378-7788(02)00076-2
30. Decker KD (2012) The solar envelope: how to heat and cool cities without fossil fuels. https://solar.lowtechmagazine.com/2012/03/solar-oriented-cities-1-the-solar-envelope.html
31. Bournas I, Dubois MC (2019) Daylight regulation compliance of existing multi-family apartment blocks in Sweden. Build Environ 150:254–265. https://doi.org/10.1016/j.buildenv.2019.01.013
32. Franco-Medina R, Bright P, Benitez J, Beckers B (2016) A study of solar access in Bogotá: the Las Nieves neighborhood. In: FICUP an international conference on urban physics
33. Strømann-Andersen J, Sattrup P (2011) The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy Build 43:2011–2020. https://doi.org/10.1016/j.enbuild.2011.04.007
34. Kontokosta CE (2012) In: Predicting Building Energy Efficiency Using New York City Benchmarking Data, pp 163–174. https://www.aceee.org/files/proceedings/2012/data/papers/0193-000114.pdf
35. Rodríguez-Álvarez J (2016) Urban energy index for buildings (UEIB): a new method to evaluate the effect of urban form on buildings" energy demand. Landscape Urban Plan 148:170–187. https://doi.org/10.1016/j.landurbplan.2016.01.001
36. Quan J (2016) Density and energy performance of solar powered buildings in the urban context. PhD thesis, Georgia Institute of Technology. http://hdl.handle.net/1853/58618
37. Šprah N, Košir M (2019) Daylight provision requirements according to EN 17037 as a restriction for sustainable urban planning of residential developments. Sustainability 12:315. https://doi.org/10.3390/su12010315
38. Kanters J, Gentile N, Bernardo R (2021) Planning for solar access in Sweden: routines, metrics, and tools. Urban Plan Transp Res 9:347–367. https://doi.org/10.1080/21650020.2021.1944293

Multi-Objective Optimization of Energy Efficiency and Thermal Comfort Applying the MOOM Tool in Public Office Buildings in the City of San Juan, Argentina

Bruno Damián Arballo, Daniel Chuk, and Ernesto Kuchen

Abstract Buildings are responsible for 40% of the world's energy demand and CO2 emissions. In Argentina, buildings represent more than 40% of the total annual energy consumption. Energy-saving strategies can cause thermal discomfort for building's inhabitants, compromising their health and performance. The problem centers on an imbalance between providing a high quality of life and comfort in interior office spaces and the high energy cost required to meet that objective. Both a high level of comfort and energy savings represent two objectives to be achieved. This paper proposes a new methodology that combines in situ measurement with mathematical simulation tools. Innovative techniques and models are incorporated for the elaboration of the MOOM optimization tool, applying thermal-energy multi-objective optimization, which operates dynamically during working hours. Results show significant savings for energy consumption for cooling office spaces in summer, from 57.5 to 83.3%, together with an increase in the quality of thermal comfort, with improvements between 4.7 and 29.4%.

Keywords Multi-objective optimization · Energy efficiency · Thermal comfort · Office buildings · Thermal adaptation

B. D. Arballo (✉) · E. Kuchen
FAUD, Universidad Nacional de San Juan. CONICET, San Juan, Argentina
e-mail: arballobruno@conicet.gov.ar

E. Kuchen
e-mail: ernestokuchen@faud.unsj.edu.ar

D. Chuk
Instituto de Investigaciones Mineras, FI, Universidad Nacional de San Juan, San Juan, Argentina
e-mail: dchuk@unsj.edu.ar

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1 Introduction

Buildings worldwide represent around 40% of energy use, naturally constituting potential scenarios for saving energy and emissions [1]. Modern man spends most of his time indoors, 80–90% [2]. Multiple studies have validated thermal comfort as one of the variables that most affect indoor comfort and the energy efficiency of buildings [3–5]. Several international studies validate the perspective of adaptive thermal comfort as a key energy-saving strategy in office buildings [6–8], leading to savings in the range of 30–60%, especially when the evolution of the external climate is taken into account.

Previous studies developed in the project PICT2009-0014 Res.N°304/2010, "EEC, Energy Efficiency and Comfort in Work Spaces", and Ph.D. studies [9], in the city of San Juan, Argentina, grounds the thermal dissatisfaction of the inhabitants with their work environment and the potential of multi-objective optimization to improve energy efficiency and achieve significant savings.

The relationship between design variables of the architectural project and energy efficiency is explored in [10, 11]. In the Cuyo region, [12] develops a probabilistic methodology for economic energy and thermal comfort optimization applied to the residential environment. In the Argentine Litoral region, although not from architecture but rather computational mechanics, the Computational Methods Research Center (CONICET-UNL), has studied the application of BES (Building Energy Simulation) for the reduction of energy consumption [13–17].

It is especially relevant to consider the adaptability of inhabitants and the climatic variables of the site in real time, especially the outdoor temperature (T_{em}), to define acceptance ranges [18, 19]. Optimization of the building's operation is necessary [20], and the development of multi-objective optimization in real time between energy efficiency and thermal comfort of the inhabitants. These variables conflict since significant energy saving in the air conditioning energy system can result in indoor thermal discomfort conditions for the inhabitants. In turn, the energy consumption of buildings significantly depends on the demands of the indoor environment, which affects health, performance, and comfort [21].

The genetic algorithms, "MOGA" (Multi-objective Genetic Algorithm), and particle optimization algorithms, "PSO" (Particle Swarm Optimization), are the most commonly used to optimize energy performance and comfort in buildings [5], due to their favourable characteristics and a wide degree of applicability [22]. The mathematical theory of genetic algorithms or "MOGA" is presented in Coello et al. [23] and its applications to HVAC system optimization are presented by [24–27], among others. Genetic algorithms turn out to be very useful to search for an optimal preferred solution within a set of possible solutions in static situations [28]. However, they have difficulties in defining possible solutions for dynamic control due to the randomness that characterizes the operations. Less-used heuristic "ant colony optimization" algorithms have shown very good performance in dynamic situations [29].

In this chapter, a novel application of the MIDACO (Mixed Integer Distributed Ant Colony Optimization) algorithm is presented for solving an architectural optimization problem.

2 Methodology

2.1 In Situ Measurement and Mathematical Simulations

The measurement methodology is based on conducting a systematic data collection procedure. To measure thermal comfort in situ, a HOBO type U12-006 temperature and humidity sensor (interior temperature) is used, anchored to a mobile measurement device that facilitates movement inside the building [9]. At the time of measurement, in each office space, the mobile sensor is located 0.90 $\pm$0.2 m above floor level and within a radius of no more than one meter from the workplace of the evaluated inhabitant, making it possible to capture the perceived environmental conditions. This measurement provides objective data on thermal comfort. Outdoor temperature data is collected by a UA-001-64 type sensor fixed on the rooftop. In parallel to the measurement with sensors, a comfort survey is run, which provides subjective information on the inhabitant regarding their workspace. Information on the comfort vote (CV) is obtained from a 7-point scale survey [9].

Data on activity level (MET) and clothing (CLO) are also obtained, based on the ISO 7730 thermal comfort standard.

The measurement is made from Monday to Friday from 8:00 a.m. to 1:30 p.m. in weeks that have typical climatic conditions for each period of the year (summer, transitory, and winter).

2.2 Study Cases

The four selected case studies (See Fig. 1) represent the highest percentage of annual energy consumption in the city of San Juan [30], in Argentina's bioenvironmental zone III-A with a dry warm temperate climate, an average annual outdoor temperature of 17.2°C, and average relative humidity of 53% [31].

Based on the parameters stated, the significant sample of the studied cases corresponds to the following buildings (See Table 1):

1. Centro Cívico–Civil Center (CCV)
2. Obras Sanitarias Sociedad del Estado–State Sanitary Works (OSE)
3. Edificio Central de la Universidad Nacional de San Juan–Central Building at the San Juan National University (ECU)
4. Municipalidad de la Capital–Capital's Municipal Building (MUN)

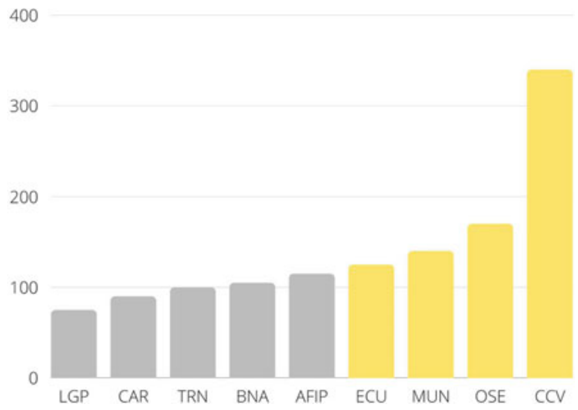

Fig. 1 Office buildings that represent the highest consumption of electrical energy (kW h/m^2 year) in the city of San Juan, Argentina. Data from [30]

Table 1 Study cases relevant information [9]

	I	II	III		IV
			A	B	
Name	CCV	OSE	MUN		ECU
Total area (m^2)	80873	2455	4920		5320
Energy consumption (kW h/m^2 year)	335	158	137		126
Survey population	885	84	86	49	121

2.3 Multi-Objective Optimization with MIDACO (MOOM)

Solving this multi-objective optimization problem between energy efficiency and thermal comfort implies making the best decision from a set of elements. In math, optimization is related to the process of obtaining the maximum or minimum of one or more evaluation functions of a system. According to the problem's complexity, a mono-objective optimization (single variable) or a multi-objective optimization can be considered. In a multi-objective optimization problem, there are a series of evaluation functions that compete with each other, so it is not possible to speak of a single optimal solution value but of a set of values that satisfy one objective or the other to a greater degree. This set of solutions meets the Pareto Optimality Criterion [23].

The objective functions are designed based on measured data. The data matrices and the evaluation functions are loaded into the MATLAB simulation program. The implementation of the MIDACO multi-objective optimization algorithm allows finding the spectrum of possible solutions (Pareto Optimum Set or Pareto front) to which a "preferred solution" is applied to reach the definitive optimum. Generally,

Table 2 Comfort Vote (CV) equations for each building [9]

Building	Comfort vote equation
CCV	$CV = 0.274 * top(k) - 6.169$
ECU	$CV = 0.365 * top(k) - 8.955$
MUN	$CV = 0.355 * top(k) - 8.842$
OSE	$CV = 0.081 * top(k) - 1.849$

the preferred solution is the "L2 norm" or ideal vector with normalized distance to the point of utopia. Multi-objective optimization of each typical office space from each building is carried out in summer, which is the most energy-demanding period of the year. Through the optimization tool, it is possible to achieve energy savings by meeting high-level thermal comfort expectations.

For validation (Sect. 3.2), comfort vote (CV) equations are uploaded into the optimization system, based on the relation between operative temperature evolution and CV of the inhabitants taken from measured data (only for the summer period) (See Table 2).

The thermal comfort value is expressed as *Disc* (% of inhabitants dissatisfied with their thermal environment). A maximum value is set for $Discmax = 15$ and a minimum for $DiscObj = 7$. The *DiscObj* variable is obtained from the adopted thermal comfort model [32]. The energy demand variable *En* is marked in the figures with dotted lines on the (x) axis (See Sect. 3.2).

Concerning the summer period energy consumption ("sp"), the following data is used for the optimization [30]: CCV = $137.5\,\mathrm{kW\,h/m^2}$ sp; OSE = $71.1\,\mathrm{kW\,h/m^2}$ sp; MUN = $50.7\,\mathrm{kW\,h/m^2}$ sp; ECU = $56.9\,\mathrm{kW\,h/m^2}$ sp.

2.3.1 MOOM Optimization Problem Definition

The fundamental variables that affect decision-making on objective or evaluation functions during the dynamic operation of the multi-objective optimization system are detailed below.

The vector of decision variables is defined as

x =	SP(1) SP(2)	SP(floor(l/p))	% Setpoint of AC (°C)
	va(1) va(2)	va(floor(l/p))	% Air velocity (m/s)
	F(1) F(2)	F(floor(l/p))]	% Operating mode {1,2,3}

Decision variables are updated for every "n" sampling interval. *F* is an input variable that differentiates the operating modes:

1. *F1*: Closed windows, air conditioning (AC) turned off, ceiling fans move the air inside the office.
2. *F2*: Cross ventilation with outdoor air intake. AC turned off.
3. *F3*: AC on. Ceiling fans are possibly on.

2.3.2 Evaluation Functions

Five evaluation functions are determined and all refer to the period when the work schedule takes place [33]:

1. *Energy Demand:* Where AC is a vector that runs through the entire work schedule where its elements are 0 if the AC is off and 1 if it is on. Therefore, *En* is not an absolute demand in (W h) but a relative demand measured as a ratio of activation times to the total time of the working hours (1)

$$f1(x) = En = \frac{\sum_{k=n_{w1}}^{n_{w2}} u_a(k)}{n_{w2} - n_{w1}} \tag{1}$$

2. *Root mean square of Disc: DiscObj* target is defined, typically = 7% (minimum possible percentage of dissatisfied), based on the thermal comfort model defined in [32]. When the *Disc* variable is less than *DiscObj*, the equation takes the form of (2), otherwise, it takes the form of (3).

$$f2(x) = \frac{\sum_{k=n_{w1}}^{n_{w2}} (Disc(k) - DiscObj)^2}{n_{w2} - n_{w1}} \forall\ Disc(k) > DiscObj \tag{2}$$

$$f2(x) = \frac{\sum_{k=n_{w1}}^{n_{w2}} (-\frac{10}{DiscObj} Disc(k) + 10000)}{n_{w2} - n_{w1}} \forall\ Disc(k) \leq DiscObj \tag{3}$$

3. *AC set point (SP) variations control:* The difference between each AC setpoint is calculated, $SP_{AC}(k)$ and the one applied in the previous instance, $SP_{AC}(k-1)$. This difference is squared to obtain an always positive value and magnify the effect, with the aim of minimizing changes and avoiding high oscillations in the indoor temperature (ta) (4).

$$f3(x) = \frac{\sum_{k=n_{w1}}^{n_{w2}} (SP_{AC}(k) - SP_{AC}(k-1))^2}{n_{w2} - n_{w1}} \tag{4}$$

4. *Air velocity (v_a) variations control:* This (5) responds to the same logic used in (4).

$$f4(x) = \sum_{k=n_{w1}}^{n_{w2}} (v_a(k) - v_a(k-1))^2 \tag{5}$$

5. *Control of the number of changes in operating mode F:* This function (6) tends to minimize variations in operating modes F. It responds to the same logic used in (4).

$$f5(x) = \sum_{k=n_{w1}}^{n_{w2}} (F(k) - F(k-1))^2 \tag{6}$$

6. *Restriction function:* Prevent *Disc* from exceeding *DiscMax*. The system activates the F3 operating mode when the operative temperature (top) exceeds the admissible values regarding the restriction of the maximum percentage of dissatisfied *DiscMax* (7).

$$Disc(k) < DiscMax \forall h_w(1) < k < h_w(2) \tag{7}$$

3 Results

3.1 Thermal Comfort

For the thermal comfort evaluation, the ISSO 74, 2014 standard is considered with the objective of class B buildings, defined in Boerstra et al. [18].

According to the ISSO 74, 2014 standard, all workspaces in the CCV building are determined as Beta (β) type [18]. The expectation level of indoor thermal comfort is defined as normal, category B. 80% of office spaces analyzed do not have access to window opening (fundamental strategy to restore personal comfort), and personal moving of the thermostat is not allowed. The average metabolic rate (MET) values are 1.35 (considered normal by ISSO 74). The CLO (clothing insulation) values average is 1.44 (values for normal office wear regulations).

In the annual data compendium (See Fig. 2), it can be seen that 70% of the data is included in the 90% acceptability area, complying with the average level of thermal comfort based on the limits proposed in ISSO [34] for office spaces type β, class B.

For the ECU building, the office spaces are determined as type β. The expectation level of indoor thermal comfort is defined as normal, category B. The office spaces have access to opening windows (a fundamental strategy to restore personal comfort), but a personal modification of the thermostat is not allowed. In all spaces, the air conditioning system is clearly perceived. The average metabolic rate (MET) value is 1.40. The CLO value (clothing insulation) is 0.76 for summer and 1.44 for winter (normal values for office spaces). For the summer period, 14% of data are within class B (90% acceptability) and an average acceptability percentage of 86%. For the transitory period, 88% of data coincides with the class B area. For the winter period, 92% of data corresponds to the class B area.

In the annual data compendium (See Fig. 2), it can be seen that 82% of data is included in the 90% acceptability area, complying with a medium/high thermal comfort level based on the limits proposed in ISSO [34] for spaces of type β, class B. The summer period is the most critical period of the year in relation to the thermal acceptability of the inhabitants of ECU.

In the annual compendium of data for the MUN building (See Fig. 2), it can be seen that 78% of data is included in the acceptability area of 90%, complying with the average thermal comfort level based on the limits proposed in ISSO [34] for office spaces type β, class B.

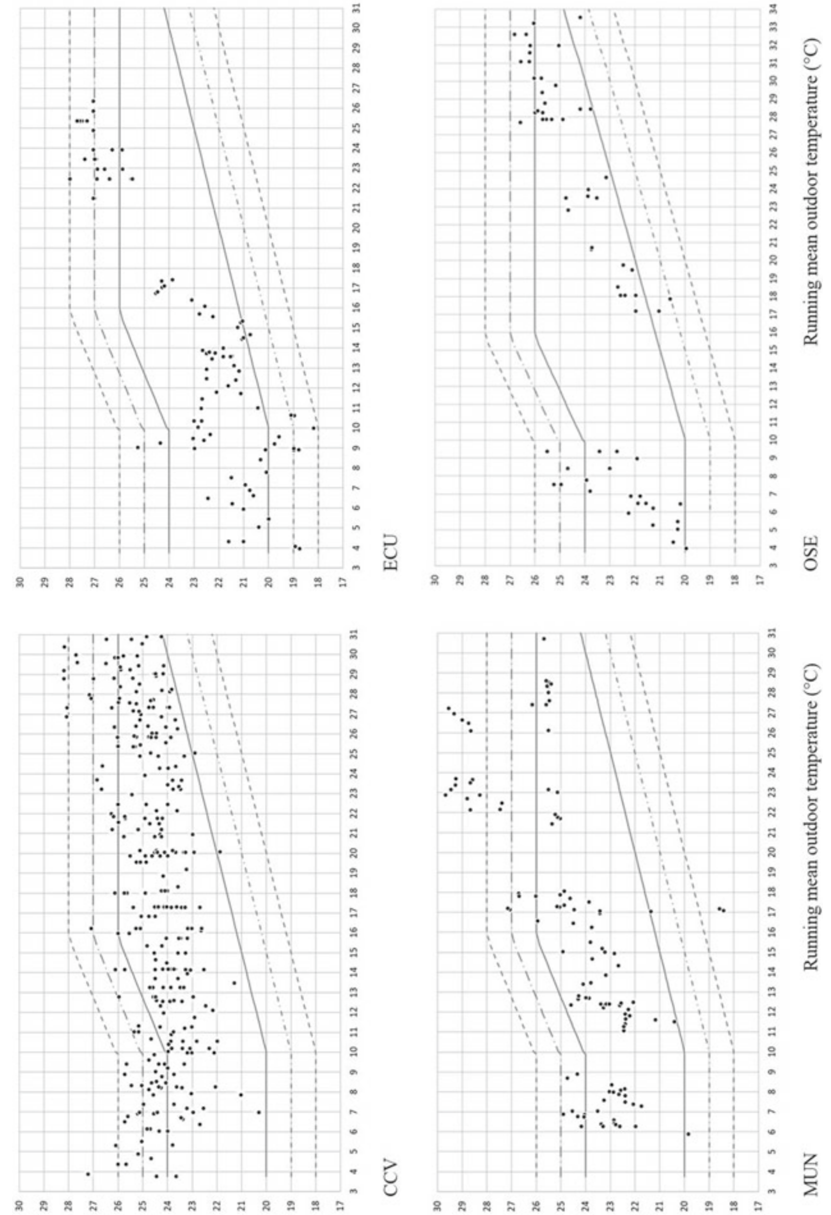

Fig. 2 Annual thermal comfort evaluation, building comparison [9]

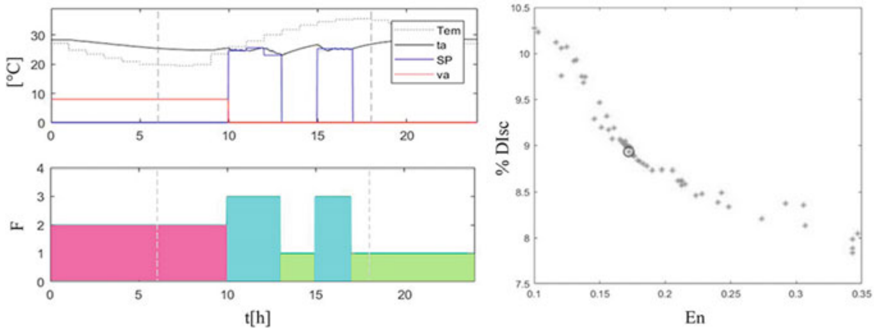

Fig. 3 Left: Hourly evolution of operating modes F. Right: Pareto front of Disc and En variables. MOOM optimization of a typical summer day for the CCV building [9]

OSE annual information (See Fig. 2) shows that 85% of data is included in the 90% acceptability area, complying with a medium/high thermal comfort level based on the limits proposed in ISSO [34] for office spaces of type β, class B.

3.2 MOOM Optimization in Studied Cases

The results obtained in each studied case are shown below. The ISSO 74 evaluation [34] always presents the thermal comfort vote in relation to the evolution of indoor temperature and the optimization profile with the values of interior temperature (ta), exterior temperature (Tem), AC activation (SP), opening of windows (va), and the summary of the combination of strategies (*F1, F2,* and *F3*), to obtain the thermal-energy benefit in each case, followed by the hourly evolution of the indoor temperature (regardless of the optimization strategy) and the set of possible solutions (Pareto front) where the objective variables *Disc* and *En* are compared.

3.2.1 Multi-Objective Optimization in CCV

Figure 3 shows the optimization results for the CCV building. According to the daily evolution, the system decides the *F2* strategy (window open, magenta) during the night, until the morning at 10:00, where due to the increase of outdoor temperature, it changes to strategy *F3* (AC-on, cyan).

For half of the working hours, it is decided to switch to strategy *F1* (Envelope, green). This cut in the use of AC allows considerable energy savings.

Figure 4 shows in detail the evolution and relationship between average outdoor temperature (Tem) and indoor air temperature (ta). As can be seen, before 10:00 a.m., ta increases, which leads to a change of strategy to *F3* (AC), with $ta = 26C$. With the use of AC, it decreases to $ta = 23.5C$. The system then turns off the AC and turns it back on when $ta = 27C$ (3:00 p.m.). It is possible that at this time (*F1* strategy from 1:00 p.m. to 3:00 p.m.), even though the system defines this option as the most optimal, this increase in temperature leads to narrow ranges of thermal acceptance for the inhabitants. However, this intermediate range in the *F1* strategy does not imply energy cost, helping to achieve significant energy savings. These results are obtained from the selection of the optimal solution by the L2 norm (minimum distance to the ideal vector) found in the Pareto front (Fig. 3). For the CCV building, a $Disc = 8.85$ and $En = 0.17$ are achieved through optimization.

3.2.2 Multi-Objective Optimization in ECU

Office hours are marked with dashed lines on the x-axis. In this case, the system decides on the *F2* strategy during the morning until 9:00 a.m., followed by 2 hours of *F1* strategy, and then it is modified to the *F3* strategy. In a similar way to the case of the CCV building, from 3:00 p.m., strategy *F1* took place for 1 hour (See Fig. 5).

Around 11:00 a.m. ta exceeds the 26°C barrier (Fig. 4), suggesting an *F3* (AC) strategy. With the use of AC, it decreases to $ta = 26C$. The system then proposes to turn off the AC and turns it back on when ta approaches almost 27.5°C. For the case of the ECU building, the optimization results in $Disc = 7.95$ and $En = 0.12$ (See Fig. 5).

3.2.3 Multi-Objective Optimization in MUN

For this situation, the system advises strategy *F2* during the morning until 10:00 a.m., starting with 2 hours of strategy *F1*, and then it is modified to strategy *F3*, which is maintained for 1 hour (See Fig. 6). In this case, energy cost is minimal, compared to CCV and ECU.

AC use decreases ta to 25°C. The system proposes turning off the AC 1 hour later, achieving significant energy savings. Towards the end of office hours, ta reaches 28°C (See Fig. 4). Figure 6 shows the Pareto front obtained based on the optimal L2 norm preferred solution. Results for the MUN building optimization are $Disc = 8.6$ and $En = 0.05$.

3.2.4 Multi-Objective Optimization in OSE

For the OSE building, the control system operates the *F2* strategy during the morning until 9:00 a.m. and continues using strategies *F1* and *F3* (See Fig. 7).

The strategy is then changed back to *F1*, which continues until the end of business hours.

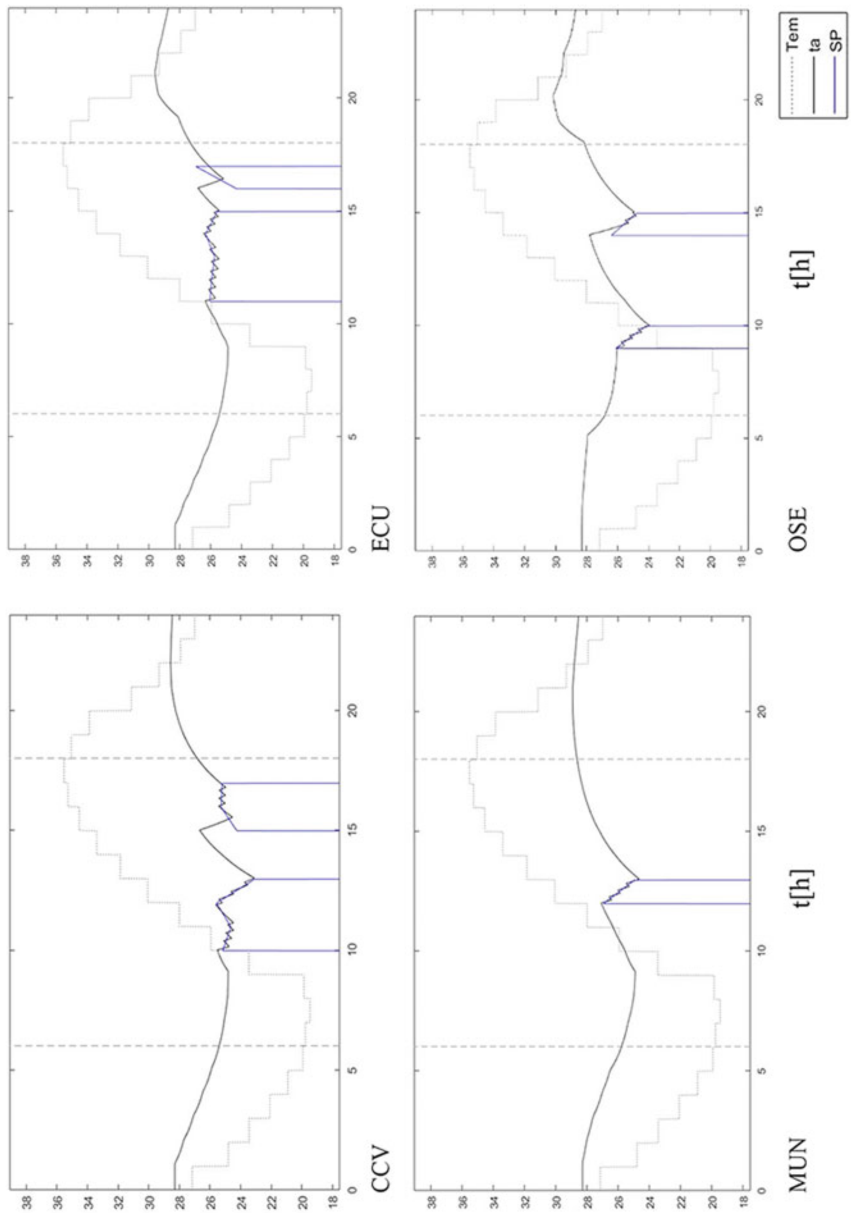

Fig. 4 Hourly evolution of Tem (running mean outdoor temperature), ta (indoor air temperature) and SP (set point temperature). MOOM optimization of a typical summer day applied to each building [9]

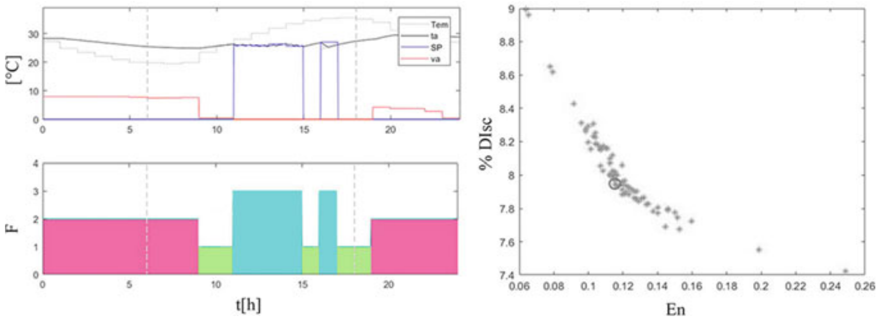

Fig. 5 Left: Hourly evolution of operating modes F. Right: Pareto front of Disc and En variables. MOOM optimization of a typical summer day for the ECU building [9]

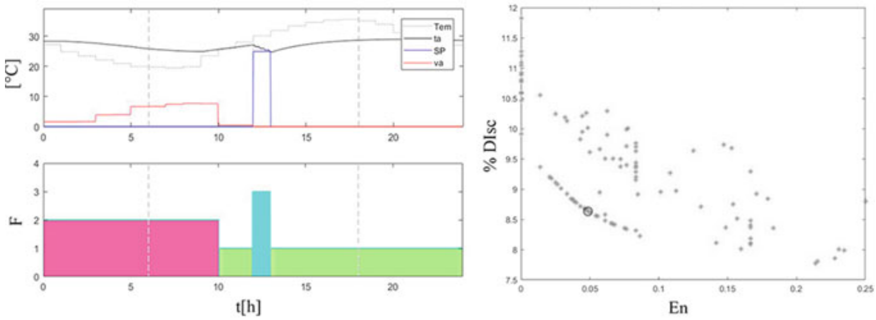

Fig. 6 Left: Hourly evolution of operating modes F. Right: Pareto front of Disc and En variables. MOOM optimization of a typical summer day for the MUN building [9]

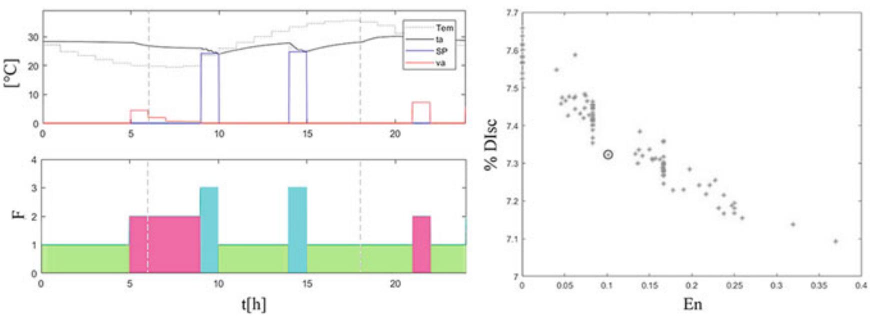

Fig. 7 Left: Hourly evolution of operating modes F. Right: Pareto front of Disc and En variables. MOOM optimization of a typical summer day for the OSE building [9]

Table 3 Summer energy consumption and cooling savings for each building [9]

	Annual energy consumption (kW h/m^2 year)	Summer energy consumption (kW h/m^2 summer period)	Summer energy consumption (kW h/m^2 cooling period)	
			No savings	With savings
CCV	335	137.5	62	26.4
OSE	158	71.1	17.1	5.7
MUN	137	50.7	6.1	1.0
ECU	126	56.9	4.6	1.3

The use of AC at 9:00 a.m. decreases the ta to 24°C (See Fig. 4). The system turns off the AC 1 hour later, achieving significant energy savings. Towards the end of the working hours, ta reaches about 28°C. In the case of the OSE building, a $Disc = 7.32$ and $En = 0.10$ are achieved through optimization (See Fig. 7).

3.2.5 Energy Efficiency Potential

Based on the building's energy consumption (for the summer period), previously shown in Fig. 1, the consumption corresponding to the "cooling" item (See Table 3) is determined, which represents the following percentages for each building: CCV = 45%; OSA = 24%; MUN = 12%; ECU = 8% [35].

Energy benefit contributions from the thermo-energy optimization design tool are evident, achieving savings of up to 83.3%—in the case of the MUN building—of energy dedicated to cooling during the summer period (See Table 3). An energy-saving projection is highlighted for the case of the CCV building (the building with the highest consumption in the city of San Juan), where its cooling energy consumption is reduced from 62 to 26.4 kW h/m^2.

For the CCV and OSE buildings (highest consumption), the percentage saving is 57.5 and 66.7%, but for buildings that consume the least, the potential savings are much higher, in a range of 71.3 and 83.3%.

The results show that by implementing the thermo-energetic multi-objective optimization tool, the energy demand for the air conditioning of office spaces can be greatly reduced, and simultaneously the quality of thermal comfort can be significantly improved.

4 Discussion

Both nationally and internationally, there is a consensus on the prevailing need to reduce electricity demand from the air conditioning of buildings. In this context, buildings with habitable spaces need to ensure healthy thermal comfort conditions.

This research contributes to the creation of techniques and tools for architects and engineers. The MOOM optimization tool is applicable to the design stage of new buildings, considering that predicting energy demand-saving potential before defining the envelope, would adequately determine functional organization schemes for indoor spaces, thermal insulation values, cross ventilation, window sizes and location, HVAC sizing and design, for the least impact on the use of energy resources, assuring high-quality thermal comfort and sustainability.

This research shows that when applying the proposed multi-objective optimization tool—for the summer period—, improvements in thermal comfort (lower results in the *Disc* variable) are obtained in all cases, with an average percentage of 20.53%. The normalized energy variable *En* is reduced in all cases, with an average percentage of 69.6%. The results show that, through the implementation of the MOOM multi-objective optimization tool, the energy demand for the air conditioning of office spaces can be greatly reduced, and simultaneously the quality of thermal comfort can be significantly improved.

The development of the MOOM tool is based on the observation of four office buildings, which represent the greatest energy use impact in the city of San Juan. Among them, the CCV has the most unfavourable energy efficiency coefficient. Based on the development of the optimization tool in this research, the combination of passive/active strategies with an impact on the consumption of resources allows for ensuring energy savings (for the summer period) of 57.5%, in the case of CCV, and up to 83.3% in the case of MUN. In the case of OSE, an improvement of 66.7% is obtained and for the ECU building, 71.3%.

5 Conclusions

This work highlights techniques implemented for the first time in the architectural discipline addressing office building's energy retrofitting through the MIDACO multi-objective optimization. These contributions expand the scope of optimization tools, compared to previous applications to office buildings in the design stage, managing daily dynamic optimization with future applicability towards the development of smart control systems and the definition of architectural design guidelines. Significant energy savings in the four case studies (57.5–83.3%) validates the new MOOM optimization design tool, where the gap between energy consumption and thermal comfort is reduced. The system provides high-level indoor thermal comfort conditions for the inhabitants (thermal acceptance above 90% in all cases).

This paper aims to consolidate the multi-objective optimization tool as a key step within the framework of energy efficiency policies. Currently, this research grounds a technological development of a control system to optimize comfort variables and air conditioning/ventilation strategies in interior spaces in real time and dynamically. It has been awarded a state subsidy for the purchase of high-quality supplies and start-ups.

It is also proposed to extend the study of the MOOM tool to residential, educational, and commercial buildings and its applicability to different climatic contexts.

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References

1. Verhaart J, Veselý M, Zeiler W (2015) Personal heating: Effectiveness and energy use. Build Res Inf 43:346–354. https://doi.org/10.1080/09613218.2015.1001606
2. van Hoof J, Mazej M, Hensen JLM (2010) Thermal comfort: Research and practice. Front Biosci 15:765–88. https://doi.org/10.2741/3645
3. Holmes MJ, Hacker JN (2007) Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. Energy Build 39:802–814. https://doi.org/10.1016/j.enbuild.2007.02.009
4. Yau Y (2008) A preliminary thermal comfort study in tropical buildings located in Malaysia. Int J Mech Mater Eng 3:119–126
5. Nguyen AT, Reiter S, Rigo P (2014) A review on simulation-based optimization methods applied to building performance analysis. Appl Energy 113:1043–1058. https://doi.org/10.1016/j.apenergy.2013.08.061
6. Dounis A, Caraiscos C (2009) Advanced control systems engineering for energy and comfort management in a building environment'a review. Renew Sustain Energy Rev 13:1246–1261. https://doi.org/10.1016/j.rser.2008.09.015
7. Chandel S, Sharma V, Marwah BM (2016) Review of energy efficient features in vernacular architecture for improving indoor thermal comfort conditions. Renew Sustain Energy Rev 65:459–477. https://doi.org/10.1016/j.rser.2016.07.038
8. Sánchez-García D, Rubio-Bellido C, Marrero Meléndez M, Guevara-García FJ, Canivell J (2017) El control adaptativo en instalaciones existentes y su potencial en el contexto del cambio climático. Revista Hábitat Sustentable 7:06–17. https://doi.org/10.22320/07190700.2017.07.02.01
9. Arballo B (2020) Eficiencia energética y confort térmico adaptativo-variable en espacios de oficina mediante optimización multiobjetivo. PhD thesis, Universidad Nacional de San Juan. San Juan, Argentina
10. Ajmat R (2017) Precision daylight and thermal modelling of shading devices. PhD thesis, Institute of Energy and Sustainable Development, De Montfort University Leicester, Leicester, UK
11. Mestre Martínez N (2014) De la eficiencia energética a la redundancia ecológica. Itinerario conceptual y sintaxis razonada del híbrido arquitectónico. PhD thesis, Universidad Europea de Madrid. Madrid, España
12. Sulaiman H (2011) Confiabilidad y economía en la optimización del diseño bioclimático. PhD thesis, Universidad de Mendoza. Mendoza, Argentina
13. Bre F, Fachinotti V, Bearzot G (2013) Simulación computacional para la mejora de la eficiencia energética en la climatización de viviendas. Mecánica Computacional 32:3107–3119
14. Bre F, Albanesi A, Fachinotti V (2014) Diseño y optimización de protecciones solares externas usando simulación energética de edificios. Memorias del 1er Congreso de Energías Sustentables. Bahía Blanca, Argentina, pp 98–105
15. Bre F, Fachinotti V (2017) A computational multi-objective optimization method to improve energy efficiency and thermal comfort in dwellings. Energy Build 154:283–294. https://doi.org/10.1016/j.enbuild.2017.08.002

16. Bre F, Fachinotti V (2016) Generation of typical meteorological years for the Argentine Littoral Region. Energy Build 129:432–444. https://doi.org/10.1016/j.enbuild.2016.08.006
17. Bre F, Silva AS, Ghisi E, Fachinotti V (2016) Residential building design optimisation using sensitivity analysis and genetic algorithm. Energy Build 133:853–866. https://doi.org/10.1016/j.enbuild.2016.10.025
18. Boerstra A, van Hoof J, van Weele A (2015) A new hybrid thermal comfort guideline for the Netherlands: background and development. Architect Sci Rev 58:24–34. https://doi.org/10.1080/00038628.2014.971702
19. UNE-EN (2008) UNE-EN 15251. Parámetros del ambiente interior a considerar para el diseño y la evaluación de la eficiencia energética de edificios incluyendo la calidad del aire interior, condiciones térmicas, iluminación y ruido
20. EnBop (2008) Energie betriebsoptimierung. http://www.enob.info
21. Bliuc I, Rotberg R, Dumitrescu L (2007) Assessing thermal comfort of dwellings in summer using EnergyPlus. In: Proceedings of the CLIMA 2007 world congress well being indoors. Helsinki, Finland
22. Chambers L (2000) The practical handbook of genetic algorithms: applications. Chapman and Hall/CRC, New York, USA
23. Coello C, Veldhuizen D, Lamont G (2007) Evolutionary algorithms for solving multi-objective problems, vol 242. Springer, US, Boston, MA. https://doi.org/10.1007/978-0-387-36797-2
24. Atthajariyakul S, Leephakpreeda T (2005) Neural computing thermal comfort index for HVAC systems. Energy Convers Manag 46:2553–2565. https://doi.org/10.1016/j.enconman.2004.12.007
25. Lu L, Cai W, Xie L, Li S, Soh YC (2005) HVAC system optimization-in-building section. Energy Build 37:11–22. https://doi.org/10.1016/j.enbuild.2003.12.007
26. Huang W, Lam H (1997) Using genetic algorithms to optimize controller parameters for HVAC systems. Energy Build 26:277–282. https://doi.org/10.1016/S0378-7788(97)00008-X
27. Asiedu Y, Besant R, Gu P (2000) HVAC duct system design using genetic algorithms. HVAC R Res 6:149–173. https://doi.org/10.1080/10789669.2000.10391255
28. Stanislav H (2003) Systems and control. Oxford University Press, New York, USA
29. Yuan Y, Yuan J, Du H, Li N (2012) An improved multi-objective ant colony algorithm for building life cycle energy consumption optimisation. Int J Comput Appl Technol 43:60. https://doi.org/10.1504/IJCAT.2012.045842
30. EPRE (2017) Energy consumption data. Tech. rep, provincial energy regulatory entity, San Juan, Argentina
31. Arballo B, Kuchen E, Chuk D (2019) Optimización de la eficiencia energética aplicando confort térmico adaptativo en un edificio de oficinas público en San Juan-Argentina. Revista hábitat sustentable 9:58–67
32. Kuchen E (2008) Spot-monitoring zum thermischen komfort in bürogebäude. PhD thesis, Der Andere Verlag, Tönning, Deutschland
33. Arballo B, Kuchen E, Chuk D (2022) Optimización multiobjetivo de la eficiencia energética y el confort térmico en edificios de oficina públicos. Periodo crítico de verano en la ciudad de San Juan-Argentina. Revista Hábitat Sustentable 12:102–113, 10.22320/07190700.2022.12.01.07
34. ISSO (2004) ISSO 74. Thermische Behaaglijkeid, Rotterdam, Netherlands
35. Kuchen E, Alonso-Frank A, Alamino-Naranjo Y, Arballo B, Galdeano M, Accolti E (2016) Eficiencia energética en edificios públicos. In: VIII Congreso Regional de Tecnología de la Arquitectura-CRETA, San Juan, Argentina

Comparison of Comfort and Energy Performance in Naturally Ventilated Classrooms, Based on the Application of Passive Architectural Design Strategies

Olga Lucia Montoya, Natalia Saavedra, and Juan G. Gutiérrez

Abstract Comfort and energy consumption in classrooms are closely related topics. In naturally ventilated classrooms and non-controlled environments, it is necessary to delve into the effect of ventilation, solar incursion, and façade control devices, among other strategies, on energy consumption. This is the framework of this chapter, which aims at evaluating the thermal and visual comfort regarding the energy consumption of classrooms built under the design parameters of the Colombian Technical Standard NTC-4595 for comfortable environments. Moreover, it looks to determine improvements in the thermal and visual environment, based on the application of passive architectural design strategies recommended by resolution 0549 on energy saving. The previous objective is achieved through an experimental model, simulated through Sefaira, a plugin of SketchUp. Conclusions allow validating the effect of design recommendations on thermal and visual comfort, their effect on saving energy, and finally contribute to the applicability of the standard focused on designers of educational spaces in the Global South.

Keywords Thermal comfort · Visual comfort · Energy consumption · Ventilated classrooms · Tropics

O. L. Montoya (✉) · N. Saavedra · J. G. Gutiérrez
Universidad de San Buenaventura, Cali, Colombia
e-mail: olmontoy@usbcali.edu.co

N. Saavedra
e-mail: nsaavedras@correo.usbcali.edu.co

J. G. Gutiérrez
e-mail: jggutierreza@correo.usbcali.edu.co

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1 Introduction

Energy consumption in Latin America to operate buildings represents between 24 and 30% of CO_2 emissions [1]. Energy consumption in Colombia for the services sector, where schools are included, is mainly due to lighting (31%) and air conditioning (22.8%) [2], both directly related to the building's design and envelope. Even though the consumption percentage of thermal conditioning systems is lower than in the United States (37%) [3], the percentage is increasing and could be reduced through design.

In Colombia, the mandatory Resolution 0549 determines some passive and active design strategies to be implemented on buildings to achieve water and energy savings [4]. On the other hand, regarding comfort directly impacting energy consumption, a range between 22 and 25°C is proposed, with no details about the measurement model, except the direct reference to Fanger [5]. Therefore, it is necessary to refer to the Colombian Technical Standard NTC-5316: Thermal Environmental Conditions of Buildings for People [6], which is an identical translation (IDT) of the ASHRAE 55 Standard.

Comfort and energy consumption in schools have started to be researched in countries with differentiated climatic seasons, where comfort conditions occur most of the year, thanks to mechanical air conditioning systems. This situation is different to warm and naturally ventilated environments, where a better tolerance to higher temperatures has been proven. However, research has shown the benefits of applying passive architectural design strategies for comfort as well as for energy consumption [7]. Furthermore, the results obtained when comparing the thermal sensation of people in air-conditioned classrooms versus naturally ventilated classrooms [8, 9] demonstrated that air-conditioned environments were more demanding.

The analysis made by Ho et al. [10] demonstrated the relationship between visual comfort and energy consumption in subtropical classrooms. That analysis showed that the right choice of façade elements to reflect light improved lighting conditions inside classrooms and also influenced power saving by implementing the right horizontal parasol [10], leading to 70% savings over regular consumption.

Relationships such as thermal and visual comfort with architectural aspects are addressed by Kwok and Grondzik [11], where they show physical standards for an acceptable thermal environment. Other researchers analyze thermal comfort in relation to the building envelope. Subhashini and Thirumaran [12] quantify the thermal performance achieved through a greater level of solar protection. Some researchers [13, 14] analyze the effect of the building envelope on the students' perception of comfort. And others include some less explored strategies like nighttime cooling assisted by thermal mass and dehumidification [15]. To design classrooms in the tropics, it is necessary to protect them from solar radiation [12, 16] and avoid the uncontrolled entrance of direct sunlight into the space, which has negative consequences such as undesired glare and high contrasts [17], while increasing temperatures and visual discomfort [18].

Research in the Global South has mainly occurred in places with seasons, such as Chile [19], Argentina, and Brazil, while few studies have been made in Colombia in the equatorial tropic strip [20]. As several reports indicate [21], most studies on thermal comfort have been made in mild climates (65%), and only 20% in tropical (or subtropical) climates such as Hawaii, Australia, Malaysia, Singapore, Thailand, Nigeria, Ghana, and India. Meanwhile, studies made in zones near the equator are rare [22].

This document presents a study of comfort and energy consumption in tropical climate classrooms. In particular, it analyzes the incidence of applying passive architectural design strategies to educational spaces to have efficient spaces; specifically, spaces promoting good academic performance [23] as well as the applicability of domestic and international standards in a zone very near to the equator.

2 Methodology

This analysis was made in a school located in the city of Cali, representing the analysis context. Cali is a city with a dry warm climate. The average temperature is around 25°C, with variations during the day and night between 17 and 34°C, and average relative humidity of 70%. The climate has two periods during the year: a dry period from December to February and July to August and a rainy period from April to May and in September.

Although the adaptive model is valid as a proposal for naturally ventilated environments, the range considered is that proposed by the Colombian Technical Standard NTC-5316, which regulates thermal comfort in buildings. It defines a comfort range for summer in Colombia of $22.5°\text{C} < T_o < 26°\text{C}$, 60% RH, met ≤ 1.2, where at least 80% of the population is satisfied, where T_o = Operative temperature, RH = Relative Humidity, and met = metabolic activity [6].

The methodology is based on the analysis of an experimental model of a real classroom, which is organized into three stages: (i) Analysis of average temperatures in the basic situation and under application of improvement strategies; (ii) Analysis of comfort; and (iii) Energy consumption using the range proposed by the standard. Below, the design of the building's thermal simulation model is described, focused on the studied prototypical classroom, and later the design strategies for improving the classrooms are described.

Sefaira (a plugin of SketchUp) proposes a new modeled paradigm, associated with the design process, in real time, from the first conceptual stages up to the construction documents. This is a plugin of associated 3D work software like Revit and SketchUp, which is closer to architecture graphical environments.

Fig. 1 School building represented on the model. On the left, view of the classroom façade. On the right, view of the classroom interior. *Source* Photograph of the authors

2.1 Design of the Thermal–Visual Simulation Model

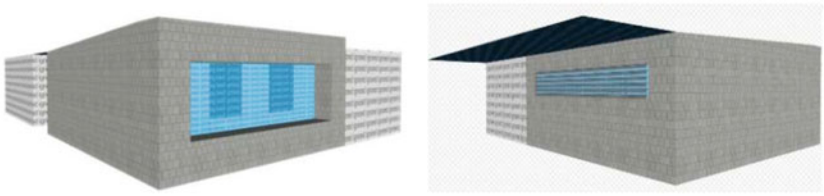
Sefaira tool, created in 2009, currently allows analyzing thermal, visual, and energy performance in the cloud, based on climatic data. The advantage of this tool is that it is possible to use it in different architectural software, making these energy consumption analysis processes more accessible.

The model represents an existing school building (see Fig. 1), from which a top-floor classroom is chosen to apply and evaluate the design strategies. It is a typical classroom with a ceiling height of 3 m. Its façade is northwest facing, with a window whose surface is 1/2 of the floor area; the window measures 8 m wide by 2 m tall = 14 m^2 (58% of the exposed facade) and has a grid measuring 7 m wide by 0.4 m tall = 2.8 m^2 and one window in the inner façade toward the corridor of 5.6 m wide by 0.6 m tall = 3.36 m^2 (14% of the façade). Full details of the model are shown in Fig. 2.

2.2 Design Strategies for the Thermal, Visual, and Energy Improvement of Classrooms

Four design alternatives are applied to the base case, first, because they are recommended by the sustainable construction guide for energy saving in buildings, and second, by emblematic authors and specialized literature on the subject of warm climates, these are presented in Fig. 3.

To analyze the energy consumption, the classrooms are simulated in a natural ventilation mode, where all the mechanical conditioning systems are turned off (air conditioning systems as well as fans). However, the Sefaira software indicates the consumption that may be generated, when the space moves away from the indicated Setpoint, a value that allows making the comparison, please refer to Fig. 4.



DESCRIPTION	BASE CASE	
Building Type	Top Floor Classroom	
Dimensions	8m x 8.6m x 3m (wide x long x height) (206.4m^3 and 68.8 m^2)	
Main facade orientation	Northwest, with 17.5° angle	
Exterior cover	25mm thickness. It consists of metallic surface + expanded polyurethane + metallic surface. U Value = 0.67 $W/m^2.K$ (according to supplier catalogue)	
Floor slab	100mm light concrete + tiles. U Value = 0.32 $W/m^2.K$ (according to supplier catalogue)	
Walls	200mm concrete block. U Value = 4.53 $W/m^2.K$ (IRAM Standard)	
Glass: properties	U Value = 5.8 $W/m^2.K$. SHGC*=0.82, VLT** 88%	
Main facade	Glass	Area = 14 m^2
	Shade Element	Glazed area backs down 0.60 meters of the wall
Back facade	Glass	Area 3.36 m^2
	Shade Element	Aluminum blinds every 0.10 m
Infiltration	Facade Area 75Pa design infiltration rate 7.2 m^3 /m^2.h *	
Thermal load by person	100W by person (predefined by Sefaira), or 63.9 W/m ^{2}. 100WX44 occupants = 4,400 W/68.8m^2 =63.9 W/m^2)*	
Occupation	1.56m^2/Person (44 occupants in 68.8m^2)	
Occupation Ratio	From 7 a.m. to 5 p.m., No activity in August and vacations period*	
Activity Level (met)	Constant value of 1.1 equivalent to be seated and writing *	
Internal gains by users (W/m^2)	63.9 W/m^2. 100WX44 occupants = 4,400 W/68.8m^2 =63.9 W/m^2)*	
Insulation by clothing (clo)	According to the EnergyPlus dynamic predictive clothing isolation model, in compliance with ASHRAE 55, which calculates it from the average exterior temperature *	
Ventilation rate	6.40 l/m^2.s ((44 occupants X10l/s)/68.8 m^2)*	

Fig. 2 Description of the base case model. SHGC: Solar Heat Gain Coefficient; VLT: Visible light transmittance *Source* [24]; * Thermal Data *Source* Compiled by authors from Sefaira Support [25]

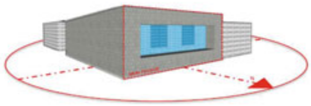
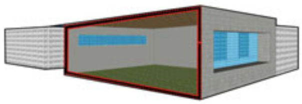
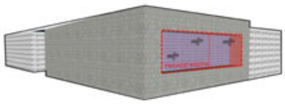
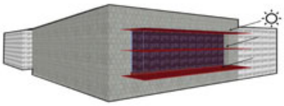
MODEL	STRATEGY
	**Orientation:** Main Façade facing north.
	**Insulation:** Increase thermal insulation in all the envelope of the classroom: walls, roof and floor to the minimum U value of 0.1 W/m²·K.
	**Ventilation:** the effective area to ventilate is expanded, thus: i. Corridor facade: blinds eliminated; ii. Main facade: all the windows are operable; iii. All the windows remain opened 24 hours.
	**Shading:** main facade with vertical window-height *brise soleils* every 0.60 m. and three shading elements of the length of the window x 1 meter. They are just defined as shading elements but on the software neither material nor thickness is specified.
	**Glazing area reduction:** the glazing area of the facade is reduced (same as the window area towards the corridor). The ratio of window area that can be opened is half the glass area, the other half is fixed glass

Fig. 3 Design strategies. *Source* Compiled by authors

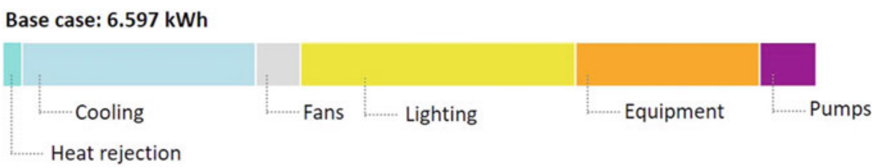


Fig. 4 Energy consumption items in kWh of Base Case. *Source* Compiled by the authors from Sefaira Web image

2.3 *Metrics for Visual Performance*

There are static metrics, such as daylight factor (DF) and solar incidence to quantify sunlight, that allow identifying, through simulations and manual geometric methods, the direct solar incidence on a space or work plane. On the other hand, in recent years, dynamic metrics have been developed from computational lighting calculations based on CBDM (climate-based daylight modeling) climatic databases.

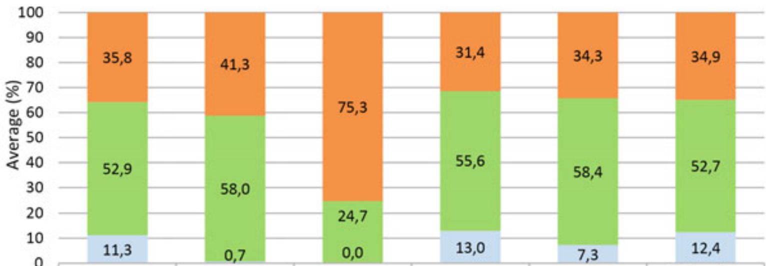
The IESNA (Illuminating Engineering Society of North America) developed two metrics that complement themselves [26] and strengthen the analysis of lighting performance:

- sDA (spatial daylight autonomy) indicates the percentage of the area analyzed over an illuminance value determined in 400 lux, during a specific timeframe. 75% is considered the reference value.
- ASE (annual sunlight exposure) refers to the percentage of the floor area that receives at least 1000 lx for at least 250 occupied hours during the year [27]. The value accepted for this indicator is a maximum of 10% [28].

3 Results and Discussion

3.1 *Thermal Performance*

The base case has 52.9% of the hours in comfort (22.5 and 26°C). It is possible to identify in Fig. 5 that this percentage improved through the application of passive



	Base Case	Orientation	Insulation	Ventilation	Shading	Glazing área reduction
Too hot discomfort	35,8	41,3	75,3	31,4	34,3	34,9
COMFORT	52,9	58,0	24,7	55,6	58,4	52,7
COLD DISCOMFORT	11,3	0,7	0,0	13,0	7,3	12,4

Fig. 5 Bar graph with percentage of hours in comfort and discomfort, and table with averages of temperature in comfort, heat and cold discomfort

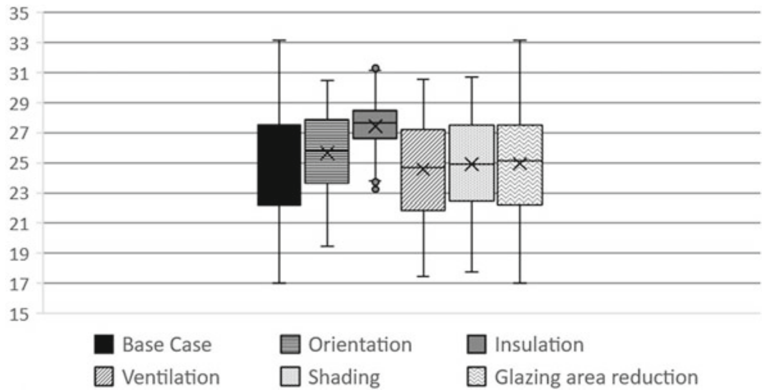


Fig. 6 Base case and strategy temperatures in the hottest month

architectural design strategies, except in the insulation strategy, where the comfort percentage is only 24% of the time, while 75% of the time it is too hot.

In the same figure, it is possible to identify those strategies obtaining a higher percentage of hours in thermal comfort, such as orientation and shading with corresponding percentages of 58 and 58.4%. It is worth mentioning the variation of these comfort and discomfort percentages between the strategies, even though average temperatures in each strategy are quite similar, with average temperatures between 23.2 and 23.6°C, >20.9°C between 20.2 and 20.5°C, and <26.1°C between 27.5 and 27.9°C.

Hours in comfort in temperatures over 24°C are different from air-conditioned classrooms in warm climates, where comfort temperature is assumed as between 18 and 24°C, and it may differ a lot from the average outdoor temperature [29].

A more detailed analysis made during every hour of the month of August, which has the highest temperatures, shows the thermal performance of the base case and the implemented strategies. While outdoor temperatures ranged between 22.01 and 31.8°C, the base case displayed an average temperature of 25°C, with high temperatures of up to 33°C and low temperatures down as far as 17°C.

Figure 6 shows how the temperatures from the base case are higher than those from the strategies, while the lowest temperatures are similar. The strategy with a different performance is the one incorporating thermal insulation, where such low temperatures are not reached.

For a more detailed view, please refer to Fig. 7 which contains the same strategies during some typical days of the month. As can be observed, all the strategies manage to reduce maximum and minimum temperatures. However, the orientation strategy not only manages to reduce the maximum temperatures (up to 2K) but achieves fewer temperatures below the lower limit of the comfort range (21°C), with a behavior closer to the range. These results are opposite to the recommendation of Olgyay [30], which recommends for Cali, rotations in volumes up to 17° in relation to the North–South axis (situation of the base case), without entailing greater thermal gains in the space.

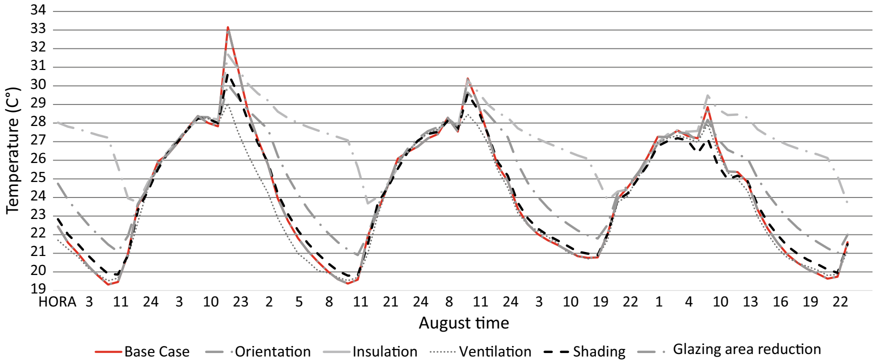


Fig. 7 Temperature during typical days of the month. *Source* Compiled by the authors

Also, the shading strategy with similar behavior to the orientation (see Fig. 7) manages to reduce maximum temperatures (by between 1 and 2°C). Nevertheless, the behavior toward the minimum temperatures is very similar to the base case. It also manages to improve hours in comfort by up to 58.4%. This result concurs with other studies, where protecting the glass surface can benefit thermal comfort [12], thus resulting in the entire building having a high thermal performance [14].

The insulation strategy displays the most stable behavior, with lower thermal oscillation (9°C), when compared to the base case (up to 18°C); it keeps temperatures between 23 and 32°C, with a high-temperature trend above the comfort range. This result concurs with the statement from Thomas Mosquera [31], who stated that thermos-type architecture tends to hold heat, while the brise-soleil-type architecture is more appropriate for a warm dry climate.

To this effect, ventilation manages to reduce maximum temperatures by up to 2.5°C, proving its benefit, but it also increases cold discomfort as can be seen in Fig. 7. This is a demonstration of how careful this strategy needs to be, beneficial during school hours, but causing cold discomfort at the beginning of the day, thanks to the low temperatures gained in the early morning without façade control devices [7].

3.2 Visual Performance

Analyzing the visual performance of the base case, the percentage of the classroom area over 400 lx does not achieve the 75% which indicates suitable lighting while entering direct sunlight maintains the necessary percentages. In general, strategies such as ventilation and insulation came up like the base case, with slightly lower values (69%) than the one recommended for SDA (75%) and ASE (<10%), while the strategy of orienting the main façade toward the North improves ASE to 0%. However, it reduces SDA to 65%. Similarly, the strategies with lower ASE are shading

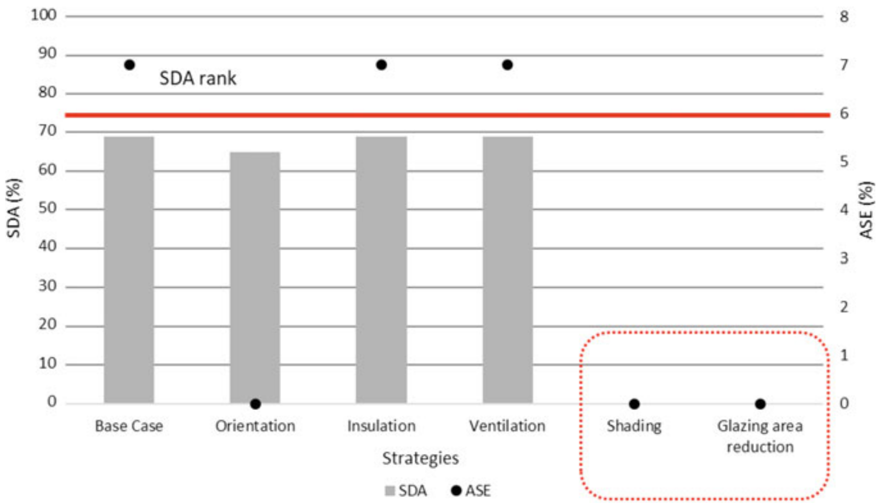


Fig. 8 SDA and ASE in the design strategies. *Source* Compiled by the authors

and reduction of the glazing area. These strategies, unlike the orientation, reduce the lighting quality of the classroom, since sDA is the lowest of them all at 0%, and DF is under 2% as required by the standard for educational environments [32] (see Fig. 8).

The role of the shading devices on the façade to improve the visual performance is worth greater analysis from finishing and color aspects, which improve light reflection and energy-saving qualities [10]. This finding demonstrates that conventional lighting in classrooms, with emphasis on the main façade and a smaller window toward the corridor (as the base case), is not sufficient to reach the optimum level of visual performance. Given this, greater exploration of strategies in that direction is required, such as additional light shelves, skylights, and other additional elements.

3.3 Energy Consumption Performance of the Strategies

After comparing the energy consumption of the strategies, Fig. 9 displays all the strategies applied which would imply a lower energy consumption to cool down (cooling and fans), except for the reduction of the glazing area. These results support the statement by Al-Saggaf et al. [3], who claimed that in warm climates, cooling loads are mainly reduced by the building orientation, shape, and glazing of windows.

On the other hand, although the insulation strategy can contribute to energy consumption by cooling [14], it does not indicate comfort.

The energy consumption results of the design strategies applied in the base case (See Fig. 10) show different results from those indicated in Annex 1 of Resolution

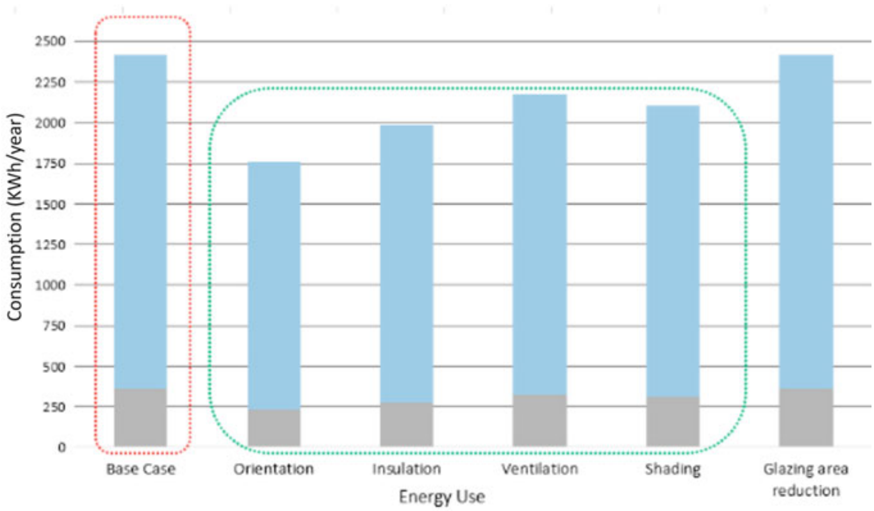


Fig. 9 Strategies and energy consumption. *Source* Compiled by authors

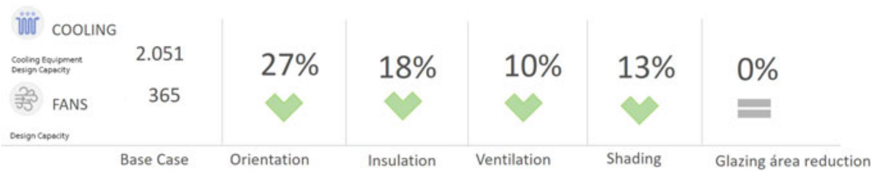


Fig. 10 Percentage of energy consumption saved with fans and cooling design strategies. *Source* Compiled by the authors from Sefaira Web data

0549 (including energy, comfort, and water), where glazing area and shading strategies are indicated as the ones generating greater energy savings: between 5 and 6%, respectively. As shown in Fig. 10, the greatest saving in consumption is represented by the orientation strategy with 27% lower consumption, followed by shading and ventilation.

However, the insulation strategy has an effect on consumption (18% less) but none on comfort, because although there is a performance saving, the temperatures maintained are higher than average, which affects comfort.

4 Conclusions

The differences between the performance of the base case and the strategies allow determining the benefit and potential incorporation of passive architectural design strategies in naturally ventilated spaces to improve thermal comfort and energy consumption, such as orientation, shading, and ventilation. However, these strategies do not manage to improve visual comfort.

An integrated comfort perspective in classrooms of the tropic is necessary, given that the Colombian standard, just as other standards in Global South countries, addresses comfort in an undecisive way, which not only complicates addressing this comprehensively but, on many occasions, the improvement in thermal comfort is detrimental to visual comfort, having an impact in energy consumption (as in this article).

The comfort range proposed by the Colombian standard, just as other standards in tropical countries, is a range imported from other climates, which may imply a greater thermal requirement and, therefore, greater energy consumption. Appendix 1 of sustainable construction must demonstrate the analysis of the energy-saving percentages set out therein, to be able to progress in the evaluation of their impact on the building, which had differences in the case analyzed.

Finally, research may contribute with experimental analyses of cases to evaluate the applicability of the standard and its possible lines of further development, not only at a national level but on an interdisciplinary and interterritorial scale, which allows learning from the experience on standard-related issues in other Global South countries with greater progress in these subjects.

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References

1. Cozzi L, Gould T (2021) World energy outlook 2019. Int Energy Agency 1–13
2. UPME (2022) Informe de gestión. Tech. rep, Unidad de Planeación de Minas y Energía, Bogota
3. Al-Saggaf A, Taha M, Hegazy T, Ahmed H (2020) Towards sustainable building design: The impact of architectural design features on cooling energy consumption and cost in Saudi Arabia. Procedia Manufact 44:140–147. https://doi.org/10.1016/j.promfg.2020.02.215
4. Ministerio de Vivienda Ciudad y Territorio (2015) Resolución 0549. Colombia
5. Fanger P (1970) Thermal comfort. Analysis and applications in environmental engineering, 1st edn. Danish Technical Press
6. ICONTEC (2004) NTC 5316: Condiciones ambientales térmicas de inmuebles para personas. Colombia
7. Montoya OL, Viegas G (2019) Confort térmico en aulas escolares del trópico, a partir de la aplicación de estrategias de diseño bioclimáticas pasivas. Avances en Energías Renovables y Medio Ambiente (AVERMA) 23:55–65. http://sedici.unlp.edu.ar/handle/10915/109499
8. Kwok AG (1997) Thermal comfort in naturally-ventilated and air-conditioned classrooms in the tropics. PhD thesis, University of California, Berkeley. https://escholarship.org/uc/item/65d3k1jt
9. Tablada A, de la Peña A, de Troyer F (2005) Thermal comfort of naturally ventilated buildings in warm-humid climates: Field survey. PLEA2005–The 22nd conference on passive and low energy architecture. Veirut, Lebanon, pp 1–6
10. Ho MC, Chiang CM, Chou PC, Chang KF, Lee CY (2008) Optimal sun-shading design for enhanced daylight illumination of subtropical classrooms. Energy Build 40:1844–1855. https://doi.org/10.1016/j.enbuild.2008.04.012

11. Kwok AG, Grondzik W (2018) The green studio handbook, 3rd edn. Routledge
12. Subhashini S, Thirumaran K (2018) A passive design solution to enhance thermal comfort in an educational building in the warm humid climatic zone of Madurai. J Build Eng 18:395–407. https://doi.org/10.1016/j.jobe.2018.04.014
13. Lee J, Alshayeb M, Chang JD (2015) A study of shading device configuration on the natural ventilation efficiency and energy performance of a double skin façade. Procedia Eng 118:310–317. https://doi.org/10.1016/j.proeng.2015.08.432
14. Zhou J, Nazi WIWM, Wang Y, Roskilly A (2019) Investigating the impact of building's facade on the building's energy performance-a case study. Energy Procedia 158:3144–3151. https://doi.org/10.1016/j.egypro.2019.01.1016
15. Daemei AB, Eghbali SR, Khotbehsara EM (2019) Bioclimatic design strategies: A guideline to enhance human thermal comfort in cfa climate zones. J Build Eng 25:100758. https://doi.org/10.1016/j.jobe.2019.100758
16. Appah-Dankyi J, Christian K (2012) An assessment of thermal comfort in a warm and humid school building at Accra, Ghana. Adv Appl Sci Res 3:535–547
17. Wu W, Ng E (2003) A review of the development of daylighting in schools. Light Res Technol 35:111–124. https://doi.org/10.1191/1477153503li072oa
18. Villalba A, Monteoliva J, Pattini A, Yamín J (2011) Control solar sobre superficies vidriadas. Evaluación lumínica mediante métricas dinámicas y preferencia de usuarios a filtros solares. Avances en Energías Renovables y Medio Ambiente (AVERMA) 28:27–36
19. Trebilcock M, Bobadilla A, Piderit B (2010) Environmental performance of schools in areas of cultural sensitivity. In: 28th international PLEA conference, Lima, Peru
20. Arango-Díaz L, Montoya Flórez OL, Rendón Gaviria L, Tilano Vega LM, Zapata Rueda CM (2021) Influence of the thermal and lighting performance in classrooms on the cognitive productivity of students in Colombia. J Green Build 16:135–164. https://doi.org/10.3992/jgb.16.4.135
21. Zomorodian ZS, Tahsildoost M, Hafezi M (2016) Thermal comfort in educational buildings: A review article. Renew Sustain Energy Rev 59:895–906. https://doi.org/10.1016/j.rser.2016.01.033
22. Nematchoua MK, Tchinda R, Orosa JA (2014) Adaptation and comparative study of thermal comfort in naturally ventilated classrooms and buildings in the wet tropical zones. Energy Build 85:321–328. https://doi.org/10.1016/j.enbuild.2014.09.029
23. de Abreu-Harbich LV, Chaves VL, Brandstetter MCG (2018) Evaluation of strategies that improve the thermal comfort and energy saving of a classroom of an institutional building in a tropical climate. Build Environ 135:257–268. https://doi.org/10.1016/j.buildenv.2018.03.017
24. Sefaira Support (2017a) Dayligthting design
25. Sefaira Support (2017b) HVAC design: Natural ventilation and thermal comfort
26. IESNA–The Daylight Metric Committee (2012) IES LM-83-12. Aproved method: IES Spatial Daylight Authonomy (sDA) and Annual Sunlight Exposure (ASE). New York, USA
27. Elghazi Y, Wagdy A, Mohamed S, Hassan A (2014) Daylighting driven design: optimizing kaleidocycle facade for hot arid climate. Aachen: Fifth German-Austrian IBPSA Conference. RWTH Aachen University, Aachen, pp 314–321
28. USGBC (2019) LEED v4.1 Building design and construction
29. González Cruz EM, Bravo Morales GC (2009) Sobre el confort térmico: Temperaturas neutrales en el trópico húmedo. Palapa 4:33–38
30. Olgyay V (1968) Clima y arquitectura en Colombia, 1st edn. Universidad del Valle, Cali, Colombia
31. Thomas Mosquera A (2010) La arquitectura en el cauca: del barro a lo virtual. https://www.camarahispanocolombiana.es/php/pdf_fichas/AlvaroThomas1.pdf
32. ICONTEC (2005) NTC 4595. Norma Técnica Colombiana Ingeniería Civil y Arquitectura. Planeamiento y Diseño de Instalaciones y Ambientes Escolares. Colombia

Optimized Housing Enclosures for Piura, Peru

David Resano

Abstract The city of Piura (lat. 5°S, long. 80°W) is located north of the Sechura Desert. Its typical weather is characterized by high temperatures throughout the year and low levels of precipitation that only change when the El Niño phenomenon cyclically occurs. However, almost all of the constructions in Piura use conventional enclosure solutions. The façades are brick-made, coated in some cases, basically following structural resistance criteria, but without any consideration for their thermal behavior. The same problem applies to the roof, which also needs to be impermeable due to the regular flooding caused by the El Niño phenomenon (ENSO). The lack of proper design concerning the enclosure becomes a barrier to the thermal comfort, habitability, and energy efficiency of these buildings. In this chapter, we analyze the socioeconomic, urban, constructive, and climatic context of Piura to propose suitable solutions for the design of an opaque thermal envelope for its houses. This project has been possible thanks to a research project supported by competitive funds from the University Enclosure.

Keywords Climograph · Thermal comfort · Building constructive solutions · Housing enclosure

1 Introduction

The city of Piura (lat. 5°S, long. 80°W) is located north of the Sechura Desert in Peru. Its typical weather has high temperatures and high levels of solar radiation throughout the year, and low precipitation levels, albeit altered when the El Niño Southern Oscillation (ENSO) occurs. This warm climate has led Piura to be known as "the city of eternal heat".

D. Resano (✉)
Department of Architecture, Universidad de Piura, Piura Campus, Peru
e-mail: david.resano@udep.edu.pe

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However, almost all the houses built in Piura are conventional enclosures that are not adapted to these specific climatic conditions. This constitutes a barrier to thermal comfort. In this chapter, this situation is analyzed, proposing constructive solutions to adapt the enclosure of Piura's homes to the prevailing climate.

This work presents some of the results of a research project, financed with competitive funds, made between 2017 and 2018 at the University of Piura. The project focuses on studying the thermal behavior of the opaque part of enclosures to propose contextualized solutions. Section 2 explains the methodology, and Sect. 3 analyzes the base situation in terms of the climatic, social, construction, and urban contexts. Based on this, in Sect. 4, different constructive enclosure solutions adapted to the climate and the local reality are discussed. Finally, Sect. 5 is devoted to conclusions regarding optimized proposal solutions to solve thermal barriers to comfort.

At the time this work was carried out, no studies related to the thermal behavior of opaque enclosures were found for the city of Piura. The sources and methods used to study the thermal behavior of the building shell are well known. However, finding specific ways to apply this knowledge to a concrete case, such as Piura, requires a novel approach. There are general works related to the whole of Peru [1], or specific façade construction typologies [2]. The novelty of this research lies precisely in combining both approaches and developing specific construction systems adapted to the climate of the region and local limitations.

Section 2 outlines the work methodology for this study. The authors suggest that it could be replicated in similar case studies, providing innovative integrated approaches to the design of opaque housing enclosures that overcome the thermal comfort barrier, considering the local context.

2 Methodology

As has been indicated above, the objective of this work has been to optimize the opaque enclosures of living spaces in Piura to overcome the constructive barrier to thermal comfort and energy efficiency, given the local social, economic, and technological conditions. To achieve this goal, the methodology comprises the following four phases: analysis of the base conditions, parameterization of the enclosure design components, development of constructive solutions, and monitoring of climatic behavior (see Table 1).

The analysis phase focused on four main dimensions: climate, urban environment, socioeconomic conditions, and technological context. Given the importance of this phase to guide the research results, the following section explains the methods and references used for this analysis. Regarding the weather data, the source is the weather station installed on the campus of the University of Piura [3]. The following three climographs were made: a general one tabulating the outside air temperature and relative humidity, precipitation, and radiation, and another two covering the comfort temperatures for these data, following the methods proposed by Olgyay [4] and Givoni [5]. For the urban analysis, city plans were studied, distinguishing the types

Table 1 Summary of conditions and strategies applied for enclosure optimization

Conditions urban	Intervention	Enclosure	Heat strategy	Rain strategy
I–Isolated	N–New	F–Facade	TI–Thermal Insulation	WP–Waterproofing
D–Divided	R–Restoration	D–Deck	TN–Thermal Inertia	PI–Pitch
		G–Ground floor	SP–Solar Protection	CT–Coating
			VE–Ventilation	SL–Sealing
			RR–Radiation Reflection	
			RD–Radiation Dissipation	
Design materials	**Technique**	**Form**	**Execution**	**Cost**
ADB–Adobe	QNC–Quincha	G–Geometry	COA–Coating	AC–A Class
BRC–Brick	SPA— Sandwich Panel	T–Thickness	LIN–Lining	BC–B Class
BMB–Bamboo	VEF–Ventilated Facade	H–Height	SSP–Self-supporting	CC–C Class
WOO–Wood	DSC–Dissipative Coating	L–Layers		DC–D Class
PLS–Plastic				
CCT–Concrete				
GLS–Glass				
MTL–Metal				

of urban fabric based on the following basic parameters: road width, building size, block type, block subdivision type, and building height. The sociological data were taken from the report on Peruvian socioeconomic levels [6], collecting the most relevant data for the objective of the research. The technological context was analyzed through visits to local industrial and artisanal raw material producers and distributors, collecting data on the cost, dimensions, and typologies of available construction elements.

In the following two phases, the methodologies aimed at synthesizing the information and establishing the basic parameters of enclosure design in terms of materials, construction techniques, geometric characteristics, installation, and cost. Based on the relationship of these parameters with the base conditions, several suitable design strategies were proposed for incident solar radiation: insulation, thermal inertia, protection, ventilation, reflection, and scattering as well as for the ENSO rain: waterproofing, pitch, coating, and sealing. The design phase was developed from this map, synthesized in Table 1, combining the available construction solution materials that would satisfy the aforementioned heat and rain strategies. These solutions are explained in Sect. 4, focusing on thermal comfort.

3 Analysis of the Base Conditions

As pointed out earlier, to find constructive solutions for façades and roofs adapted to the local reality, the base conditions of Piura related to the climate, urban fabric, socioeconomic conditions, and construction context were analyzed. The analysis of these conditions is explained below.

3.1 Weather and Comfort Parameters

Figure 1 shows the climograph of Piura, prepared using the data recorded by the UDEP weather station [3]. This graph summarizes the following monthly parameters: average, maximum, and minimum air temperatures; average rainfall accumulated in typical and ENSO periods; and maximum, medium, and minimum solar radiation. It highlights two peculiarities: the high rainfall level during ENSO and the high solar radiation value throughout the year. The psychrometric diagram in Fig. 1 [5] shows two main facts. First, there is stable weather throughout the year. Second, maximum and minimum monthly temperatures and humidity lie outside the comfort zone.

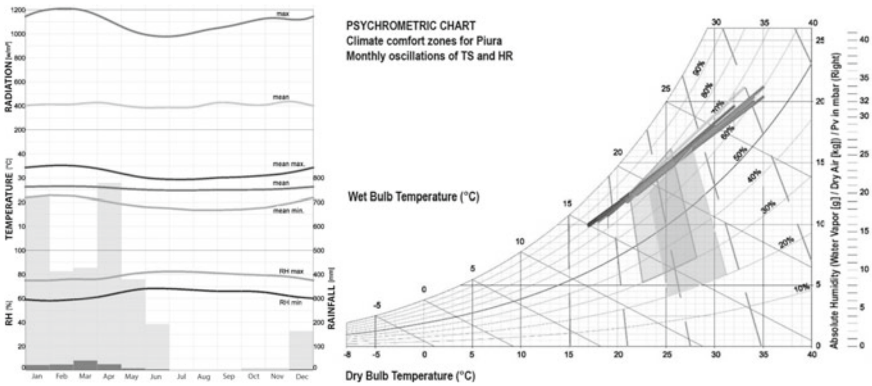


Fig. 1 Outdoor climate climograph of Piuray and Givoni's climograph of comfort conditions regarding maximum and minimum monthly temperature and relative humidity

3.2 Urban Fabric

To prepare the enclosure proposals, the main characteristics of the typical urban fabric surrounding the city dwellings were analyzed. Aside from the orientation, the urban layout was analyzed to determine the prevailing type of opaque enclosures (façades, dividing walls) and their typical dimensions. Four basic urban fabric typologies are synthesized, involving the following parameters: urban block, main and side street width, housing grouping, and urban plot dimensions (see Fig. 2).

The first typology is the historic downtown's original checkerboard, characterized by massive blocks of between 75 and 80 m on each side, with narrow streets barely 10 m wide and variable lot areas.

The second typology encompasses the urbanizations built beyond Grau-Bolognesi Avenue, with terraced lots that create orthogonal plots with 24 m avenues, 14 m secondary roads, and 9-meter-wide sidewalks. The lots represent the typical Gothic subdivision of current Peruvian cities, with about 8 meters wide and 20 meters deep. They form closed urban blocks of 20–40 m in width, and 100–150 m in length, built to surround public spaces. From the 1970s onward, streets were widened, and buildings rose to 3–4 stories.

The third typology is that of the gated condominium, with considerably wider roads (between 17 and 30 m) and the abandonment of the narrow frontage of the plot, allowing building detached houses.

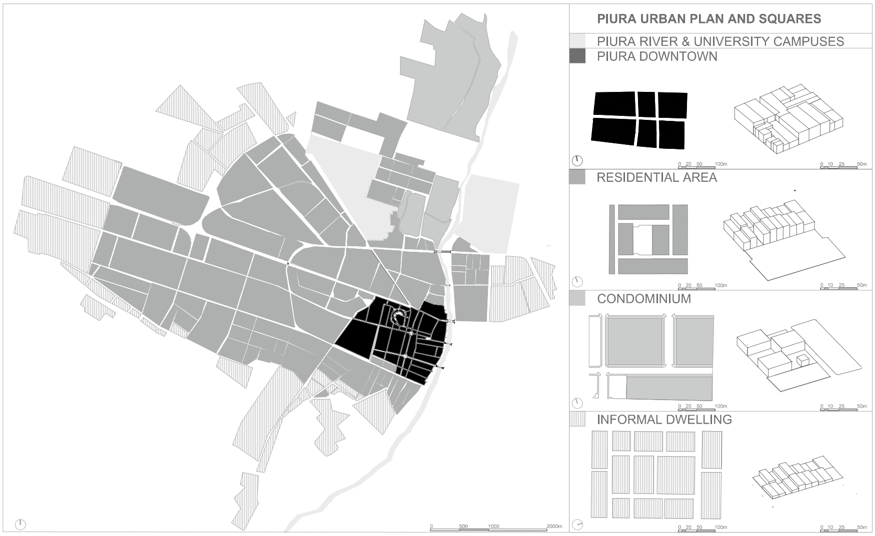


Fig. 2 Map of the city of Piura distinguishing the types of urban fabric and typical block lots

Finally, there are the city suburbs. These are characterized by the same urban block and lot pattern found in the urbanizations, but built with informal constructions, predominantly single-level houses, ones which the inhabitants built themselves.

3.3 Socioeconomic Context

Most houses in Piura have not been individually designed by an architect. This is a result of the owner's low socioeconomic level, which leads to them preferring self-construction processes. Consequently, there are no architectural quality parameters or technical criteria to guarantee adequate technical solutions, as analyzed in this case for thermal well-being. This lack of a constructive design of the enclosure is one of the main reasons that make the thermal envelope a barrier to the environmental comfort of homes. Here, social and constructive contexts are described as conditioning factors for the current building solutions concerning opaque enclosures.

Statistics show that the materials used predominantly in facades and roofs depend on the socioeconomic level of the building owner [6]. For façades, higher socioeconomic groups are built with brick, while the lower classes opt for adobe. As for the roof, the prevailing solution in the highest socioeconomic groups is that of reinforced concrete joist slabs and ceramic lightened slabs. The roofing used by the less wealthy is corrugated plastic or metal sheets. Traditional wall systems such as quincha are rare. The quincha façades (cane reeds with mud) only appear in 2% of the socioeconomic level C (SEL-C) and 4% of SEL-D. Cane mat and mud roofs are found in 7% of SEL-D and 6% of the SEL-C population, while only mat roofs appear in only 3% of SEL-D houses and 1% of SEL-C ones. Only 1% of SEL-D uses dry palm leaves for roofing.

There are cultural and economic reasons behind the different use of enclosure building systems [7]. The Peruvian population associate quality housing with brick cladding and wrought-iron roofing with joists and vaulted ceilings, mainly because of its greater mechanical strength and durability. Statistics show that most of the population aspire to build their home with walls based on ceramic elements such as brick and tray or vaulted ceilings.

3.4 Technical and Building Context

Piura is located in a seismic zone of the Nazca tectonic plate. This entails the need to consider resistance and stability features when it comes to choosing the characteristics of enclosing walls. The planning of Piura, as analyzed earlier, has led to the development of urban blocks formed by grouping housing lots separated by party walls without openings. It consequently leads to prioritizing the resistance of construction elements over issues of environmental comfort. This is a crucial point given the constant high solar radiation throughout the year (see Fig. 3).

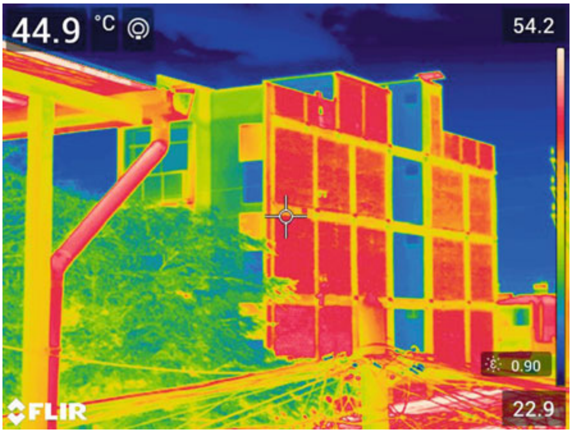


Fig. 3 Thermographic photograph of a standard residential building in Piura considering the urban fabric. June 18, 2020, at 1:15 pm

The prevailing construction system in Piura's urban homes is the use of brick walls, into which reinforced concrete columns are inserted every 2 or 3 m to increase resistance and stability against the horizontal loads produced by an earthquake. This walling system is called a confined wall, and it is the construction technique that prevails in the façades and dividing walls of the city.

Thus, brick and reinforced concrete are the predominant construction techniques used in the city, both for confined walls and lightened slabs, with numerous industrial and artisanal brick-producing companies. Concrete and steel for reinforcement are also available. This type of construction, statistically and socially, is associated with construction quality based on the need for resistance, but, as shall be shown, its thermal behavior is not the most appropriate for the climate and should be optimized.

Wood obtained from the Andean Highlands such as pine, fir, and eucalyptus is also used, as is tropical species from the Amazon forest. Wood, cane (reed), and mud are the predominant materials employed for enclosures in the city's peripheral areas, fundamentally using the "quincha" style building. As has been said, the typical roofing materials in these areas are corrugated sheet metal, plastic, or fiber cement panels. These materials are not produced locally and are provided by construction merchants. However, insulating materials are hard to find. Currently, they are limited to expanded polystyrene panels (called technopor) or mineral wool, used fundamentally as fillers in drywall inner partitions.

Therefore, the technological and building industry context favors current constructive enclosure solutions such as confined walls, lightened slabs, and corrugated panels. Nowadays, the local construction market does not promote products designed to be thermally opaque enclosures adapted to the local climate. This is both because of a lack of a thermal constructive culture and the high price of non-conventional systems.

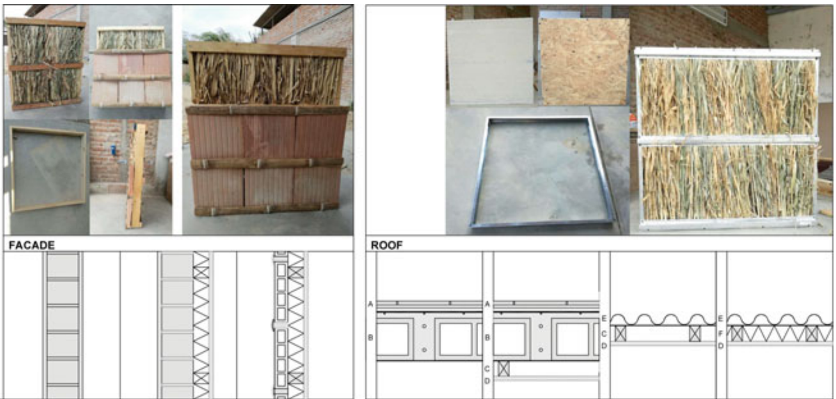
4 Proposed Optimized Constructive Solutions and Discussion

The main strategies to prevent opaque enclosures from being a barrier to thermal comfort are insulation and thermal inertia. The next section discusses these two aspects regarding the proposed solutions.

Since 2014, Peru has had a non-mandatory standard that regulates thermal and lighting comfort in buildings in terms of energy efficiency [8]. For this standard, the climate of Piura is classified as “Desert” [8, Annex I.A], indicating suitable maximum thermal transmittance values (U) of 3.20 W/(m^2 K) for walls and 2.20 W/(m^2 K) for roofs. However, this standard does not refer to suitable values for thermal inertia.

Figure 4 shows the values of thermal transmittance (U), thermal lag (DT), and effective thermal mass (mtu) of the current construction solutions used for enclosures as well as the optimized solutions proposed here. The calculation of these values is related to the properties of the materials indicated in Appendix 3 of the RNE-EM.110 standard. The current prevailing solution in the form of resistant brick wall facades (F.EX1) has a U-value of 2.610 W/(m^2 K), while in the lightened roof solution (C.EX1) it is 0.51 W/(m^2 K). Although U-values of wall and roof enclosure solutions would be in line with their respective limits according to RNE-EM.110, thermal behavior improvement is possible using a thermal inertia approach.

Regarding facades, the thermal lag (DT) of the F.EX1 solution is 3.29 hours. Considering the high solar radiation values in Piura, which peak during the middle of the day, namely, around three and a half hours into the afternoon, the façade begins to



LAYERS	F.EX1 27.0 cm (A B A)	F.EX1-OPT 33.0 cm (A B C D)	F.NV1-OPT 12.5 cm (E C D)	C.EX1 22.5 cm	C.EX1-OPT 30.0 cm	C.EX2 07.8 cm	C.EX2-OPT 07.8 cm
	A.- Cement 01.5 cm B.- Perforated Brick 24.0 cm	A.- Cement 01.5 cm B.- Perforated Brick 24.0 cm C.- Cane (reeds) 06.0 cm D.- Plaster 01.5 cm	E.- Perforated Brick 05.0 cm C.- Cane (reeds) 06.0 cm D.- Plaster 01.5 cm	A.- Tiles / Cement 02.5 cm B.- Hollow brick roof 20.0 cm	A.- Tiles /Cement 02.5 cm B.- Hollow brick roof 20.0 cm C.- Air chamber 06.0 cm D.- Plaster 01.5 cm	E.- Corrugated roof 00.3 cm C.- Air chamber 06.0 cm D.- Plaster 01.5 cm	E.- Corrugated roof 00.3 cm C.- Cane (reeds) 06.0 cm D.- Plaster 01.5 cm
U	2.10	1.00	1.30	0.51	0.48	2.52	1.20
DT	3.29	5.31	3.02	18.60	18.73	2.03	3.74
m_{tu}	20.4	10.6	05.5	32.4	1.07	1.01	2.92

Fig. 4 Proposed optimized enclosure solutions compared to the current ones

discharge the heat accumulated during the day inside the building, producing thermal discomfort. The F.EX1 solution considers a 24 cm thick brick wall. Lower thicknesses would reduce this DT, which would not contribute to thermal well-being. It would be advisable to extend this DT time so that the heat transfer from the enclosure inside occurs when temperatures drop at night. It is possible to achieve this by increasing the thermal mass or by placing thermal insulation inside. The proposed F.EX1-OPT optimized solution includes a 6 cm thermal insulation layer of a low-cost material such as reed cane, readily available in Piura. With this additional layer, DT increases to 5.31 hours, which is closer to the recommended value, given that the sunset in Piura occurs around 6:30 p.m. More efficient insulation or a greater thickness would increase DT so that its effect would extend into the night hours. Air conditioning is common during the midday hours in summer, so combining thermal insulation and light walls, such as that found in option F.NV1-OPT, could be an appropriate solution for new buildings conditioned with active systems. In conclusion, aiming for high mtu values and well-calibrated DT constructive solutions is recommended to balance thermal comfort with energy efficiency.

Concerning ceilings or roofs, the lightened ceiling solution has good thermal behavior. It has a relatively low thermal conductivity, according to the data indicated in RNE-EM.110, which recommends a conductivity of 0.35 W/(m K) for the ceramic filler block component which is the main feature of this slab. Likewise, its broad DT favors the discharge of energy from the construction element in the cold hours of the night. However, the same does not happen with corrugated roofs (C.EX2) made of sheet metal, plastic, or fiber cement that predominate in the unplanned areas of the city. It can be seen how its thermal conductivity exceeds the recommended limit of 2.20, and that its thermal inertia is non-existent. In the C.EX2-OPT solution, a 6 cm cane thermal insulator has been put in place, considerably improving its behavior in terms of transmittance, and increasing its DT by almost 2 hours. It would still be advisable to increase the thickness of the insulation layer or adjust its conductivity to meet a proper DT value. From June 2017 to January 2018, two meteorological stations were installed in each test module, registering the air and soil temperature and relative humidity both inside and outside. Consequently, it was possible to validate the numerical calculations, checking how the optimized enclosure solutions reduced the maximum indoor temperature and favored a proper thermal gap.

5 Conclusions

This research project is sought to optimize the thermal behavior of opaque enclosures in the city of Piura, given that their current design and construction constitute a barrier to thermal comfort and energy efficiency. This work has focused on the shell layers without committing to the study of transparent glass, sun protection, or cross ventilation, whose impact on thermal comfort is also high. The comfort conditions based on temperature and humidity were also analyzed without delving into other relevant parameters such as radiant temperature. These issues could be the subject of future research.

Two well-known strategies to improve thermal comfort regarding the opaque envelope are insulation and thermal inertia. In the case of a desert climate (low precipitation, high temperatures, and solar radiation) such as is found in this case study, from a theoretical point of view, it is ideal to recommend thermal inertia [1]. However, the necessary thickness that this entails complicates its practical application, especially in the case of walls. That is why the decision was made to investigate a combination of thermal mass with insulation as an optimal solution that would be applicable in these climates. Thermal insulation of not very low conductivity materials such as cane, in a thickness of about 6 cm, reduces the thermal transmittance of a brick wall by 51%, with resulting energy savings in situations using active systems such as air conditioning. Likewise, this insulating layer increases the thermal gap time by 38%, causing heat transfer at dusk. The use of this system could be the first step in terms of optimizing vertical enclosures adapted to the specific conditions of Piura. However, better or thicker insulating materials or layers would optimize this performance to an even greater extent.

In the case of roofs, although those made with unidirectional ceramic tray ceiling slabs have acceptable thermal behavior, the same is not true of light corrugated sheet roofs, which are common in unplanned areas of the city. In this case, it was confirmed how roofing insulation could reduce conductivity by 52% and almost double the thermal gap time.

This work led to conclude that the most effective practical solution to overcome the barrier to thermal comfort presented by the current enclosure system of the houses in Piura is as follows: in the case of facades, a combination of layers of materials with a thermal mass on the outside and thermal insulation inside; in the case of heavy hollow ceramic tray ceilings, it was possible to verify that they offered acceptable behavior from the thermal point of view. Finally, in the case of light corrugated sheet roofs, it would be essential to have thermal insulation layers inside.

However, although the work focused on the situation considering the opaque envelope, it is necessary to continue undertaking studies that improve the urban boundary conditions. There are parameters such as the orientation of the urban fabric, street width, vegetation, shadows between buildings, relationship with the prevailing wind, and the thermal behavior of the enclosures that the city's current urban development plan should consider to improve thermal comfort.

Likewise, the Peruvian regulatory framework should strengthen its criteria and reference values so that the enclosures of homes are not an obstacle to comfort. In this sense, reviewing limits and procedures to validate thermal inertia, and studying in greater detail the thermal transmittance limit values in each case seem to be pertinent improvements.

On the other hand, as explained in the text, the current enclosures of the houses in Piura have prioritized mechanical resistance over thermal behavior. This is not the case in rural areas, where the traditional quincha system (a wooden framework filled with cane reeds and covered with mud) continues to be used, with good performance from a thermal point of view. Although these rural areas also suffer from problems related to the thermal behavior of roofs, which is the same as found in unplanned areas of the city.

The authors consider that this study is replicable in other Peruvian cities or southern areas of the planet with a climate difference, but with similar social conditions. Targeting constructive solutions that transform enclosures from barriers to opportunities for thermal comfort, if adapted to the local context, will improve energy efficiency and the well-being of the population. Ultimately, the transference of technical knowledge from academia or professional offices to the population, in general, is critical as a means of subverting the self-construction process into one accounting for environmental design criteria to improve the quality of life.

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References

1. Wieser M (2011) Consideraciones bioclimáticas en el diseño arquitectónico: El caso peruano, Edición digital 10
2. del Valle Ruiz Valero L (2013) Optimización y propuesta de sistema opaco de cerramiento multicapa lige-ro con estructura de light steel frame como alternativa competitiva a los sistemas de cerramientos tradicionales. PhD thesis, Universidad Politécnica de Madrid. Escuela Técnica Superior de Arquitectura
3. Universidad de Piura (2020) Weather Station at Universidad de Piura, Piura, Perú. https://2020.udep.edu.pe/met/
4. Olgyay V (2013) Arquitectura y clima: Manual de diseño bioclimático para arquitectos y urbanistas., 1st edn. Gustavo Gili, Barcelona, Spain
5. Givoni B (1969) Man, climate and architecture. Elsevier Publishing Company Limited
6. APEIM (2016) Niveles socioeconómicos 2016. Asociación Peruana de Empresas de Inteligencia de Mercados
7. Resano D (2017) Cerramientos de vivienda optimizados para Piura (Perú). Mejorar la calidad de vida desde la envolvente construida. In: ML L, MC C (eds) Arquitectura y Sociedad. Aproximaciones temáticas, Universidad Anáhuac, Mexico, pp 146–158
8. Ministerio de Vivienda Construcción y Saneamiento (2014) RNE-EM.110. Reglamento Nacional de Edificaciones de Perú. Confort térmico y lumínico con eficiencia energética

Constructive Measures to Counterbalance Climate Change Impacts on Low-Income Housing in the Brazilian Savannah Climate

Ivan Julio Apolonio Callejas, Emeli Lalesca Aparecida da Guarda, and Luciane Cleonice Durante

Abstract An important issue for bioclimatic measures is research that is easy to implement for low-income housing (LIH) to enhance its habitability to face climate change. This study investigates whether construction measures incorporated in the building envelope are capable of counterbalancing climate change impacts on the thermal performance of LIH found in the Tropical Savannah climate, in the Brazilian Central-Western region. A base scenario is considered alongside future climate change scenarios, using the Fourth Report of the Intergovernmental Panel on Climate Change (IPCC). Building computational simulation was run to quantify the cooling degree-hours (CDH) and the indoor thermal comfort conditions in Standard and Efficient LIH. The predictions show that buildings in the Savannah region will be hit hard by global warming. Thermal inertia, insulation, and low absorptance construction measures enable LIH to be resilient in the 2020s, neutralizing the impact on CDH and thermal comfort conditions. For the 2050s, measures provided five months within comfort conditions and three months almost complying with the prescribed requirements. The bioclimatic measures suggested are an alternative strategy for removing barriers to adapting buildings to global warming, especially those destined for the low-income population, promoting building sustainability.

Keywords Building thermal performance · Resilient building · Global warming impacts · Thermal comfort

I. J. A. Callejas (✉) · E. L. A. da Guarda · L. C. Durante
Federal University of Mato Grosso, Cuiabá, Brazil
e-mail: ivan.callejas@ufmt.br

E. L. A. da Guarda
e-mail: emeliguarda@gmail.com

L. C. Durante
e-mail: luciane.durante@ufmt.br

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1 Introduction

According to the Intergovernmental Panel on Climate Change [1], human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels and this is expected to reach 1.5°C between 2030 and 2050 if anthropogenic emissions (including greenhouse gases, aerosols, and their precursors) continue to increase at the current rate. Despite the magnitude of the projection's uncertainties, climate changes have had widespread impacts on human and natural systems. These include a rise in the average temperature for most land and ocean regions, hot extremes in most inhabited regions, and heavier precipitation in several regions, among others that have arisen from human activities. Considering that the number of hot days is projected to increase in most regions, with the highest increases between the tropics, the potential effect of climate change on the built environment is an important issue and constitutes a barrier to be faced, especially for its design and operation. Furthermore, global warming will affect buildings' thermal behavior, increasing hot season cooling, decreasing cold heating demand, and raising energy consumption during the operational phase [2].

The Tropical Savannah Climate is very common, covering 11.5% of the world's land. It is found in 60.1% of South America [3] and, in Brazil, it represents 81.4% of its territory [4]. This climate is characterized by high air temperatures throughout the year, inducing high hours of thermal discomfort inside buildings [5]. Due to its geographical location, future projection scenarios for climate change and world socioeconomic development (usually used as a baseline for the 2050s) have indicated an increase in hot days in the tropics, degrading thermal comfort conditions. As a result, existing buildings in these regions may be greatly affected by future climate change which constitutes a barrier that can be addressed by using design measures and bioclimatic strategies to adapt buildings for global warming, especially those destined for a low-income population. Thus, providing comfortable buildings is an important issue since those populations do not have the financial resources to cover increased energy consumption, exacerbating energy poverty, especially in developing countries.

Mitigation and adaptation are strategies to address climate change. The first focuses on the causes (accumulation of greenhouse gases in the atmosphere) whereas the latter, on adapting to the impacts [6, 7]. Adaptation may mainly be reducing or eliminating the risks of climate change impacts. In the building environment, this can be achieved by enabling adaptation capacity through better building energy performance [8].

In this sense, this research focuses on the habitability principle, which aims at providing buildings that guarantee physical safety with adequate space, and protect against the cold, heat, rain, wind, other threats to health, and structural hazards. Particularly in Brazil, there is still a 6.355 million deficit [9] and to reduce this number, the Brazilian government established a policy for the low-income population, implementing a national social housing program called "My House, My Life", with approximately five million housing units built by 2019 [10]. However, the units tend to prioritize lower costs, executing low-income housing (LIH) with similar typologies, designed basically with the same design and materials throughout the country, despite the climate variations seen in Brazil. Some researchers have analyzed representative LIH projects and demonstrated their insufficient thermal performance [11–13], indicating the need for adequate measures to handle habitability and reduce operational costs, which is an important aspect for the low-income population [14]. In general, quantity has been prioritized over quality, compromising habitability. In addition, the possible threats emerging from climate change and responses to its effects have become important aspects to consider in housing for low-income populations.

The use of a building simulation method is recommended to predict building thermal performance, although they use current weather files based on data collected between 1961–1990, which do not capture the potential climate change trend. Studies have been conducted in the country to evaluate building behavior under the global warming effects [8, 15], but there is a lack of information on buildings found in Savannah climate regions. In addition, adaptation strategies have been suggested, but they usually focus on measures for the design phase, which are often difficult to implement in the operational phase.

In this context, this research investigates whether passive construction practical measures applied to LIH are capable of providing thermal resilience to counteract the effects of climate change in the Brazilian Savannah climate region, using the scenarios established by the A2 emission scenario described in the Fourth Assessment Report (AR4). Since the Savannah Tropical climate (Aw) covers a vast area of the planet (practically between the Tropic of Cancer and Capricorn), the building measures proposed in this research may potentially be applied to other regions with the same weather pattern to improve thermal habitability, helping them to remove barriers to face the impacts of climate change, especially in the built environment deployed in developing countries located in Latin America, where a review of the literature has indicated the lack of housing conditions to provide adequate health, quality of life, and well-being [16].

2 Material and Methods

This research is classified as applied research, which is conducted to generate knowledge for practical applications, aiming at solving specific problems. Thus, this current research was developed considering a base scenario approach, which was built based on primary and secondary climate data files, i.e. with and without the potential influence of the global warming phenomenon. Future tendencies or desirable future scenarios, i.e., the climatic conditions which may prevail in future periods due to the effects of climate change, have been generated for this scenario, which uses climate data from the 1961–1990 period [17, 18].

The following steps were undertaken: (a) city climate and bioclimatic zone characterization; (b) future weather files preparation; (c) building materials and envelope

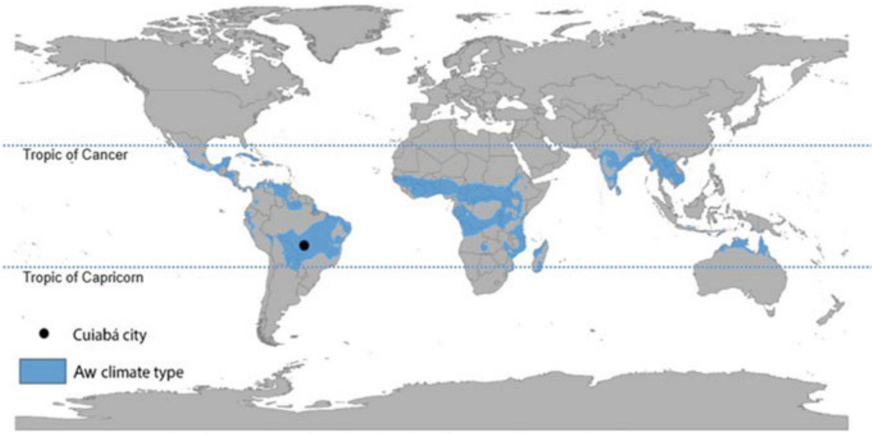


Fig. 1 Tropical savannah climate zones (Aw) worldwide. Adapted from [3]

characterization; (d) considerations for building computer simulation modeling; (e) definition of representative parameters for building thermal simulation considering natural ventilation; and, (f) definition of practical passive measures for climate adaptation and their evaluation using indicators in the operational phase.

2.1 Climate and Bioclimatic Zone Characterization

The focus here is to provide thermal resilience for LIH in the Tropical Savannah (Aw) climate. Thus, this study chose the city of Cuiabá, located in the Brazilian Central-Western region (15°36′56″S; 56°6′1″W). This climate type has a high air temperature throughout the year, wide hygrothermal variations, and an undefined or absent winter season [5]. This type can be found in several locations around the world, between the Tropics of Cancer and Capricorn (See Fig. 1).

Brazilian bioclimatic zoning comprises eight zones, with Z1 being the coldest, and Z8, the hottest. Cuiabá is inserted in bioclimatic zone Z7 [19]. The strategies for passive thermal cooling recommendations for this zone are evaporative cooling, thermal mass for cooling, and selective ventilation when the indoor temperature is higher than the outdoor one.

2.2 Generation of Future Climatic Data

The Climate Change World Weather Generator (CCWorldWeatherGen tool) [20] tool was used to process current Brazilian weather files and convert them to future weather files. This tool uses "morphing" methodology [21] to input climatic anomalies by modifying a set of historical climatic variables (from 1961–1990) of 8760 hours per year, and this way incorporating the effects of global warming on the climate files, thus making it possible to obtain projections of future climate data. It considers the Hadley Centre Coupled Model version 3 (HadCM3). This model represents the A2 scenario of AR4 greenhouse gas emissions [7], which considers moderate economic growth, high population growth, and high energy consumption, with a global average temperature increase ranging from 2.0 to 5.4°C from the 1961–1990 period until the century's end.

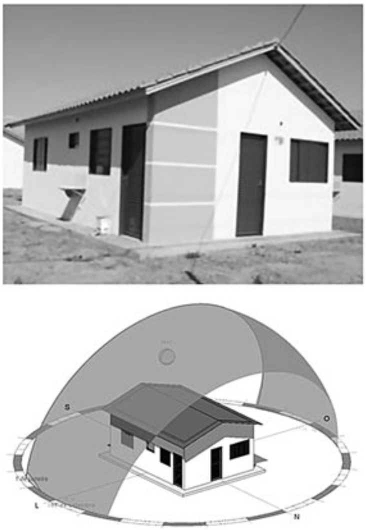
As a base for this research, the Cuiabá EnergyPlus Weather file (EPW) was used as current climatic data (base scenario). It was obtained from the Solar and Wind Energy Resource Assessment (SWERA) for the 1961–1990 period. This database is considered without the influence of urban density on the climate of the study region due to climate change. From this database, the periods of the 2020s (period from 2011–2040), 2050s (2041–2070), and 2080s (2071–2100) were generated using the CCWorldWeatherFileGen tool.

2.3 Building Materials and Envelope Characterization

A representative detached LIH characterized by Guarda et al. [12], which is widely replicated in all regions of Brazil, was selected for the study (See Fig. 2a). Its choice was based on the fact that these dwellings are handed out without adaptation for the region's climatic conditions, resulting in buildings with poor thermal performance [11, 13], compromising their indoor thermal comfort conditions [14]. It was also considered that low-income populations are the most vulnerable to the impact of climate change due to their lack of resources to bear the financial costs to keep the building's thermal conditions within required habitability standards.

The LIH in question, is a single-family detached house in contact with the ground, with a 39.5 m^2 of built area. The windows have metal frames with two opaque sliding panels and 3 mm thick single glass (windows dimensions–living room: 1.5 × 1.0 m; kitchen: 1.0 × 1.0 m; bedrooms: 1.2 × 1.0 m; bathroom: 0.6 × 0.5 m). The ventilation factor (VF) and lighting factor (LF) were considered as 0.45 for all windows. Internal and external doors are made of wood and metal (0.8 × 2.1 m), respectively. The ceiling has a free-hanging structure of PVC sheets (Fig. 2b). The thermophysical properties of the building components were obtained from NBR 15.220-2 [19]. The attic space has thermal resistance equal to 0.21 m^2 K/W (See Fig. 3).

(a)



(b)

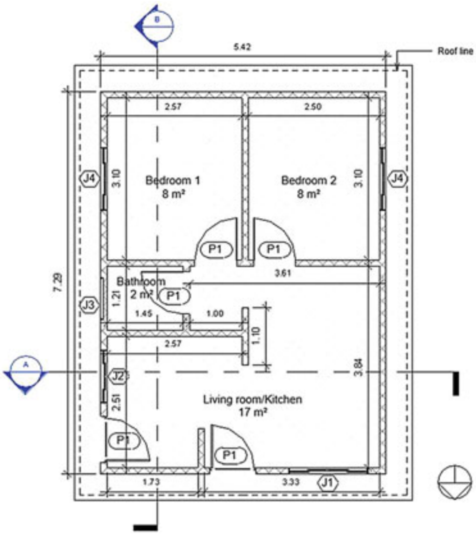


Fig. 2 **a** House photo and 3D model representation with solar chart; **b** Floor plan (dimensions in meters)

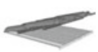
Envelope		Materials (layers)	Thickness (m)	R (m^2K/W)	U (W/m^2K)	TC (J/m^2K)	Absorptance
Wall		Mortar (internal and external)	0.015	0.40	2.49	177.3	0.3
		Ceramic brick	0.09				
Roof		Ceramic tiles (brown)	0.01	0.48	2.08	29.9	0.8
		Attic	-				
		PVC ceiling (White)	0.01				

Fig. 3 Thermophysical properties of the Standard LIH envelope. R: Thermal Resistance; U: Thermal Transmittance; TC: Thermal capacity

2.4 Building Computer Simulation

The OpenStudio plugin was used to model the LIH project and the EnergyPlus software [22] to make a thermal simulation. The indoors and roof attic were set as thermal zones. In the simulation, the building uses natural ventilation during the whole day, considering 20°C as the indoor temperature control for the opening or closing of windows. The Brazilian regulation for energy efficiency in buildings (RTQ-R) [23] was considered to define the occupation for 4 and 2 people in the living room and the bedroom, respectively.

LIH Heating Degree-Hours (HDH) and Cooling Degree-Hours (CDH) were used as building thermal performance indicators under natural ventilation conditions. To calculate heating and cooling degree-hours, base temperatures were set at 22 and 26°C, respectively. These indicators were estimated annually based on the indoor operative temperature for extended stays in rooms (bedrooms and integrated kitchen/living room). Only one indicator was considered in thermal performance, obtaining the weight of room areas. Soil temperature significantly influences thermal simulation, thus the "ground domain slab" from EnergyPlus software was used to estimate temperatures under dwellings for the scenarios.

The effectiveness of building measures adopted to improve indoor building thermal comfort was evaluated since it is typical for the low-income population not to have an air conditioning system in their home due to its operation costs. In this way, the index based on the study of adaptive thermal comfort proposed by de Dear and Brager [24] was considered, where thermal comfort levels are defined based on the monthly neutral temperature (T_n, in °C) related to monthly outdoor air temperature averages (T_{Emed}, in °C), following Eq. (1)–valid between 10.0 and 33.5°C. Thermal comfort ranges were determined following the procedures of ASHRAE Standard 55 [25]. The monthly upper and lower limits were defined for 90% of satisfied users.

$$T_n = 17.8 + 0.31 T_{\text{Emed}} \tag{1}$$

Based on a literature review, no individual passive measures can neutralize the increase of cooling demand on LIH. Therefore, a combination of passive strategies is needed to counterbalance the potential effects of climate change. NBR 15.575 [26] and NBR 15.220 [19] are used as references, to prescribe the following practical passive construction measures:

- Improvement of envelope components' thermal performance: measures are related to the wall and roof systems. The LIH envelope was enhanced, improving the thermal insulation and reducing the solar absorptance;
- Building envelope should be level 'A' in the Brazilian Energy Label for residential buildings. Level 'A' is reached for Cuiabá when the weighted CDH in the long-stay rooms is equal to or lower than 12,566°Ch;
- Passive constructive adaptation measures should be technically capable of being implemented simply in deployed buildings, i.e. in-use condition since there are many standard LIH in operation in many Brazilian regions;
- Material availability in the region and affordable costs for low-income populations focuses on removing barriers to its implementation. The chosen materials are commonly found in building supply shops. Thus, they can be implemented in other Brazilian regions or countries with similar climates.

As a result, the combined passive constructive adaptive measures indicated in Fig. 4 were implemented in the building envelope (internal components remained the same as indicated in Fig. 3): (a) *Wall system:* insertion of expanded polystyrene sheets (EPS) (0.04 m) only on external walls together with increasing external mortar thickness (from 0.015 to 0.025 m); The external walls absorptance was reduced by

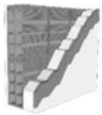
Envelope		Materials (layers)	Thickness (m)	R (m^2K/W)	U (W/m^2K)	TC (J/m^2K)	Absorptance
Wall		Mortar (internal and external)	0.025	1.13	0.89	169.4	0.15
		EPS sheet	0.040				
		Ceramic brick	0.09				
Roof		Ceramic tiles	0.01	0.85	1.2	41.9	0.15
		Aluminum foil	-				
		Attic space	-				
		PVC ceiling	0.01				

Fig. 4 Modified thermophysical properties adopted for the RTQ-R efficient LIH envelope. R: Thermal Resistance; U: Thermal Transmittance; TC: Thermal capacity

changing their color to white (α from 0.3 to 0.15); (b) *Roof system:* an aluminum foil layer was added under the ceramic tile for thermal insulation (elevating air thermal resistance in the attic to 0.61 m^2 K/W), and the external side of tiles was painted white (α from 0.8 to 0.15).

3 Results

3.1 Thermal Energy Performance Analysis

The impact on external air temperature and relative humidity will aggravate the indoor thermal conditions of existing buildings in the Savannah region and their building degree-hours indicators (Fig. 7). The CDH indicator for the Standard LIH will increase by 37,891°Ch and the HDH indicator will reduce by 499°Ch between the base scenario and 2080. The cooling demand will increase by 38% in the 2020s, 68% in the 2050s, and 114% in the 2080s, directly related to the air temperature increase. On the other hand, heating demand will decrease by 46% in the 2020s, 64% in the 2050s, and 85% in the 2080s compared to the base scenario.

Despite the improved bioclimatic measures, climate change will also worsen Efficient LIH's thermal performance, progressively reducing its efficiency in future scenarios. In the 2020 scenario, the CDH indicator increases by 10,356°Ch, almost doubling due to the climate changes that may prevail in this period. Despite that, it is remarkable that CDH in this typology is lower than that observed in the current scenario in Standard LIH. Thus, passive measures, whether applied on external walls and the roof system, have the potential to improve the resilience of buildings to counterbalance the impacts of global warming in the 2020 scenario. Similar behavior is seen in the 2050 scenario, with CDH almost tripling the base scenario (rising 22,456°Ch). Nevertheless, the thermal performance for Efficient LIH is almost the same as that observed in standard LIH for the current scenario, which indicates that

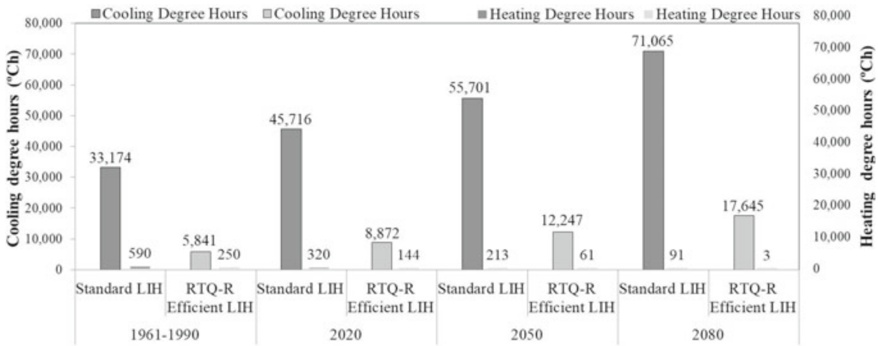


Fig. 5 CDH and HDH of the Standard and RTQ-R Efficient LIH (CDH and HDH in °Ch)

passive measures implemented in the envelope are still capable of counterbalancing the impacts of global warming. However, for the 2080 scenario, the climatic conditions completely degrade the building's thermal performance but are still better than the Standard LIH.

Based on Brazilian regulations for energy efficiency in buildings, Standard and Efficient LIHs have energy efficient levels rated 'E' (CDH > 30,735°Ch) and 'A' (CDH ≤ 12,566°Ch), respectively in the base scenario. The lack of adequate performance of Standard LIH is related to the building envelope characteristics, which have low thermal insulation as previously described. With such an elevation as described in the CDH indicator previously, the performance of Efficient LIH is progressively deteriorated, becoming level 'C' in the 2020s (18,622 < CDH ≤ 24,679°Ch). In the 2050s, it reaches the same level of Standard LIH (level 'E'), while in the 2080s, it keeps a worse level of efficiency but exceeds the one observed in the current condition (CDH > 33,174°Ch). In this regard, it should be pointed out that benchmarks established in the Brazilian regulation should be corrected for climate change effects for a fair comparison.

Concerning the HDH indicator, due to the high frequency of elevated temperatures throughout the year, aggravated by global warming, a decreased trend was observed in both buildings (See Fig. 5). Thus, climate change will drastically affect such indicators, almost eliminating indoor heating needs. However, this potential future impact brings no benefit to the house's energy consumption as the heating system is not used in the region due to the preponderance of high temperatures throughout the year [5].

3.2 Thermal Comfort Analysis

The practical adaptation measures implemented in Standard LIH effectively improved building habitability in the base scenario, increasing thermal comfort, and reducing

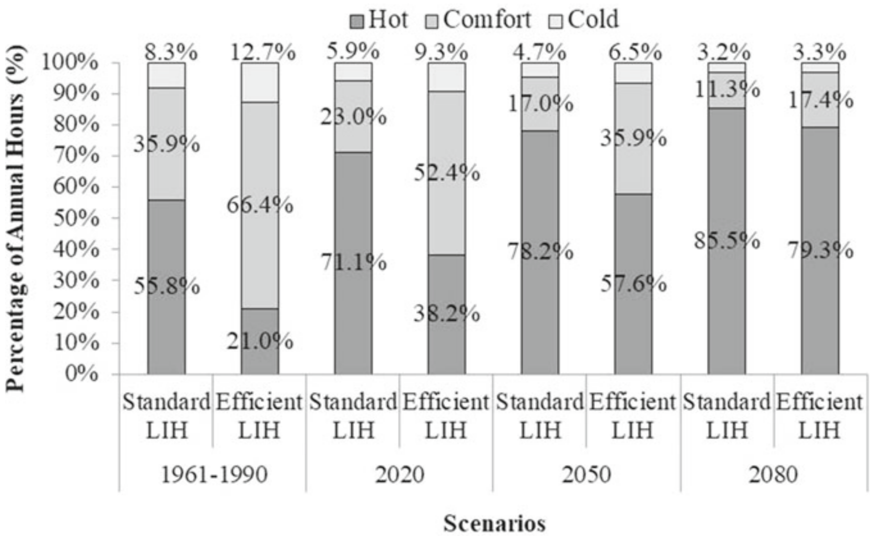


Fig. 6 Hours of comfort and thermal discomfort in Standard and RTQ-R Efficient LIH

hot discomfort hours inside the building (See Fig. 6). It is possible to notice that Efficient LIH is more effective in providing thermal comfort hours (66.5%) than Standard LIH (35.9%) since this typology is handed out to users disregarding climatic adaptation to the region in question. Therefore, the proposed passive measures improved the building's habitability for the researched location in the base scenario.

In future scenarios, comfort and cold discomfort hours are progressively reduced by the increase in air temperature. Until the 2020s, Efficient LIH can provide more hours of thermal comfort than hot discomfort (>50%). Thereafter, hot discomfort predominates within the building, driving a strong impact on the building's habitability in the tropical savannah climate. For hot, hours of comfort should be superior to hot discomfort hours, Efficient LIH will provide adequate living conditions until the period from 2011 to 2040 (>50%). This is associated with the lack of building thermal insulation and the rising external air temperature which lowers the capacity to remove indoor heat by the use of cross-ventilation, compromising the effectiveness of adaptation measures and others that intend to increase the building's insulation, since the more significant the insulation, the greater the heat retained inside the building.

As for monthly thermal comfort in the base scenario, just in June and July, the mean indoor temperatures remain inside the adaptive thermal comfort range (dashed lines) in Standard LIH due to the lack of thermal insulation. However, the insulation improvement provided by the practical measures deployed in the building's envelope can control thermal gains, providing milder indoor air temperatures which fall within thermal comfort limits (See Fig. 7a).

Even considering that the thermal comfort range will shift because of users' adaptability to climatic conditions which may prevail in the 2020s (Fig. 7b), thermal

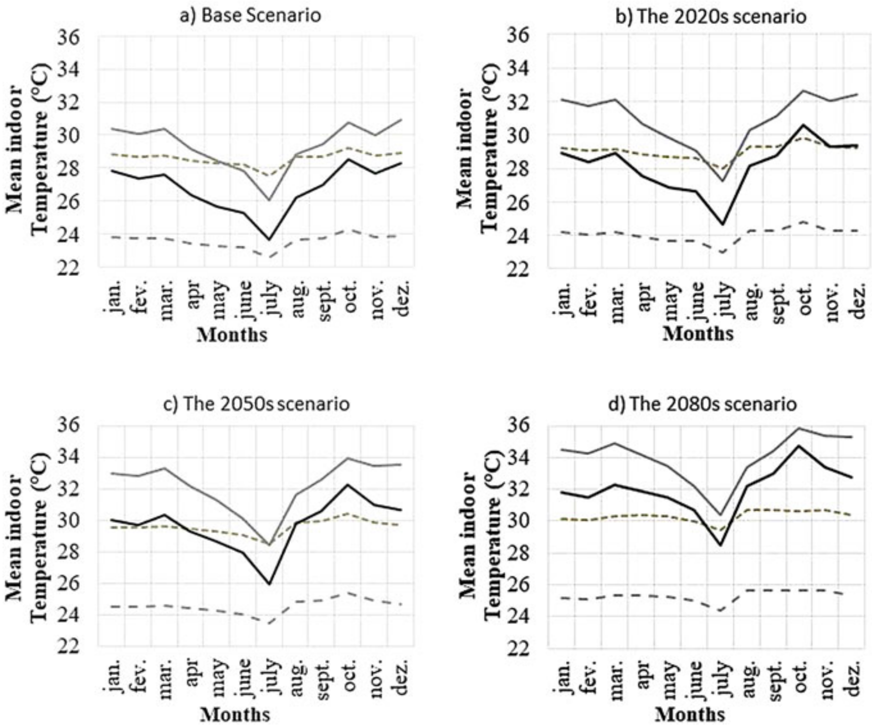


Fig. 7 Thermal comfort conditions in Standard and Efficient LIH

comfort conditions in Standard LIH are only reached for the indoor environment in July (the coldest month of the year), while in Efficient LIH, this is found in all months of the year except for October. Thus, practical measures can provide resilience to the building, improving thermal conditions in the 2011 to 2040 period. However, for the 2050 and 2080 scenarios (Fig. 7c, d), it is noticed that indoor monthly average temperatures are gradually rising, moving outside thermal comfort range limits. In these periods, thermal discomfort conditions are preponderant in both buildings. Thus, the desired resilience to the effects of global warming is not achieved even with its envelope being considered level A on the efficiency scale. As a result, designers must consider alternative bioclimatic measures to improve the building's ability to counteract climate change impacts.

4 Discussion

It has been ratified that Standard LIH has been handed out to users with insufficient thermal isolation for the Savannah climate. However, it has been possible to improve dwellings' thermal performance by incorporating bioclimatic efficiency measures into Standard LIH projects for current weather conditions, as observed in the previous research conducted in Brazil [13, 27]. Following the Brazilian Regulation's recommendations, practical adaptation measures applied to Efficient LIH provided better isolation for the envelope, decreasing the CDH of the base scenario by 21,053°Ch in the base scenario, which represents a 174% reduction compared to Standard LIH. It also provided more hours of thermal comfort than discomfort (>50%), improving its habitability. When considering its applicability in retrofit cases, the proposed building measures allow easy implementation outside the building envelope, not requiring profound interference in existing buildings.

Although Efficient LIH has energy efficient levels rated 'A', the future climatic conditions which may prevail, drastically affect the building's thermal performance, reducing its energy efficiency to level 'E'. A progressive reduction was seen in the building's performance with the advance of the predicted climate change, with CDH for the house, under the best combination of adaptation measures, almost double the base scenario. Thus, the concomitant use of different passive design strategies is essential to decrease the potential impact of climate change on the Brazilian building stock. A similar decrease in building energy efficiency is reported for five-star buildings analyzed in Darwin, Australia, and in Guangdong Province, China, due to the rising energy requirement in the 2050 scenario [28, 29]. This fact indicates the need to establish specific design guidelines in building certification codes to deal with this potential issue.

Despite envelope improvements, for thermal comfort conditions, practical measures only provide resilience to the building in the 2020s although it provides five months within comfort conditions in the 2050s period, with three months almost (from January to March) reaching the upper thermal comfort threshold. This suggests that a small increase in the building envelope's insulation can help it reach resilience for this period. On the other hand, the 2080s are characterized by complete indoor thermal discomfort. Therefore, practical measures cannot completely help one adapt to become resilient to climate change. A study evaluated the future effects of climate change on thermal comfort conditions of a single-family residential building located in Belém, a region with hot weather conditions in Brazil [18] and according to the authors, the use of passive design strategies may not provide the necessary indoor thermal comfort through the use of natural ventilation until the 2080s, only in the 2020s. Therefore, alternative adaptation measures need to be implemented, especially to achieve resilience in the 2050s. However, they might require profound modifications to the building envelope, affecting the occupants' living conditions during the implementation phase, which is not the scope of this research. In this regard, the increasing thermal insulation in the building envelope should be carefully studied so as not to worsen indoor thermal conditions and not incorporate ineffective construction measures for the building environment.

This research recognizes and anticipates potential habitability problems related to hot thermal discomfort that impact dwellings in the current and future climate change scenarios in the Savannah region. This issue is important since low-income populations often do not have the financial resources to cover possible electricity costs related to air conditioning systems to adapt the building's thermal comfort or to implement proposed construction design measures. Overcoming these barriers will require government programs to help adapt low-income buildings to global warming. By providing investment for the construction sector and fostering technological innovation, the design of new improved building envelopes might help offer better thermal conditions to users. For dwellings in use, habitability improvements can be achieved by granting subsidies to purchase the construction materials needed to implement the constructive measures proposed in this research, and an application led by professional technical support.

5 Conclusions

The thermal analysis indicated that implementing passive practical construction measures is successful in improving building performance and habitability, acting as a potential climate-response strategy for the Tropical Savannah Climate (Aw).

Due to improper specifications of materials and constructive systems, the current building envelope does not cover all the recommendations and guidelines established for the bioclimatic code. As a result, the representative project showed a poor performance in current climate conditions, performing even worse if projections for cooling demand, increasing 114% in the 2080s, occur due to climate change.

Following the recommendations and guidelines established in the bioclimatic code, it was possible to design an Efficient LIH incorporating the practical constructive measures of thermal inertia, insulation, and low absorptance. These measures provided a building envelope energy efficiency classification level of 'A'. Despite being 23% more efficient on average than the Standard one, its efficiency was reduced in each period due to the effect of global warming. Due to the expected increase in air temperature, the use of natural ventilation as a strategy to cool residential buildings is affected, reducing heat transfer from indoor to outdoor environments. Thus, global warming may restrict keeping adequate building thermal performance and comfort within required standards. In this sense, practical measures can only provide building resilience for the 2020s scenario. For the other scenarios, bioclimatic solutions are required to adapt the building to potential climate change.

The addressed building envelope energy efficiency measures for climate change adaptation are conducted in a specific building typology, representing existing practices in the Brazilian housing lower-income sector. This was chosen due to its building envelope, which comprises roofs and walls with traditional materials (brick masonry and ceramic roof tile), commonly used in most Brazilian buildings. Therefore, the research findings help to overcome barriers to the low-income population since these measures can improve current and future building performance, contributing to not worsening energy poverty, especially in developing countries. Moreover, the proposed measures may be extended to other typologies with similar envelopes since they were idealized to be installed on the outside building envelope, and, in retrofit cases, they can be easily installed in the building envelope, not compromising its use.

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References

1. IPCC (2018) Summary for policymakers. Accessed 18 Jun 2022, from https://www.ipcc.ch/sr15/
2. Levesque A, Pietzcker RC, Baumstark L, De Stercke S, Grübler A, Luderer G (2018) How much energy will buildings consume in 2100? A global perspective within a scenario framework. Energy 148:514–527. https://doi.org/10.1016/j.energy.2018.01.139
3. Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the köppen-geiger climate classification. Hydrol Earth Syst Sci 11:1633–1644. https://doi.org/10.5194/hess-11-1633-2007
4. Alvares CA, Stape JL, Sentelhas PC, de Moraes Gonçalves JL, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Z 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507
5. Callejas IJA, Nogueira MCJA, Sacardi Biudes M, Durante LC (2016) Seasonal variation of surface energy balance of a Central Brazil city. Mercator 15:85–106. https://doi.org/10.4215/RM2016.1503.0006
6. Tol RS (2005) Adaptation and mitigation: trade-offs in substance and methods. Environ Sci Policy 8:572–578. https://doi.org/10.1016/j.envsci.2005.06.011
7. IPCC (2007) Climate change 2007: Synthesis report. contribution of working groups i, ii and iii to the fourth assessment report of the intergovernmental panel on climate change. Tech. rep., Intergovernmental Panel on Climate Change
8. Triana MA, Lamberts R, Sassi P (2018) Should we consider climate change for Brazilian social housing? Assessment of energy efficiency adaptation measures. Energy Build 158:1379–1392. https://doi.org/10.1016/j.enbuild.2017.11.003
9. FJP (2020) Housing deficit in brazil 2016-2019. Accessed 18 Jun 2022, from https://antigo.mdr.gov.br/images/stories/ArquivosSNH/ArquivosPDF/Publicacoes/capacitacao/publicacoes/deficit_habitacional_2011-2012.pdf
10. Ministério da Economia (2020) My house my life–evaluation report. Accessed 19 Sep 2021, from https://encurtador.com.br/aACE1
11. Triana MA, Lamberts R, Sassi P (2015) Characterisation of representative building typologies for social housing projects in Brazil and its energy performance. Energy Policy 87:524–541. https://doi.org/10.1016/j.enpol.2015.08.041
12. Guarda ELA, Durante L, Callejas IJA (2018) Effects of global warming on passive design strategies through bioclimatic charts. Eng Sci 7:54–69
13. Invidiata A, Lavagna M, Ghisi E (2018) Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. Build Environ 139:58–68. https://doi.org/10.1016/j.buildenv.2018.04.041
14. Guarda ELA, Gabriel E, Domingos RMA, Durante LC, Callejas IJA, Machado Sanches JC, de Andrade Carvalho Rosseti K, (2019) Adaptive comfort assessment for different thermal insulations for building envelope against the effects of global warming in the mid-western Brazil. IOP Conf Ser: Earth Environ Sci 329:012057. https://doi.org/10.1088/1755-1315/329/1/012057
15. Neto AH, Durante LC, Callejas IJA, Guarda ELA, Moreira JVR (2022) The challenges on operating a zero net energy building facing global warming conditions. Build Simul 15:435–451. https://doi.org/10.1007/s12273-021-0809-4
16. McTarnaghan S, Martín C, Srini T, Collazos J (2016) Literature review of housing in Latin America and the Caribbean. Urban Institute, Research Report, Washington, USA

17. Flores-Larsen S, Filippín C, Barea G (2019) Impact of climate change on energy use and bioclimatic design of residential buildings in the 21st century in Argentina. Energy Build 184:216–229. https://doi.org/10.1016/j.enbuild.2018.12.015
18. Invidiata A, Ghisi E (2016) Impact of climate change on heating and cooling energy demand in houses in Brazil. Energy Build 130:20–32. https://doi.org/10.1016/j.enbuild.2016.07.067
19. ABNT (2005) NBR 15220–2: Thermal performance of buildings-part 2: Method of calculating thermal transmittance, thermal capacity, thermal delay and solar factor of elements and components of buildings. Brazilian Association of Technical Standards, Rio de Janeiro, Brazil
20. SERG (2020) Climate change world weather file generator for World-Wide Weather Data. Accessed 18 Jun 2022, from http://www.energy.soton.ac.uk/ccworldweathergen/
21. Belcher S, Hacker J, Powell D (2005) Constructing design weather data for future climates. Build Serv Eng Res Technol 26:49–61. https://doi.org/10.1191/0143624405bt112oa
22. DOE (2016) Department of energy 2016. EnergyPlus. Accessed 16 Jan 2022, from https://energyplus.net
23. INMETRO (2012) Technical regulation on the level of energy efficiency quality for the residential buildings (RTQ-R). National Institute of Metrology, Quality and Technology, Brasilia, Brazil
24. de Dear R, Brager G (1998) Developing an adaptive model of thermal comfort and preference. ASHRAE Trans 104:1–18
25. ASHRAE (2013) ANSI/ASHRAE Standard 55: Thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Enginieers, Atlanta, USA
26. ABNT (2013) NBR 15575–1: Housing developments- Performance-Part 1: General requirement. Brazilian Association of Technical Standards, Rio de Janeiro, Brazil
27. Callejas IJA, Apolonio RM, da Guarda ELA, Durante LC, de Andrade Carvalho Rosseti K, Roseta F, do Amarante LM, (2021) Bermed earth-sheltered wall for low-income house: Thermal and energy measure to face climate change in tropical region. Appl Sci 11:420. https://doi.org/10.3390/app11010420
28. Wang X, Chen D, Ren Z (2010) Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. Build Environ 45:1663–1682. https://doi.org/10.1016/j.buildenv.2010.01.022
29. Song X, Ye C (2017) Climate change adaptation pathways for residential buildings in Southern China. Energy Procedia 105:3062–3067. https://doi.org/10.1016/j.egypro.2017.03.635

Impact of Passive Design Measures on the Thermal Comfort of Social Housing in the Context of Climate Change in Montevideo, Uruguay

Lucia Pereira-Ruchansky and Alexis Pérez-Fargallo

Abstract The thermal comfort problem has usually been studied from energy perspective, using energy demand as an indicator, disregarding that, in contexts of poverty and energy vulnerability, there are dwellings that do not use air conditioning or only partially do so. This approach constitutes a barrier to understanding the phenomenon and achieving context-appropriate solutions. Additionally, climate change projections show that for these dwellings, the main problem will be adapting to achieve comfort in the future climate. On the other hand, energy regulations, in our context, focused on new buildings and construction measures, limit comfort conditions in existing dwellings to the economic possibilities of inhabitans to implement improvements. This article evaluates improvement measures for typical social housing in Uruguay. It considers the time in comfort as an indicator, using adaptive thermal comfort models. It studies passive, constructive, and operational improvements, to eliminate economic barrier. It evaluates, by simulation, their current and future thermal performance, demonstrating that operational, ventilation, and solar protections parameters, have high impact with zero cost on thermal comfort, being decisive to avoid overheating in cases combined with high insulation levels and airtightness, underlining the need to consider them from the design as well as training inhabitants in their use.

Keywords Adaptive comfort · Thermal performance · Climate change · Social housing

L. Pereira-Ruchansky (✉)
Institute of Technologies, Faculty of Architecture, Design and Urbanism, University of the Republic, Montevideo, Uruguay
e-mail: lpereira@fadu.edu.uy

A. Pérez-Fargallo
Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: aperezf@ubiobio.cl

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1 Introduction

Today, the depletion of non-renewable resources coupled with global warming is demanding more efficient buildings and the use of renewable energies [1]. Buildings throughout their life cycle are energy consumers and, therefore, sources of greenhouse gas emissions, and at the same time, their energy performance is conditioned by the climate to which they are exposed, and as a consequence, they will be directly affected by changes in climatic conditions. This duality has promoted two lines of approach, mitigation, and adaptation of buildings to climate change (CC).

At a global level, from the mitigation perspective, building regulations have focused on establishing performance standards to reduce energy consumption for air conditioning and, thus, reduce CO_2 emissions [2]. At the same time, the efficiency of active systems used by buildings has been promoted, the replacement of fossil energy consumption with renewable energy, and the production of onsite energy, leading to the development of the concepts of nearly/new Zero Energy Buildings [3]. Hence, the focus has been on energy aspects to reduce consumption.

The energy consumption for air conditioning is determined, among other factors, by the energy efficiency of the building and the air conditioning system, the intensity of use of the system, and the thermal comfort requirements of its users. However, in energy poverty contexts, energy consumption is not a reflection of the amount of energy needed to reach comfort conditions inside the house, as they do not use air conditioning systems or do so only in extreme climatic conditions [4], and often only use it when at room and at limited times, due to difficulties in accessing energy and its affordability.

The approach to comfort from the energy perspective, when the deficit of comfort conditions is not associated with energy consumption, is identified as a first barrier to the real understanding of the problem in the context studied. Associated with this, thinking about the problem of CC from mitigation is also a limitation to understanding how this phenomenon will affect inhabitants in these contexts, with the main CC-related consequence for these houses being the adaptation they must undergo to achieve comfort in the future climate conditions.

For this reason, some authors have questioned the use of energy demand or consumption as an indicator to quantify the performance of dwellings, identifying that the percentage of time that dwellings can operate in free oscillation within comfort ranges using adaptive comfort models (ATC) is a more accurate indicator in these cases [2, 5]. In this line, previous research has shown that the use of both indicators, energy demand and time in comfort, is not analogous, with it being necessary to know the mode of use of housing to evaluate the performance of improvement strategies [6].

ATC models were mainly developed in offices, and despite this, it is acknowledged that they are particularly suitable for dwellings because inhabitants have the freedom to adapt their clothing, and open or close windows to improve the thermal sensation [7]. In the local context, as in other countries of the region, an important part of the housing stock does not reach thermal comfort conditions [8], due to the conditions of their envelopes, on mostly old houses, built before thermal regulations came into force [9]. This has a direct impact on the energy demand associated with air conditioning and, as a consequence, on the habitability conditions and the possibility of the user to assume the economic cost entailed to maintain indoor comfort conditions [10].

Regulations and programs for existing housing are incipient in this context, despite the extensive number of old buildings. The generalization of regulations focused on new buildings, as well as requirements focused on buildings' constructive aspects, are also identified as barriers to achieving comfort in existing dwellings, especially in vulnerable situations, where improving the performance of the building and consequently improving comfort conditions, are conditioned to the economic possibilities that their users have.

Passive strategies aim to take advantage of climatic conditions to have naturally conditioned spaces, controlling energy flows between indoor and outdoor spaces. As Andrić et al. [11] point out, conventional passive energy renewal measures in dwellings focus on the envelope: increase in thermal insulation, improvement of airtightness, incorporation of efficient glazing, incorporation of green roofs and walls, modification of surface reflectivity and absorptivity, use of fixed and mobile solar protections, natural and nighttime ventilation. With most of them being constructive improvements, mobile solar protections and ventilation stand out as operational measures [7, 12], where the effectiveness is determined by the use the inhabitants give it.

The application of passive strategies in buildings constitutes both a mitigation and adaptation measure. They reduce the demand for air conditioning energy and generate positive impacts on the living conditions of dwellings and the well-being of users, especially in cases where comfort conditions are poor due to economic difficulties in accessing energy [13], thus contributing to reducing energy poverty situations [1, 7].

This chapter, in response to the identified barriers, studies an existing social housing case, considering for its evaluation, the specifics of the local context: climatic (current and future) and mode of use (free oscillation). The objective is to evaluate the impact over time on comfort, under the adaptive thermal comfort model, when applying constructive and operational energy improvements, considering that they must satisfy thermal comfort requirements in current and future climate conditions. In addition, the impact of the CC on thermal comfort was evaluated in the cases studied to understand the adaptation that dwellings will require for future climate conditions.

This is how it is proposed to shift the focus of the macro-global gaze concentrated on energy-environmental problems, to the scale of living spaces and their inhabitants. Moving from evaluating the energy performance of dwellings to evaluating the thermal performance and comfort conditions of their inhabitants.

2 Methodology

2.1 *Study Case and Context*

2.1.1 Social Housing–Uruguay

The case study is determined considering the representative characteristics of the housing stock, based on the data analysis of the distribution and typologies of housing in Uruguay, as well as their material characteristics and age [14, 15].

A detached single-family house is considered, part of the social housing program of the Intendency of Montevideo. It has a surface area of 70.4 m^2, on one floor, with three bedrooms, a living room, a kitchen, and a bathroom (See Fig. 1). It is studied in a free and unobstructed environment, as these are the typologies that have the largest exposed envelope surface and, consequently, greater thermal exchange, which is assumed as the most unfavorable situation. The south-facing main façade was considered for the case study.

The housing envelope uses a heavy construction system without thermal insulation and has concrete block walls ($U = 2.62\ W/(m^2\ K)$), a concrete slab ceiling ($U = 3.40\ W/(m^2\ K)$), a floor in contact with the ground ($U = 2.60\ W/(m^2\ K)$), and iron single glazed windows ($U = 5.80\ W/(m^2\ K)$). The operation and use conditions were established based on the average household size of the lowest quintiles, determining an occupation of four people [16], while the occupancy and use loads and schedules followed Picción et al. [17]. In addition, a ventilation flow rate of 2.5 L/s person and 0.3 L/s m^2 was established [18].

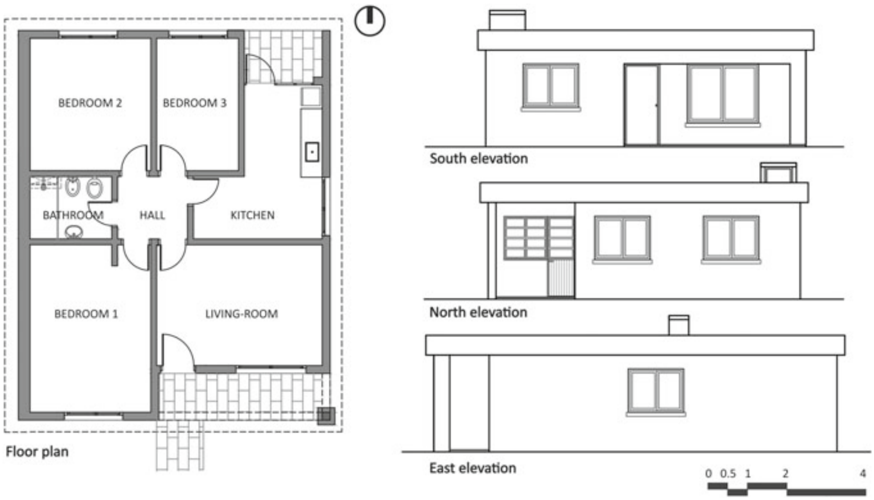

Fig. 1 Case study: floor plan and façade

In a previous article [6], the calibration of this house was made, obtaining a maximum Mean Bias Error (MBE) of 3.5%, lower than the 10.0% required by ASHRAE [19], and a maximum Coefficient of Variation of the Root Square Mean Error (CV (RSME)) of 6.7%, less than the 30.0% required by the same regulations.

2.1.2 Current and Future Climate

The climate type of Montevideo (34°50′S, 56°12′W, 16.27 MAMSL) is, according to the Koppen climate classification, a "Cfa", temperate, moderate, and rainy with mild winters and humid and warm summers, and precipitation throughout the year. It is characterized by a significant thermal amplitude, both in the seasonal period (12.1°C between January and July) and in the daily thermal amplitude (between 7.8°C in July and 10.4°C in January).

The study, apart from the current climate scenario, considers the climate scenario the dwelling will be exposed to in the future, considering the scenario of the Intergovernmental Panel on Climate Change (IPCC) A2 for 2050 on this being a suitable period considering the service life of an energy retrofit for an existing dwelling [20].

The energy simulation requires using climatic files in epw format, representative of the climatic conditions of the context where the buildings being analyzed are located. The weather files for the current and future weather were made in ©Meteonorm. For the current climate, the typical meteorological year (TMY) was used for Montevideo. For the future climate, this was generated by a downscaling process at a local scale, using the Hadley CM3 climate model for IPCC AR4 scenarios. It is important to consider that the future climate files represent projections of typical meteorological years with little representation of localized climate variations or extreme event phenomena associated with CC [21].

2.2 Evaluation by Adaptive Thermal Comfort

The thermal performance of the studied cases was evaluated by applying the ATC model of the ASHRAE 55 standard [22] for a thermal acceptability of 80%, as it is applicable in social housing [5].

The thermal comfort ranges and neutral temperature in the adaptive comfort model are directly related to outdoor temperatures and, therefore, were calculated for each climate scenario evaluated under the climate files used.

The evaluation was made for each case in two rooms with different orientations and uses: Living Room and Bedroom 2, considering the percentage of annual time in thermal comfort when the house works in free-running. In addition, the percentage of annual time where the house remains in discomfort due to heat and cold was evaluated.

2.3 Passive Improvements and Selected Cases

The base case and cases with improvements, under current climate and future scenario conditions, were evaluated experimentally from the results obtained by energy simulation in ©DesignBuilder.

Improvement strategies and thermal energy were determined by analyzing the performance of the base case under current and future climate conditions, considering that according to Montevideo's climate conditions, it has a cold and a hot period; and considering two types of constructive and operational improvements.

For the cold period, solar gains were favored by keeping the windows free of solar protections, and the heat losses through the envelope were controlled, reducing thermal transmittance (walls, roof, and windows) and infiltrations. The levels to be evaluated for each improvement were based on existing local regulations and from similar climates and materials available in the local market [23–26]. In all cases and as the initial construction has a thermal mass level that is considered favorable, the incorporation of insulation in the envelope was considered from the outside.

For the hot period, shading was considered to avoid solar gains, using exterior PVC roll-up curtains in all orientations, active when the outdoor temperature exceeds 19°C and the incident solar radiation is greater than 120 W/m^2, and nighttime ventilation to dissipate the heat accumulated inside, considering ventilation between 10 pm and 9 am from December to March, with two flows, 2.7 and 5.3 L/s m^2. Operation and flow were determined from the analysis of the discomfort due to heat conditions for the base case.

To study the multiple possible combinations between the variables, the optimization module of the DesignBuilder program was used, obtaining as a result, a set consisting of 175 cases (initially there were 457, but cases that presented minimal differences were discarded). From all the simulations run, and the resulting set of cases, a total of 14 cases were chosen to evaluate their thermal performance, 6 cases with individual measures, and 8 cases with combined measures (see Table 1). Case A represents the current condition of the dwelling, and cases B to G represent the application of individual improvements (6 cases): incorporation of solar protection (SP) (case B); replacing window (transmittance and infiltrations) (case C); reduction of the infiltrations (Case D); integrated window change (transmittance, protection, and infiltrations) (Case E); modification of the wall transmittance (Case F); and modification of the roof transmittance (Case G). Cases H to O (8 cases) represent the combination of all the improvements with different demand levels. All these cases are studied considering only hygienic ventilation [18]. In addition, the base case (Case A), and the chosen cases with combined means (H, I, J, K, L, M, N, O), were simulated with the operational improvement of nighttime ventilation, thus generating another 16 cases (For example, A1 and A2).

Table 1 Cases evaluated

	Case	U value (W/(m^2 K))			Inf. ACH	Solar	Ventilation
		Wall	Ceiling	Wind	n50	Prot.	(L/s per + L/sm^2)
Cases with individual measures	A (A1,A2)	2.62	3.4	5.8	8.2	–	2.5 + 0.3*
	B	2.62	3.4	5.8	8.2	100%	2.5 + 0.3
	C	2.62	3.4	2.7	5	–	2.5 + 0.3
	D	2.62	3.4	5.8	1	–	2.5 + 0.3
	E	2.62	3.4	2.7	5	100%	2.5 + 0.3
	F	0.5	3.4	5.8	8.2	–	2.5 + 0.3
	G	2.62	0.32	5.8	8.2	–	2.5 + 0.3
Cases with selected combined measures	H (H1,H2)	0.85	0.85	2.7	8.2	100%	2.5 + 0.3
	I (I1;I2)	0.61	0.47	2.7	5	100%	2.5 + 0.3*
	J (J1;J2)	0.5	0.32	2.7	8.2	100%	2.5 + 0.3*
	K (K1;K2)	0.5	0.32	2.7	5	100%	2.5 + 0.3*
	L (L1;L2)	0.5	0.32	2.7	1	–	2.5 + 0.3*
	M (M1;M2)	0.5	0.32	5.8	1	100%	2.5 + 0.3*
	N (N1;N2)	0.61	0.32	2.7	1	100%	2.5 + 0.3*
	O (O1;O2)	0.5	0.32	2.7	1	100%	2.5 + 0.3*

*These cases have also been simulated incorporating nighttime ventilation between December and March from 10 pm to 9 am with two ventilation flows, 2.7 L/sm^2 (A1, H1, I1, J1, K1, L1, M1, N1, O1), and 5.3 l/s·m2 (A2, H2, I2, J2, K2, L2, M2, N2, O2)

3 Results

The base case together with the selected improvement cases were analyzed using the ASHRAE 55-2017 adaptive comfort model, applying the comfort ranges corresponding to each climate scenario for a thermal acceptability of 80%. The results are presented for the current and future climate, by total annual time in thermal comfort, in discomfort due to cold, and in discomfort due to heat, allowing identifying the impact of the evaluated strategies.

3.1 Thermal Comfort in the Base Case

The thermal performance of the base case (Case A) is presented in Fig. 2 by room studied, for the current climate and future scenario A2 in 2050.

For the current climate, the percentage of annual time in comfort conditions in the house varies between 45.8 and 48.9% depending on the room, while in the percentage of time in discomfort, discomfort due to cold prevails with 31.3 and 29.5%, compared to discomfort due to heat of 22.9 and 21.6%, in the living room and bedroom 2 respectively.

By 2050 in scenario A2, the total time in comfort presents a slight decrease, reaching 44.1 and 47.2%, the time in discomfort due to cold decreases to 23.7 and 22.2%, and discomfort due to heat increases to 32.2 and 30.6% in the living room and bedroom 2 respectively.

The analysis of the base case allows verifying that in future climate conditions, users will experience a total time in comfort similar to that of the current climate. However, as a result of the projected temperature increase, as other research has presented [2, 27], an inverse behavior to that of the current climate is expected in future climates in the discomfort conditions in this house, with discomfort due to heat prevailing over discomfort due to cold.

3.2 Impact of Passive Improvements on Thermal Comfort

The results obtained by case with improvements, and comparatively regarding the base case (Case A), by climate scenario and room, are presented in Fig. 2.

The individual improvements, cases B to G, had variations of less than 5% compared to the base case in the percentage of time they are in comfort, in discomfort due to cold, and in discomfort due to heat, in both scenarios and rooms studied.

On the other hand, nighttime ventilation as an individual improvement (Cases A1 and A2), stands out for its impact on reducing the percentage of time in discomfort due to heat and, consequently, in the increase of time in comfort compared to the base case. This increased in the current climate by 7.2 and 6.4% for a level of 2.7 L/sm^2, and by 10.5 and 10.3% for a level of 5.3 L/sm^2, for the living room and bedroom 2 respectively. For the future scenario. the variation is similar, 7.0 and 6.4% for a level of 2.7 L/sm^2, and 11.2 and 10.8% for a level of 5.3 L/sm^2 for the living room and bedroom 2 respectively.

The cases studied with combined improvements, H to O, except for case L, show that the higher the level of insulation (in walls, ceilings, and windows) and air-tightness, the more discomfort due to heat increases and the discomfort due to cold decreases. While case H (improvements combined with lower levels of opaque thermal transmittance and higher levels of infiltrations) from this set, has the least discomfort due to heat and most discomfort due to cold. Case O (the most demanding case in both aspects) presents the reverse.

Fig. 2 Percentage of time in comfort or discomfort by case study, Current and future A2 2050 climate scenario, Living room: **a** Total time in comfort, **b** Time in discomfort due to heat, **c** Time in discomfort due to cold, Bedroom 2: **d** Total time in comfort, **e** Time in discomfort due to heat, **f** Time in discomfort due to cold

Evaluating the impact of improvements over the base case for this set, while all decrease the time in discomfort due to cold, by between 1.2 and 9.9%, in the current climate, and by between 3.2 and 10.4% in the future climate, in some cases for the Living Room (Case N and O in the current climate, and K, M, N, and O in the future climate) the time in discomfort due to heat slightly exceeds that of the base case, with 2.4 and 2% rises from the current climate and future respectively.

Despite these variations, the total comfort time between these cases is similar, with a difference of less than 6% in both rooms and scenarios; and in all cases, the improvements represent an increase in the total comfort time compared to the base case, on average 7.5 and 18.4% in the current climate, and 7.4 and 12.7% in future climate, for the living room and bedroom 2 respectively.

The differences in the comfort results between both rooms are increased in the evaluation of the time in discomfort due to heat, allowing identifying the impacts of other factors, such as use loads and occupation or orientation. These results are consistent with the observations made by Fosas et al. [28] which showed that the overheating risk is associated with multiple housing design and operation parameters, and not just the insulation level.

Case L (improvement of the envelope without using solar protection) stands out in the combined improvements cases, as it had in both rooms and scenarios, an increase in discomfort due to heat of between 2.7 and 7.1%. As a result, this improvement case has smaller increases in the total time in comfort compared to the base case, 2.5 and 6.5% in the current climate, and 7.6 and 5.1% in the future climate, for the living room and bedroom 2 respectively, evidencing how much impact the improvement of insulation and airtightness levels can have without the use of suitable solar protections.

The incorporation of nighttime ventilation during the hot period (flows of 2.7 and 5.3 L/sm^2), in cases H to O, impacted with very significant increases in comfort time in both rooms: between 16.7 and 31.0% in the current climate, and between 17.2 and 35.3% in the future scenario. In addition, it is identified that with a flow of 5.3 L/sm^2, discomfort due to heat in the bedroom is reduced to a minimum, with levels lower than 1% in the current climate, and less than 6.0% in future scenarios, in all cases except cases A and L that present minor reductions. Noting that ventilation is maintained as an appropriate strategy even in projected temperature increase conditions in the future.

Analyzing the set of cases it can be observed that all the constructive improvements reduce the discomfort due to cold, but some for the living room increase slightly the discomfort due to heat, and confirm the importance of user behavior for ventilation and the correct use of solar protections, in line with the work of Escandón et al. [7] and van Hooff et al. [12].

3.3 Evolution of Thermal Performance in CC Scenarios

Based on the results obtained, the trend presented by the evaluated cases under the climate changes projected in scenario A2 to 2050 for the annual percentage of time in comfort, time in discomfort due to cold, and due to heat, was studied.

For the future scenario A2 2050, the time in comfort is projected with minimal variations, in most cases with a slight downward trend in the total time in comfort, and with a change in the distribution of its composition. According to the average of the cases studied without ventilation, the distribution in comfort will vary from a composition of 26–20–54% in the current climate to 18–31–51% in A2, the time in discomfort due to cold, time in discomfort due to heat, and total time in comfort, respectively; it can be seen that it projects a slightly greater variation in discomfort due to heat than discomfort due to cold, the cause being, in most cases, the downward trend of the total time in comfort. In the cases that incorporate ventilation, the average distribution among the cases studied is 24–5–71% in the current climate, 16–13–71% in A2, time in discomfort due to cold, time in discomfort due to heat, and total time in comfort, respectively.

4 Conclusions

The thermal quality of a large part of the housing stock in our context is currently deficient, directly affecting the thermal comfort conditions of those inhabitants unable to consume energy for air conditioning. Therefore, passive improvements applied to dwellings acquire special relevance, as they allow improving comfort conditions without forcing users to consume energy to reach them.

In response to the barriers identified that condition indoor comfort in existing dwellings, the study presented in this chapter aimed to address the problem from the perspective of the user, incorporating the perspective of comfort considering the specifics of the context. The evaluation of passive improvement measures was done on an existing case, typical of the housing stock of Uruguay. Both constructive and operational improvements were evaluated, as the latter has zero implementation cost for users, constituting an alternative that avoids possible economic barriers to making improvements. The approach presented, focused on the evaluation of the annual time in comfort and thermal discomfort based on ATC, instead of evaluating the dwelling's energy performance. This is the first point to understand and address the conditions of users who do not consume energy to meet their comfort needs. Likewise, it has been studied how the time in comfort and the time in discomfort due to cold and heat will vary in the A2 2050 scenario compared to the current climate to contribute to implementing adaptation measures for existing dwellings.

The results demonstrate the potential offered by passive strategies to increase the annual time in thermal comfort, both for the current climate conditions, and in the future scenario studied. For its part, the broken down study of the impact of the improvements on the time in discomfort indicates that all the construction improvements evaluated, the increase of insulation and airtightness of the envelope, reduce or equal the time in discomfort for cold in comparison to the base case, but these improvements without applying operational parameters, ventilation and use of solar protection, can increase the time in discomfort due to heat.

The study of these cases allowed verifying that the CC temperature increase projected in the climate studied, saw a slight downward for the total annual time in comfort, projecting an increase in the time in discomfort due to heat, over the time in discomfort due to cold. This highlights the need to adapt existing housing to guarantee habitability and comfort conditions without conditioning reducing the discomfort due to heat of its inhabitants to energy consumption.

The evaluation made shows the importance of operational improvements related to their impact on the significant reduction of discomfort due to heat, both in the current and future scenarios. This indicates the need to provide from the project side, design solutions that facilitate these measures, and mainly to guide people about the best use practices, especially in an energy poverty context, on being highly effective strategies at no cost to the inhabitants. Therefore, these are essential factors to consider in retrofitting policies for climate conditions such as those analyzed.

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References

1. Santamouris M (2016) Innovating to zero the building sector in Europe: Minimising the energy consumption, eradication of the energy poverty and mitigating the local climate change. Solar Energy 128:61–94. https://doi.org/10.1016/j.solener.2016.01.021
2. Rubio-Bellido C, Pérez-Fargallo A, Pulido-Arcas JA, Trebilcock M (2017) Application of adaptive comfort behaviors in Chilean social housing standards under the influence of climate change. Build Simul 10:933–947. https://doi.org/10.1007/s12273-017-0385-9
3. Cellura M, Guarino F, Longo S, Mistretta M (2014) Energy life-cycle approach in net zero energy buildings balance: Operation and embodied energy of an Italian case study. Energy Build 72:371–381. https://doi.org/10.1016/j.enbuild.2013.12.046
4. Sánchez-García D, Rubio-Bellido C, del Río JJM, Pérez-Fargallo A (2019) Towards the quantification of energy demand and consumption through the adaptive comfort approach in mixed mode office buildings considering climate change. Energy Build 187:173–185. https://doi.org/10.1016/j.enbuild.2019.02.002
5. Pérez-Fargallo A, Pulido-Arcas J, Rubio-Bellido C, Trebilcock M, Piderit B, Attia S (2018) Development of a new adaptive comfort model for low income housing in the Central-South of Chile. Energy Build 178:94–106. https://doi.org/10.1016/j.enbuild.2018.08.030
6. Pereira-Ruchansky L, Pérez-Fargallo A (2020) Integrated analysis of energy saving and thermal comfort of retrofits in social housing under climate change influence in Uruguay. Sustainability 12:4636. https://doi.org/10.3390/su12114636

7. Escandón R, Suárez R, Sendra JJ, Ascione F, Bianco N, Mauro GM (2019) Predicting the impact of climate change on thermal comfort in a building category: The case of linear-type social housing stock in Southern Spain. Energies 12:2238. https://doi.org/10.3390/en12122238
8. INE (2011) Encuesta Continua de Hogares 2011. Instituto Nacional de Estadística, Uruguay, https://www.ine.gub.uy/web/guest/encuesta-continua-de-hogares
9. MIEM (2013) Características de sector residencial. Ministerio de Industria, Energía y Minería, Uruguay, https://www.gub.uy/ministerio-industria-energia-mineria/datos-y-estadisticas/estadisticas/encuesta-sobre-consumo-energia-sector-residencial-datos-2013
10. Triana MA, Lamberts R, Sassi P (2018) Should we consider climate change for Brazilian social housing? assessment of energy efficiency adaptation measures. Energy Build 158:1379–1392. https://doi.org/10.1016/j.enbuild.2017.11.003
11. Andrić I, Koc M, Al-Ghamdi SG (2019) A review of climate change implications for built environment: Impacts, mitigation measures and associated challenges in developed and developing countries. J Clean Prod 211:83–102. https://doi.org/10.1016/j.jclepro.2018.11.128
12. van Hooff T, Blocken B, Hensen J, Timmermans H (2015) Reprint of: On the predicted effectiveness of climate adaptation measures for residential buildings. Build Environ 83:142–158. https://doi.org/10.1016/j.buildenv.2014.10.006
13. García de Diego MDL, Gómez Muñoz G, Román López E (2015) Cuentas energéticas no habituales en edificación residencial. Informes de la Construcción 67:m028. https://doi.org/10.3989/ic.14.059
14. INE (2011) Censo Nacional 2011. Instituto Nacional de Estadística, Uruguay, https://www.ine.gub.uy/web/guest/censos-2011
15. Casacuberta C (2006) Situación de la vivienda en Uruguay. Informe de divulgación. Instituto Nacional de Estadística (INE) y Programa de las Naciones Unidas para el Desarrollo (PNUD), Montevideo, Uruguay
16. MIDES (2017) Observatorio Social. Tamaño medio de hogares particulares según quintiles de ingreso. Total país. Ministerio de Desarrollo Social, Uruguay, https://www.gub.uy/ministerio-desarrollo-social/observatorio/indicadores
17. Picción A, Camacho M, Cheirasco G, Salgado ML, Milicua S (2009) Evaluación de pautas de diseño bioclimático aplicadas en edificios de vivienda en Uruguay (clima templado húmedo). Avances en Energías Renovables y Medio Ambiente (AVERMA) 13:187–194
18. ASHRAE (2019) ANSI/ASHRAE standard 62.2-2019. Ventilation and acceptable indoor air quality in low-rise residential buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers
19. ASHRAE (2014) ASHRAE guideline 14-2014. Measurement of energy, demand, and water savings. American Society of Heating, Refrigerating and Air-Conditioning Engineers
20. Lautsen J (2008) Energy efficiency requirements in building codes. Energy efficiency policies for new buildings, International Energy Agency, Paris, France
21. Rubio-Bellido C, Pulido J, Ureta-Gragera M (2015) Aplicabilidad de estrategias genéricas de diseño pasivo en edificaciones bajo la influencia del cambio climático en Concepción y Santiago, Chile. Revista Hábitat Sustentable 5:32–41
22. ASHRAE (2017) ANSI/ASHRAE standard 55–2017 thermal environmental conditions for human occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers
23. CTE (2017) Documento Básico de Ahorro de Energía (DB-HE). Código Técnico de la Edificación, https://www.codigotecnico.org/DocumentosCTE/AhorroEnergia.html
24. IM (2009) Título III.I, Capítulo Único. De la reducción de la demanda de energía para acondicionamiento térmico. In: Normas para edificios destinados a vivienda, vol XV, libro xvi edn, Digesto Municipal, Uruguay
25. Ministerio de Vivienda y Urbanismo (2016) Estándares de Construcción Sustentable para viviendas de Chile. Tomo II Energía. https://csustentable.minvu.gob.cl/edificacion-residencial/
26. Municipalidad de Rosario (2011) Ordenanza N°8757. https://www.rosario.gob.ar/normativa/ver/visualExterna.do?accion=verNormativa&idNormativa=75004

27. Pérez-Fargallo A, Rubio-Bellido C, Pulido-Arcas J, Gallego-Maya I, Guevara-García F (2018) Influence of adaptive comfort models on energy improvement for housing in cold areas. Sustainability 10:859. https://doi.org/10.3390/su10030859
28. Fosas D, Coley DA, Natarajan S, Herrera M, de Pando MF, Ramallo-Gonzalez A (2018) Mitigation versus adaptation: Does insulating dwellings increase overheating risk? Build Environ 143:740–759. https://doi.org/10.1016/j.buildenv.2018.07.033

Residential Heating Use Profiles in Central-Southern Chile

Jorge Muñoz-Fierro, Ariel Bobadilla-Moreno, and Alexis Pérez-Fargallo

Abstract The estimation of energy demand has many inputs that must be reviewed to build simulation models that allow reaching results that are closer to reality. Air-conditioning profiles stand out among the variables to consider. Currently, the heating profiles used in Chile are mainly based on data from standards, guidelines, or simulation tools. This chapter uses data from environmental monitoring centers in central-southern Chile to build representative heating profiles for housing. The study is relevant given that the main heating source is wood-burning; seen in 74% of Chilean homes. The results show that the hourly profiles identify two periods in the day (morning and late afternoon–evening) where use is concentrated, with a use intensity that ranges between 8 and 13 hours a day, depending on the harshness of the weather in the month. Finally, it has to be highlighted that the Top-Down method used in this study, validated through Bottom-Up data, can be replicated in countries where there are environmental monitoring stations and a tradition of using wood for fuel.

Keywords Energy simulation · Occupation · Heating profiles · Environmental monitoring

J. Muñoz-Fierro · A. Bobadilla-Moreno
Center for Research in Construction Technologies (CITEC), University of Bío-Bío, Concepción, Chile
e-mail: jmunoz@ubiobio.cl

A. Bobadilla-Moreno
e-mail: abobadil@ubiobio.cl

A. Pérez-Fargallo (✉)
Department of Building Science, Faculty of Architecture, Construction, and Design, University of Bío-Bío, Concepción, Chile
e-mail: aperezf@ubiobio.cl

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1 Introduction

Energy demand is currently estimated using different simulation tools. This process is used ever more commonly to design, operate, and remodel buildings aiming at reducing costs through energy savings. However, several challenges have been laid down to improve the accuracy of models and their results [1]. The models are affected by diverse inputs associated with the weather, building geometry, air-conditioning systems, operating hours, and the users' comfort demands, among others [2].

The relationships between occupants and indoor environmental conditions are complex and closely linked [3]. Some studies state that thermal comfort is one of the primary needs linked with satisfaction and that it has a higher impact, both on energy consumption and inhabitant well-being [4]. Determining acceptable thermal conditions has been targeted by research since the mid-twentieth century, and it has been identified that these do not solely depend on the body's thermal balance, but also on the adaptation capacity of people to their context [5]. Therefore, comfort can be understood as a somewhat dynamic more than a specific condition or attribute of the environment. This leads to assuming that heating use times are also adaptive and depend on outdoor weather conditions [6].

Occupation times have been reviewed from different points of view. Some have addressed the uncertainty in the quality of the data through probabilistic models [7]. Others have proposed calibration systems for models using real data obtained from different sources such as, for example, occupation proxies incorporated in Wi-Fi connections [2], or the use of connected thermostats [8]. Although the adjustments using calibration processes are fairly regular, they imply having information on the monitored buildings, which is difficult to obtain and takes a long time [9]. On lacking information, it is normal to use approaches based on regulatory assumptions. However, this can also lead to increased gaps between the performance foreseen in the design and operation stages, sometimes reducing credibility and increasing skepticism about high-performance buildings [10].

One of the main energy characteristics of heating in Central-Southern Chile is the use of wood burners inside dwellings. According to estimations, this provides 74% of the energy used by the residential sector [11] and causes diverse environmental contamination issues [12]. In this context, numerous environmental monitoring points have been placed to identify critical contamination episodes [13].

The goal of this study was to apply a Top-Down method to establish representative housing heating profiles by analyzing information collected in the different environmental monitoring centers of Central-Southern Chile, and validating them using occupation information collated through Bottom-Up methods.

2 Methodology

This research considered a quantitative approach to make heating system use calendars where the information published by the National Air Quality Information System (SINCA) was collated, classified, and analyzed [13].

The population analyzed, forms part of 8 Chilean regions, and comprises 43 communes. 36 monitoring points were identified, grouped into 10 zones with Environmental Decontamination Plans (PDA, in Spanish). As inclusion criteria, those monitoring stations that had records in 2018, 2019, and 2020, and whose data were reported on Particulate Matter 2.5 indices ($PM_{2.5}$), were considered. For the records, measurements updated every hour throughout the year were used. After revision, there were 28 monitoring points in 17 communes, which complied with the aforementioned inclusion requirements. The information collated considers data from 75% of the total population in the zones evaluated with PDA [14].

The weather conditions are affected by the latitude and longitude of each zone. Some PDAs comprise several communes and measurement points (See Fig. 1). However, their weather conditions are representative of the zone where they are located, and on the whole, have very similar characteristics. Considering this, the results are analyzed using mean values of 2018, 2019, and 2020 (times) from the records of the communes in each PDA. Records of 2020 were not included to avoid bias associated with the lockdowns seen in Chile, related to the COVID-19 pandemic. In addition, the data were divided into weekdays (Monday to Friday), and weekends (Saturday and Sunday). However, the results are quite close in both cases, and to simplify the analysis, only the weekly results are presented.

Once the information was defined and grouped, an emissions analysis was made, to identify the typical background contamination of each zone, linked to traffic, industrial processes, and wood-burning stoves, among others. For this, the hourly data of the study period were stratified by quartiles for weekdays and weekends, to analyze their variability and identify similar trends associated with contamination sources that were relatively constant over the study periods. Afterward, the data were subjected to an adjustment process which consisted of discounting the background contamination identified, to differentiate the months where there is a relevant heating use.

With the data defined and adjusted, the weighting of the average hourly measurements of 2018, 2019, and 2020, considering annual maximums, was established. With this information, the months and hours with the highest emissions levels were identified, splitting them into the following three groups depending on the intensity of the concentrations reflected in the monthly hourly average, considering that said conditions should be met, both for weekday and weekend records and considering the harshness of the weather in the month.

- Months, where the average percentage of monthly hourly $PM_{2.5}$ emissions above the annual maximum was less than 2%.
- Months, where the average percentage of monthly hourly $PM_{2.5}$ emissions above the annual maximum was between 2 and 15% (medium intensity).

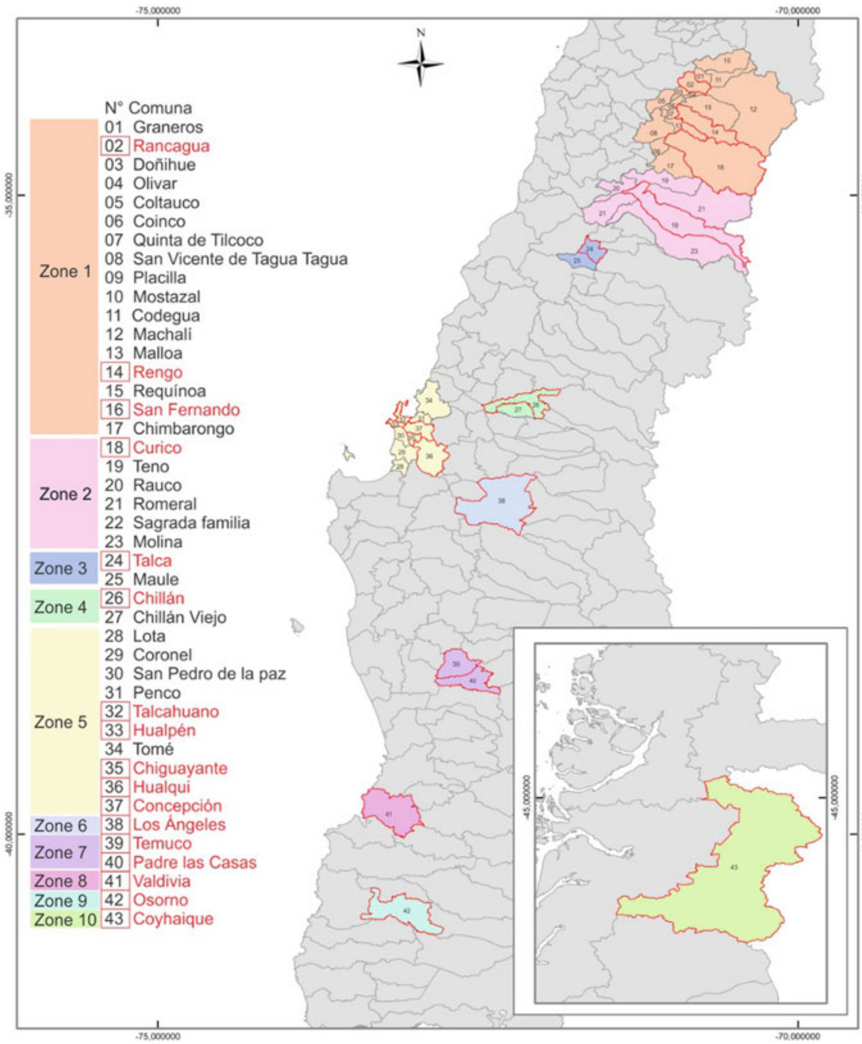

Fig. 1 Zones with Environmental Decontamination Plans, and Communes, in red, that have an environmental monitoring system

- Months, where the average percentage of monthly hourly $PM_{2.5}$ emissions above the annual maximum exceeded 15% (high intensity)

As a result, the first group was considered as months without heating use, the second was designated for "Cold Months" (CM), and the third for "Very Cold Months" (VCM).

Variations were established in hourly records by zone for the cold months (CM) and very cold months (VCM) to make the heating profiles. An algorithm was formulated for this process, that allowed defining the periods where increases in emissions showed greater use of heating. This algorithm considered the presence of heating when the emissions of an hour were higher than 60% of the maximum annual value, or when the hour studied had an increase in the emissions concentration compared to the preceding hour. Sixty percent was set, considering that if there was a percentage above 50%, then its use is representative of most homes that use wood burners for heating. The detail is presented below:

- Heating On (On): Eph-1 $\leq$ Eph or Eph $\geq$ 60% of the annual maximum record
- Heating Off (Off): Eph-1 $>$ Eph if Eph $<$ 60% of the maximum record

Where, Eph is the average emissions percentage of zones with PDA for the hour evaluated, and Eph-1 is the average emissions percentage of zones with PDA for the preceding hour.

The 60% condition of the annual maximum record was used because it was seen there were hours where the Eph was slightly lower than the Eph-1 without seeing an abrupt fall of $PM_{2.5}$ emissions. This implied there had been a dilution of the contamination caused by meteorological phenomena, or a small reduction in the use of heating systems. However, the high contamination rates, above 50% of the annual maximum value for an hour of study, led to the assumption that the wood-burning heating systems continued to be in use in more than half the dwellings, and therefore, continued to be representative of the city’s homes considering heating-ON.

The validation of the results made for hourly profiles comprised revising the occupation of a sample of 40 dwellings to determine their relationship with the proposed profiles and their behavior. The dwellings studied came from previous research whose goal was to develop adaptive comfort models for social housing in central-southern Chile [15]. In the study, data was collected through samples, whose main feature was having benefitted from some type of state subsidy. Among the typologies, 6 single-family and 6 terraced dwellings were considered, along with another 25 single-family homes and 3 apartments located in condominiums.

The occupation was established using surveys where residents were asked about the use of the dwellings. The survey was made separately for weekdays and weekends. In both cases, data was collected for all 24 hours of the day. A total of 121 people were surveyed, 57 men and 74 women, whose ages ranged between 14 and 84. With the information collected, the average hourly occupation percentage of the dwellings for the study sample was obtained, which was compared graphically with the heating use profiles obtained.

3 Results

3.1 Emissions

The average distribution of monthly emissions in the zones studied tended to increase from March, lasting to October in some cases (see Fig. 2). This coincides with the drop in temperature from autumn onwards (March to June), becoming more marked closer to winter (June to September). Both zones 9 and 10 had a higher emissions average, and a longer period (March to October), compared to the rest of the study zones. Meanwhile, the zone with the lowest average was area 5. The difference increases in colder months and asymmetric distribution of the concentrations is seen in those months. However, the months between November and February have a similar distribution, on not using wood-burning heating, the result of higher outdoor temperatures.

In general, the average distribution of hourly emissions (see Fig. 2) has a slight increase from 3 to 4 pm, increasing considerably from 6 to 8 or 9 pm, depending on the zone and period evaluated (weekday or weekend). After this time, the values fall but remain high until around 11 pm when a clear reduction is seen. Finally, from 6 to 9 or 10 am, there is an increase in emissions once more. Although the minimum and maximum values differ a lot over the day, it is seen that the first quartile has a smaller variation. The spread of the data is mainly seen in zones 8, 9, and 10, and a positive asymmetry of the data is seen in most of the hours and zones evaluated.

3.2 Background Contamination

To reduce bias in setting heating calendars, an estimation of the environmental contamination associated with different factors such as traffic, industrial processes, and wood-fired stoves, among others, was made. It is seen in the summer months (January, February, March, and December), in Fig. 2, that outdoor contamination values remain practically constant compared to the rest of the months, identifying that in those months, environmental contamination mainly came from processes other than wood-fired combustion for heating. Likewise, it can be identified that the hourly upper limit of quartile 1 of the different analyzed zones, for weekdays, has little oscillation within the 24 h period.

In Table 1, it is possible to see that the said value for weekdays oscillates between 4.5 and 20.8 μgm^3 for the different zones, with an hourly variance of between 1.0 and 10.5, and a standard deviation per hour of between 1.0 and 3.2. This allowed establishing that these values are not greatly affected by the harshness of the weather, remaining in stable ranges throughout the year, and identifying that they are very similar to the records of summer months when there is no need for heating (See Fig. 2). Therefore, it was estimated that the upper limit of the first quartile for hourly

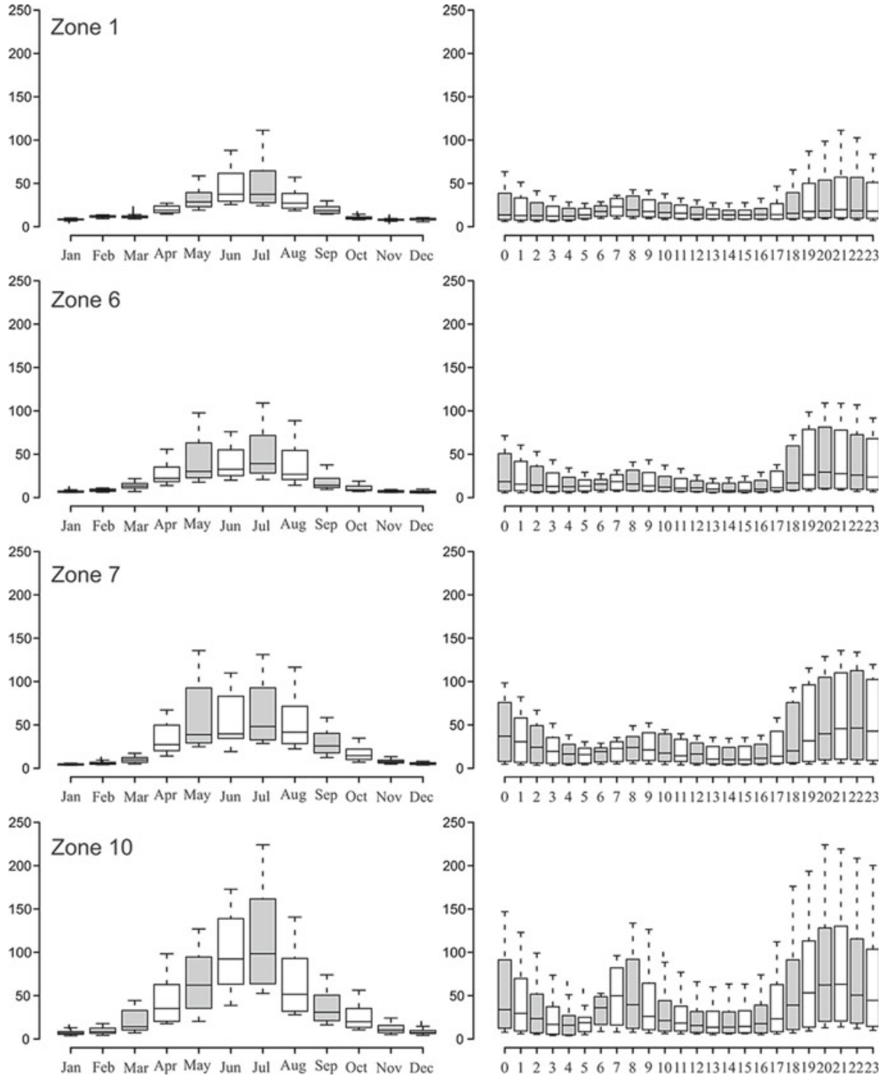

Fig. 2 Boxplot of average hourly and monthly emissions for weekdays per month of 2018–2020 period in zones 1-6-7-10 ($PM_{2.5}$ $\mu g/m^3$)

Table 1 Upper limit values of the first quartile for weekday hourly emissions by Zone ($\mu g/m^3$)

	Zones												
Time	1	2	3	4	5	6	7	8	9	10	$\overline{X}$	S^2	α
0:00	8.2	8.0	9.5	10.8	9.4	7.6	8.0	8.5	9.8	12.5	9.2	2.3	1.5
1:00	7.8	7.5	9.2	9.5	9.7	7.9	7.0	8.1	9.7	9.3	8.6	1.0	1.0
2:00	7.8	6.9	8.8	8.2	9.5	6.7	6.0	6.1	8.8	7.2	7.6	1.5	1.2
3:00	7.5	6.6	8.9	8.0	9.3	6.8	5.6	7.1	7.7	5.6	7.3	1.5	1.2
4:00	7.9	6.3	9.2	7.6	9.2	7.1	5.3	5.4	8.2	4.8	7.1	2.6	1.6
5:00	9.7	6.4	9.3	7.8	9.6	7.5	5.8	5.1	8.1	8.4	7.8	2.5	1.6
6:00	12.0	7.8	10.1	9.8	10.6	8.6	7.2	6.2	10.8	16.7	10.0	8.8	3.0
7:00	12.6	9.0	11.1	9.6	11.6	8.6	8.0	7.1	12.6	16.1	10.6	7.3	2.7
8:00	11.9	8.0	11.2	8.7	11.0	8.0	8.7	8.3	10.0	12.3	9.8	2.8	1.7
9:00	11.3	8.1	10.8	8.0	11.0	7.6	9.0	7.9	9.8	10.8	9.4	2.2	1.5
10:00	10.2	8.1	10.1	7.8	10.0	7.3	7.9	6.6	9.5	9.2	8.7	1.7	1.3
11:00	9.5	8.2	10.3	7.2	9.5	7.3	7.8	6.0	7.9	9.3	8.3	1.8	1.3
12:00	9.3	7.5	9.9	7.1	9.1	7.0	5.5	5.6	7.1	7.6	7.6	2.2	1.5
13:00	9.1	6.7	8.8	6.8	9.1	6.3	5.1	4.5	7.5	7.0	7.1	2.5	1.6
14:00	8.6	6.4	8.5	6.8	9.3	6.3	4.7	4.6	7.5	6.9	7.0	2.5	1.6
15:00	8.8	6.5	8.3	6.4	9.4	6.3	4.8	4.7	7.1	7.3	7.0	2.4	1.6
16:00	8.9	6.2	8.0	6.4	9.5	6.8	5.1	4.9	7.5	7.1	7.0	2.2	1.5
17:00	8.9	6.0	9.0	6.9	10.3	7.9	5.9	5.9	7.6	8.5	7.7	2.3	1.5
18:00	9.4	6.2	8.7	8.8	10.5	8.5	6.5	6.6	7.8	10.9	8.4	2.7	1.6
19:00	10.2	8.0	9.8	10.0	10.3	10.0	7.8	8.3	9.0	13.8	9.7	3.0	1.7
20:00	10.5	8.8	11.8	11.2	11.2	10.6	9.7	10.8	12.4	20.5	11.8	10.5	3.2
21:00	10.4	10.0	11.0	12.1	11.4	10.3	10.4	12.4	13.4	20.8	12.2	10.3	3.2
22:00	9.9	10.0	11.0	12.0	11.1	9.5	10.0	12.1	12.5	18.2	11.6	6.4	2.5
23:00	9.6	9.4	11.8	11.3	10.4	9.0	9.0	11.7	12.9	14.5	11.0	3.3	1.8
$\overline{X}$	9.6	7.6	9.8	8.7	10.1	7.9	7.1	7.3	9.4	11.1			
S^2	1.9	1.5	1.3	3.2	0.6	1.6	3.1	5.7	4.2	21.7			
α	1.4	1.2	1.1	1.8	0.8	1.3	1.8	2.4	2.0	4.7			

$\overline{X}$: Average, S^2: Variance, α: Standard Deviation

data could be assumed as the contamination associated with processes other than wood-fired heating.

3.3 Profiles

Once the values considered as background contamination are discounted, the average percentage of monthly hourly $PM_{2.5}$ Particulate Matter emissions was determined (See Table 2). Based on this, the data show that, despite discounting background contamination, some zones continue to have small concentrations at certain times

Table 2 Average percentage of monthly hourly $PM_{2.5}$ emissions compared to the annual maximum for weekdays per zone

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	$\overline{X}$
1	0.0	1.6	1.6	10.1	28.4	40.7	43.4	26.5	5.3	2.0	0.0	0.1	13.3
2	0.0	0.7	2.8	10.9	29.2	39.0	30.8	21.2	6.1	2.0	0.0	0.1	11.9
3	0.4	1.3	6.1	14.2	31.7	44.6	38.3	29.9	8.1	0.5	0.0	0.1	14.6
4	0.0	1.4	6.2	15.6	24.5	36.0	27.6	22.4	6.5	1.2	0.0	0.0	11.8
5	3.9	2.5	1.1	12.9	28.3	27.6	21.2	18.8	4.2	1.1	0.0	0.0	10.1
6	0.5	0.8	5.1	20.8	44.8	49.6	37.1	35.1	12.9	3.4	0.0	0.0	17.5
7	0.0	0.3	2.2	20.8	37.0	39.8	32.0	34.3	18.6	7.5	1.0	0.0	16.1
8	0.0	0.0	1.6	16.8	26.5	39.5	37.5	27.5	21.7	7.1	2.1	0.0	15.0
9	0.0	0.0	2.1	17.5	21.4	37.8	35.6	21.2	14.3	4.8	1.9	0.0	13.1
10	0.0	0.1	2.3	10.7	25	52.9	53.8	23.9	11.9	3.9	0.5	0.0	15.4
$\overline{X}$	0.5	0.9	3.1	15.0	29.7	40.7	35.7	26.1	11	3.4	0.6	0.0	
Zones between 2% & 15%	1	1	7	4	0	0	0	0	8	7	1	0	
Zones > 15%	0	0	0	6	10	10	10	10	2	0	0	0	
Classification			CM	VCM	VCM	VCM	VCM	VCM	CM	CM			

Table 3 Monthly average temperatures by zone (°C)

Zone	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	$\overline{X}$
1	21.8	21.5	18.9	14.8	11.3	7.9	7.9	9.4	11.8	14.6	18.7	20.8	15.0
2	22.3	22.0	19.0	15.3	11.3	8.4	8.6	9.6	12.2	14.9	19.2	21.3	15.4
3	22.2	21.9	18.7	14.5	10.9	8.2	8.2	9.3	12.0	14.5	18.6	20.9	15.0
4	20.8	20.9	17.7	13.5	10.6	7.7	7.8	8.8	11.2	13.1	16.8	19.4	14.0
5	17.7	17.8	15.9	13.5	11.7	9.5	9.5	9.8	10.9	12.3	15.2	16.9	13.4
6	20.1	20.6	17.3	13.3	10.7	7.8	7.7	8.8	10.8	12.9	16.2	18.7	13.7
7	17.0	17.8	15.5	12.5	10.5	8.2	7.9	8.3	9.8	11.5	13.8	15.7	12.4
8	17.0	17.4	15.2	11.8	10.4	8.1	7.5	7.9	9.5	11.0	13.6	15.9	12.1
9	16.1	16.9	14.4	11.1	9.3	7.2	6.5	7.3	9.3	12.1	13.8	15.8	11.7
10	13.3	14.2	11.8	8.8	6.3	2.8	2.1	4.6	6.1	8.5	11.1	13.1	8.6
$\overline{X}$	18.8	19.1	16.4	12.9	10.3	7.6	7.4	8.4	10.4	12.5	15.7	17.9	13.1

in the summer months. In general, these records are seen at times with daily peak temperatures, which leads to assuming that this is when wood-fired stoves are in use [12]. Among the zones studied, the highest summer concentrations are produced in Concepción (Zone 5) as it has an industrial hub. However, the values are close to the rest of the zones. In Table 2, it is possible to see that the emissions increase as winter approaches, and fall on moving closer to spring.

In this sense, the months were classified by zone, where the average hourly emissions were below 2% of the annual maximum value, establishing that in January, February, November, and December, there was no wood-fired heating as the outdoor temperatures were above 15°C in most zones (See Table 3). In the case of March, this is an atypical month as, despite having monthly average outdoor temperatures above 15°C, the drop off in temperature from the warmer season may lead to heating, despite temperatures being pretty similar to November, where clearly this is not used [16]. Likewise, it can be seen in Table 2, that the months of September and October have the most zones with monthly hourly emission averages between 2 and 15%, compared to the annual maximum value (medium intensity), and monthly average temperatures in most zones of between 10 and 15°C. As a result, March, September, and October have been classified as Cold Months. In the case of April, just as occurred with March, despite monthly average temperatures being between 10 and 15°C, just as in October, wood-fired heating use is estimated as being more intensive, due to the drop off in temperatures from the hotter season, even though its monthly average temperatures are pretty similar. Finally, the months where more intensive use of heating is considered and, therefore, a colder thermal sensation is assumed, are the months of May, June, July, and August, where for all the zones, the average monthly hourly emissions percentage compared to the maximum annual average, exceeds 15%.

Table 4 summarizes the hourly heating profiles on weekdays for the CM and CVM heating periods in each zone studied. The proposed profiles are defined by these, considering the statistical mode of the weekday hourly data. Figure 3 shows the proposed heating profiles for weekdays, where it is seen there are two heating periods during the day. The first is at the start of the day, from 6 to 9 am for the CM and CVM months. The second period starts at 3 pm and continues until 10 pm in the CM and from 2 pm to 12 am in the VCM.

3.4 Validation

Figure 4 represents the relationship between the proposed profiles and the characteristic occupation of a sample of 40 dwellings from the Concepción Metropolitan zone 5. The results show that this is a pretty good fit between heating use and changes in housing occupation during the day. In all the profiles, the heating use begins when the dwellings show a reduction of occupation as the occupants get up and begin their daily activities (start of the working and/or school day), except for the weekends of the CM, when this is delayed for around an hour. This entails that the dwellings require a comfortable indoor environment while the occupants prepare to leave. Likewise, the lowest occupation levels coincide with periods when the heating is off, from 9 am to 2 pm for VCM, and from 9 am to 3 or 4 pm for the CM, with the heating on in the afternoons when occupation levels in the homes begin to increase. Finally, although the highest occupation levels are seen at night, heating use is not seen from 10 pm in the CM, and from 12 am for the VCM, which is mainly associated with most of the population not having the habit of using nighttime heating in their homes.

Table 4 Hourly heating use profiles by zone for weekdays

	Zones																					
	1		2		3		4		5		6		7		8		9		10		Mo	
Time	C	V	C	V	C	V	C	V	C	V	C	V	C	V	C	V	C	V	C	V	C	V
0:00	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0
1:00	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4:00	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6:00	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
7:00	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
8:00	1	1	1	1	1	0	0	1	1	1	1	1	0	1	0	0	0	1	0	0	1	1
9:00	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
12:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
13:00	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0
14:00	0	1	0	1	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	1
15:00	0	1	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
16:00	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
17:00	1	1	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
18:00	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19:00	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20:00	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1
21:00	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	0	1	0	1	1	1
22:00	0	1	0	1	0	1	1	1	1	1	0	1	1	1	0	1	1	1	0	1	0	1
23:00	0	0	1	1	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	1

Mo: Statistical mode; C: Cold Month; V: Very Cold Months; 0: Off; 1: On

4 Conclusions

This research sought to establish characteristic heating use profiles of central-southern Chile. For this, the $PM_{2.5}$ emissions of zones with high atmospheric contamination levels were studied. The analysis showed that the highest concentrations are produced in the coldest months of the year, which is why the contribution of other particulate matter generating sources such as industry, trade, and transportation, were marginal within the overall analysis. For this same reason, it is clear that the increase in concentrations comes mainly from residential heating. This justifies its relevance for establishing heating profiles associated with the population under study.

The results showed that heating is not on all day long. The proof of this is that at night (12 to 6 am), despite having a maximum occupation, emissions fall considerably. This aspect should be kept in mind in simulation and evaluation processes,

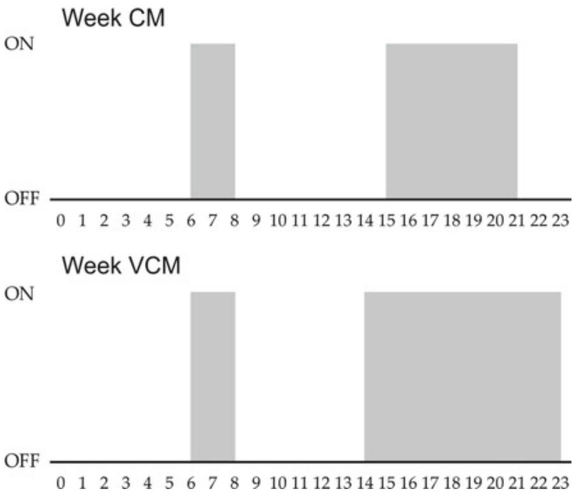

Fig. 3 Proposed hourly heating profiles

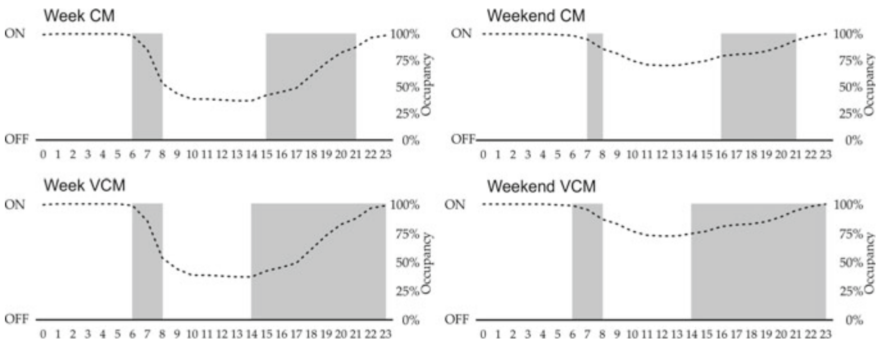

Fig. 4 Proposed heating profiles versus occupation

as considering just occupation and comfort temperatures, implies that people have enough resources to keep their homes comfortable at all times. This condition is not seen in the studied population, as the emissions are mainly concentrated in just two periods of the day. The distribution of the emissions leads to assuming that there is a relevant population that is in fuel poverty because of the intensive use of wood for energy, which is important to consider, especially when studying the effectiveness of measures associated with energy improvements for homes.

The findings of this research provide information to establish more realistic criteria on the effect energy improvement projects could have on homes, especially when detailed information on occupant behavior for heating their homes is not known. Finally, the Top-Down methodology used in this study, validated through Bottom-Up data, has to be highlighted. This can be replicated in countries where there are environmental monitoring stations and a tradition of using wood as fuel, thus being able to obtain heating use patterns that are representative of the built sector to reduce the performance gap of energy qualification systems, simulations, or energy certification processes.

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References

1. Hong T, Langevin J, Sun K (2018) Building simulation: Ten challenges. Build Simul 11:871–898. https://doi.org/10.1007/s12273-018-0444-x
2. Chong A, Gu Y, Jia H (2021) Calibrating building energy simulation models: A review of the basics to guide future work. Energy Build 253:111533. https://doi.org/10.1016/j.enbuild.2021.111533
3. Bluyssen PM (2020) Towards an integrated analysis of the indoor environmental factors and its effects on occupants. Intell Build Int 12:199–207. https://doi.org/10.1080/17508975.2019.1599318
4. Frontczak M, Wargocki P (2011) Literature survey on how different factors influence human comfort in indoor environments. Build Environ 46:922–937. https://doi.org/10.1016/j.buildenv.2010.10.021
5. Porras-Salazar J, Contreras-Espinoza S, Cartes I, Piggot-Navarrete J, Pérez-Fargallo A (2020) Energy poverty analyzed considering the adaptive comfort of people living in social housing in the Central-South of Chile. Energy Build 223:110081. https://doi.org/10.1016/j.enbuild.2020.110081
6. Bienvenido-Huertas D, Rubio-Bellido C, Pérez-Fargallo A, Pulido-Arcas JA (2020) Energy saving potential in current and future world built environments based on the adaptive comfort approach. J Clean Prod 249:119306. https://doi.org/10.1016/j.jclepro.2019.119306
7. Ekström T, Burke S, Wiktorsson M, Hassanie S, Harderup LE, Arfvidsson J (2021) Evaluating the impact of data quality on the accuracy of the predicted energy performance for a fixed building design using probabilistic energy performance simulations and uncertainty analysis. Energy Build 249:111205. https://doi.org/10.1016/j.enbuild.2021.111205
8. Ueno T, Meier A (2020) A method to generate heating and cooling schedules based on data from connected thermostats. Energy Build 228:110423. https://doi.org/10.1016/j.enbuild.2020.110423
9. Guyot D, Giraud F, Simon F, Corgier D, Marvillet C, Tremeac B (2020) Building energy model calibration: A detailed case study using sub-hourly measured data. Energy Build 223:110189. https://doi.org/10.1016/j.enbuild.2020.110189
10. de Wilde P (2014) The gap between predicted and measured energy performance of buildings: A framework for investigation. Autom Constr 41:40–49. https://doi.org/10.1016/j.autcon.2014.02.009
11. In-Data SpA & CDT (2019) Resumen ejecutivo de usos de la energía de los hogares Chile. Tech. rep, Corporacion de Desarrollo Tecnologico/In-data
12. Boso A, Oltra C, Hofflinger Á (2019) Participation in a programme for assisted replacement of wood-burning stoves in Chile: The role of sociodemographic factors, evaluation of air quality and risk perception. Energy Policy 129:1220–1226. https://doi.org/10.1016/j.enpol.2019.03.038
13. Ministerio del Medio Ambiente (2022) Sistema de información nacional de calidad del aire. Accessed 10 Jun 2022, from https://sinca.mma.gob.cl/
14. INE (2017) Descargue aquí resultados de comunas—censo 2017. Accessed 11 Nov 2021, from http://www.censo2017.cl/descargue-aqui-resultados-de-comunas/

15. Pérez-Fargallo A, Pulido-Arcas J, Rubio-Bellido C, Trebilcock M, Piderit B, Attia S (2018) Development of a new adaptive comfort model for low income housing in the Central-South of Chile. Energy Build 178:94–106. https://doi.org/10.1016/j.enbuild.2018.08.030
16. Auliciems A (1981) Towards a psycho-physiological model of thermal perception. Int J Biometeorol 25:109–122. https://doi.org/10.1007/BF02184458

The Future of Environmental Comfort in the Global South

Energy and Environmental Comfort Policies and Standards for Buildings in the Global South

Maureen Trebilcock-Kelly, Laura Marín-Restrepo, Alexis Pérez-Fargallo, Paulina Wegertseder-Martínez, and Jose Ali Porras-Salazar

Abstract This chapter reviews current policy instruments that are relevant in terms of energy and environmental comfort in buildings. Based on an overview of energy indicators worldwide, it comprises detailed information on ten Latin American countries: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Mexico, Peru, and Uruguay. For each country, the review covers information on building energy codes, energy labeling, and environmental comfort codes, among other aspects. The conclusions show that there are important differences between countries, where most of them have developed initiatives on energy efficiency in buildings that would indirectly improve comfort, but very few have developed policies and standards specifically on environmental comfort.

Keywords Policies · Standards · Environmental comfort · Building energy codes

M. Trebilcock-Kelly (✉) · P. Wegertseder-Martínez
Department Design and Theory of Architecture, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: mtrebilc@ubiobio.cl

P. Wegertseder-Martínez
e-mail: pwegertseder@ubiobio.cl

L. Marín-Restrepo
Architecture et Climat, Louvain Research Institute for Landscape, Architecture, Built environment, Université catholique de Louvain, Louvain-la-Neuve, Belgium
e-mail: laura.marinrestrepo@uclouvain.be

A. Pérez-Fargallo
Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: aperezf@ubiobio.cl

J. Ali Porras-Salazar
School of Architecture, University of Costa Rica, San Pedro de Montes de Oca, Costa Rica
e-mail: jose.porrassalazar@ucr.ac.cr

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1 Introduction

Environmental comfort standards and policies for buildings are mainly associated, today, with the development of concepts related to access to energy, energy efficiency, and renewable energies. In this sense, the Regulatory Indicators for Sustainable Energy (RISE), developed by the World Bank, allow seeing the differences in development between countries [1, 2].

Regarding energy efficiency indicators, which address multi-dimensional aspects of policies and regulations that affect environmental comfort, it has been seen that among the countries of the Global North and the Global South, there are important development gaps (Fig. 1). Although there are countries in the Global South, such as South Korea, India, Mexico, Singapore, or China, that have made major strides in energy efficiency, most countries have seen much less progress than the Global North. In Table 1 and Fig. 2, it can be seen that the indicators with the largest differences are: Carbon Pricing and Monitoring (I10), Building Energy Codes (I9), and Minimum Energy Efficiency Performance Standard (I7), with a mean difference of more than 50 points. These are followed by Incentives & Mandates: Public Sector (I4), Energy Labeling Systems (I8), and Financing Mechanisms for Energy Efficiency (I6), with differences between 33.5 and 50 points.

The indicators Building Energy Codes (I9) and Minimum Energy Efficiency Performance Standard (I7), reflect the presence of standards that regulate energy performance, so they are related to environmental comfort in buildings. Out of the 92 Global South countries with available information, 44 do not have any type of development for Building Energy Codes (I9), 35 have fewer than 59 points, and 11 are between 60 and 79 points. Only 3 countries score more than 80 points: South Korea, Tunisia, and Qatar. Regarding the Minimum Energy Efficiency Performance Standard (I7) indicator, 25 countries have no development, 43 score less than 59, 12 score between 60 and 79 points, and only thirteen score over 80. South Korea, Mexico, India, Iran, and Costa Rica stand out on scoring over 90 points.

According to the UN Environment Program 2021 Report, countries increasingly recognize that building energy codes are essential for zero-carbon emissions, yet their application remains low in some regions, such as Africa and Latin America. Building energy codes are typically implemented by governments to regulate the construction and operation of buildings to minimize energy use while achieving environmental comfort. They can take many forms, as building energy use depends on numerous aspects, from architectural typologies to the operation and efficiency of heating and cooling systems [3].

Within the Global South, the region of Latin America and the Caribbean has common cultural characteristics and an active exchange of information and cooperation. However, progress in energy efficiency and building comfort policies is uneven among its countries. The Minimum Energy Efficiency Performance Standard (I7) indicator ranges between 0 and 100, where Mexico, Costa Rica, Ecuador, and Brazil stand out with the highest development. Meanwhile, the Building Energy Codes (I9)

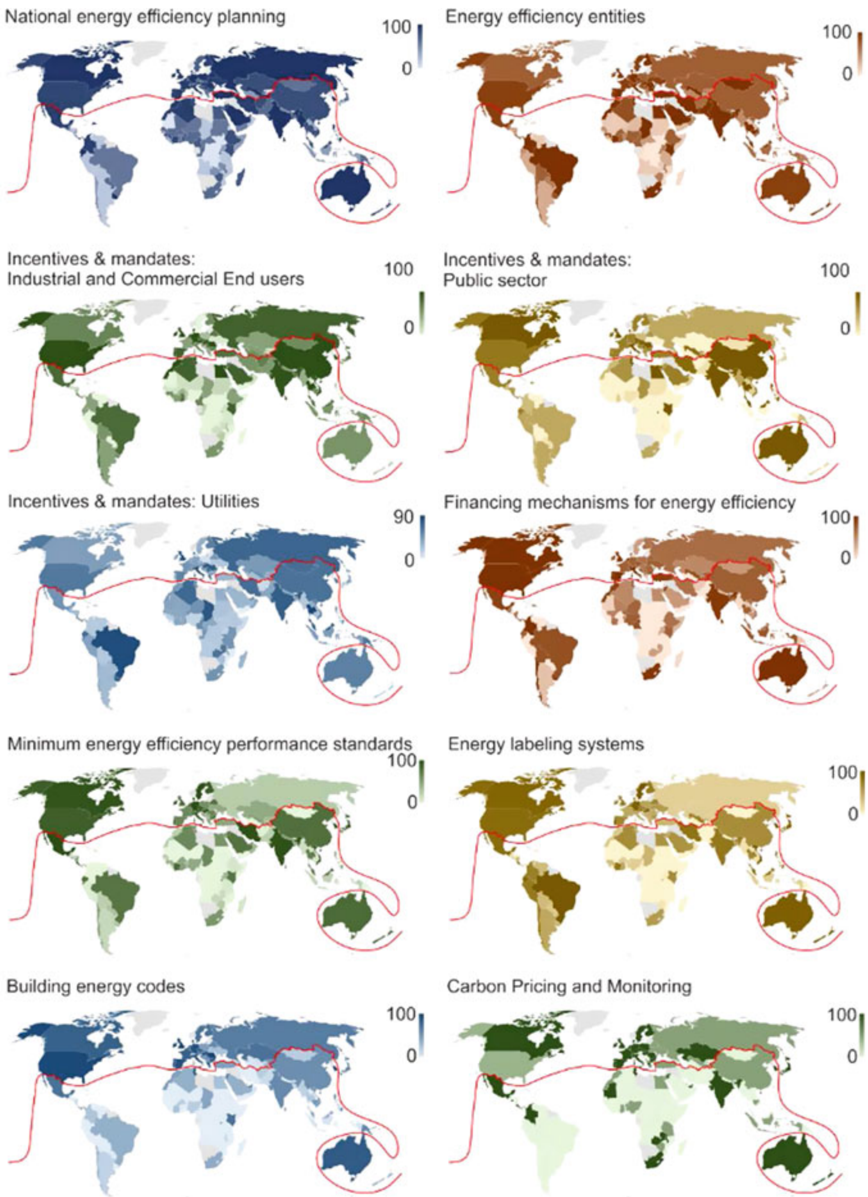

Fig. 1 Indicators associated with energy efficiency for countries in 2019. *Source* Own preparation using [1]

Table 1 Distribution by quartile of indicators associated with energy efficiency in 2019

		I1	I2	I3	I4	I5	I6	I7	I8	I9	I10
Global North (n = 43)	Upper whisker	100	100	100	100	86	100	100	100	100	100
	3rd quartile	100	100	100	100	64	91	91	88	87	100
	Median	93	92	75	75	48	75	80	71	73	100
	1st quartile	81.5	75	52	56.5	34.5	65	46	50	56.5	50
	Lower whisker	67	50	0	0	7	40	0	0	27	0
Global South (n = 92)	Upper whisker	100	100	100	100	90	100	100	100	87	100
	3rd quartile	87	100	69	63	53	75	57	52	37	50
	Median	67	67	45.9	25	38	41.5	27.3	25	5	0
	1st quartile	40	29	4	0	23.5	0	0	0	0	0
	Lower whisker	0	0	0	0	0	0	0	0	0	0

Source Own preparation using [1]

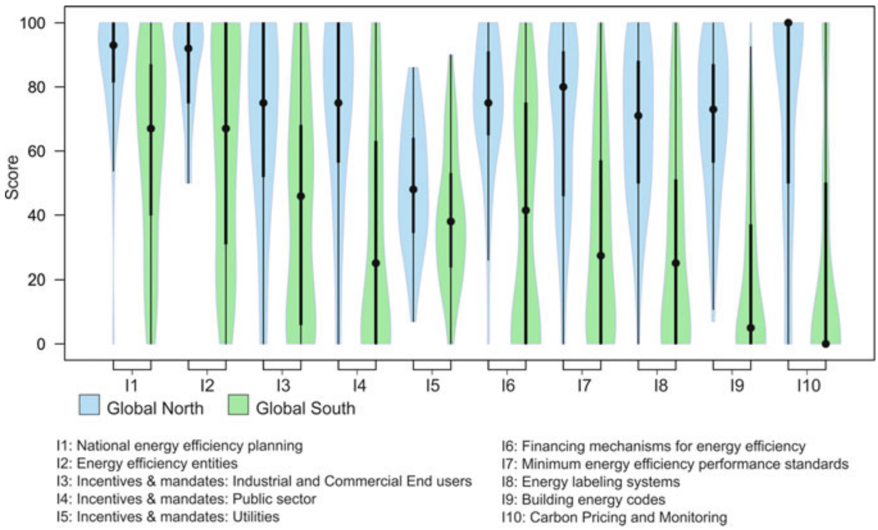

Fig. 2 Scored indicators in energy efficiency encompassing multi-dimensional aspects of policies and regulations. Own preparation, data from [1]

Table 2 Indicators associated with energy efficiency for countries in Latin America and the Caribbean in 2019

Countries	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10
Argentina	17	33	50	50	28	22	17	50	17	0
Bolivia	17	75	58	0	20	82	23	38	0	0
Brazil	60	100	83	50	86	83	77	100	37	0
Chile	47	75	83	38	38	100	50	83	33	0
Colombia	93	100	50	38	20	100	0	75	25	100
Costa Rica	47	75	75	63	53	50	92	92	0	100
Dominican Rep.	100	17	13	75	20	67	18	17	0	0
Ecuador	100	50	50	75	68	75	78	92	0	0
El Salvador	67	25	0	25	37	50	57	50	0	100
Guatemala	60	58	13	38	30	65	17	17	0	0
Haiti	0	25	0	0	27	63	0	0	0	0
Honduras	17	42	13	63	30	0	17	8	0	0
Jamaica	40	100	50	50	78	90	23	42	37	0
Mexico	93	92	83	75	48	90	100	88	73	100
Nicaragua	33	42	25	63	30	67	47	38	10	0
Panama	83	100	75	75	69	97	58	38	67	50
Paraguay	67	58	0	13	30	0	32	29	0	0
Peru	17	33	0	50	40	0	5	79	0	0
Uruguay	100	83	58	50	72	92	30	38	0	0
Venezuela	17	17	0	0	20	0	0	38	0	0

Source Own preparation using [1]

indicator has values between 0 and 73, with Mexico and Panama scoring the highest (see Table 2).

To show the variability between countries, 10 have been chosen to analyze them in detail: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Mexico, Peru, and Uruguay (See Fig. 3).

2 Policies and Standards in Latin America

This section presents the main policies, regulations, and standards that regulate energy efficiency and environmental comfort in the building sector in 10 Latin American countries.

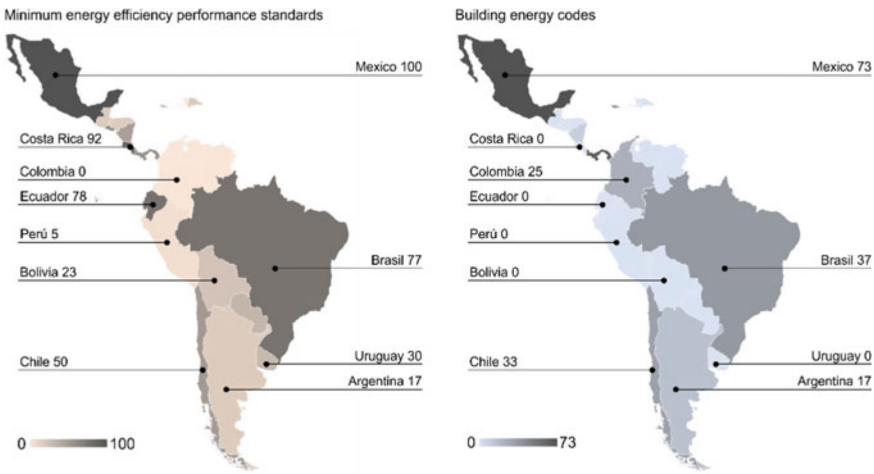

Fig. 3 Scores for Minimum energy efficiency performance standards and Building energy codes of the chosen countries in 2019. *Source* Own preparation using [1]

2.1 Argentina

Argentina kicked off a project between 2018 and 2019 to address the pillars, objectives, and goals for energy transition by 2050. Among the objectives laid out, the diversification of the energy matrix stands out, integrating renewable energies and energy efficiency in dwellings, among others [4].

The Argentinean Institute of Standardization and Certification regulates the comfort and energy efficiency of buildings through the IRAM Standards, which aim at guaranteeing the hygrothermal habitability conditions of hygiene and healthiness. Among them, IRAM 11605 establishes maximum thermal transmittance values in opaque enclosures, defining three comfort levels: “A” (recommended), “B” (medium), and “C” (minimum), for summer and winter conditions, considering the different bio-environmental zones of the country [5].

Meanwhile, IRAM 11604 establishes the calculation methodology for the Heat Loss Volumetric Coefficient (Gcal) and sets maximum admissible values. This focuses on all buildings located in the template and cold bio-environmental areas [6].

In addition, IRAM 11900, approved in 2017, establishes an Energy Efficiency Label based on a tool that allows measuring the energy efficiency of a dwelling on a scale from “A” to “G”. This is based on the Energy Supply Index (IPE, in Spanish) that represents the annual energy requirement for heating, cooling, domestic hot water, and lighting [7, 8]. The Province of Santa Fe authorized a Housing Energy Efficiency Labeling Law, that sets out the obligation of presenting an Energy Efficiency Label for the dwelling for any transfer of ownership that takes place in the region. The impact of this standard has been very important, making energy, economic, and environmental benefits visible on a label, contributing to a change of paradigm for sustainable construction [9].

2.2 Bolivia

Bolivia has shown an end energy consumption per capita that is higher than other Latin American countries [10]. For environmental comfort and/or energy efficiency matters, there is only fledgling progress, which is differentiated by municipalities. Domestically, the National Energy Efficiency Program has focused on fostering the efficient use of electricity, under standards that cover energy savings for household appliances and lighting equipment [11], such as NB 87005:2021 for LED lights (Specifications and Labeling); NB 87007:2021, characteristics and testing methods for domestic refrigeration devices; and NB 87003:2021 for refrigerator labeling and classification [12–14].

At a building level, NB/ISO 9288:2010 regulates thermal insulation and heat transmission through radiation [15]. Likewise, in the Bolivian Guidelines for Project Design and Presentation, it is stated that the architectural design must consider criteria for energy efficiency, sustainability, and protecting Mother Earth [16].

Meanwhile, municipalities have presented laws that cover the reduction of fossil fuel consumption and provide incentives for environmental sustainability in buildings. In the case of Santa Cruz de la Sierra, Regional Law N° 177 regulates rural electrification and alternative and renewable sources of energy, with the basic goal of providing electricity to the entire population, as well as improving the existing electrical services, fostering the transition from fossil fuels to alternative renewable alternatives, and mitigating climate change [17]. Since 2020, through decrees, this municipality, and also Cochabamba since 2017, has provided economic incentives for buildings that adopt environmental sustainability measures that reduce contamination, certifying their constructions as eco-sustainable [18].

2.3 Brazil

In Brazil, the NBR 15220 Standard [19], which is not regulatory in nature, focuses on the thermal comfort of homes, proposing design recommendations considering the bioclimatic zone. NBR 16401-2 from 2008, regulates the thermal comfort for air-conditioning installations and is currently being updated following the ASHRAE 55-2020 Standard, to incorporate the adaptive comfort model [20].

At a regulatory level, NBR 15575 establishes a minimum performance level that new buildings must comply with [21]. This is a comprehensive standard that looks to reach a minimum performance level for each system on the site, with requirements to guarantee habitability (water tightness, thermal, acoustic, and light performance, health, hygiene, and air quality, operation and accessibility, comfort), safety, and sustainability. The thermal performance can be obtained either through a simplified procedure or through computer simulation. The simplified method established minimum requirements for thermal transmittance, thermal capacity, and radiation absorption.

The new version of NBR 15575, 2021, incorporates a maximum surface for the transparent envelope and allows evaluating buildings under two scenarios: with and without natural ventilation. The performance of buildings with natural ventilation is determined based on occupation hour percentage indicators within an operating temperature range (PHFT), and annual maximum and minimum temperatures. The operation temperature range considered varies with the local climate, with three intervals being possible: from 18 to 26°C, up to 28°C, and up to 30°C.

Brazil has also incorporated the PBE Building Label, which assesses buildings based on primary energy consumption [22]. The classification runs from "A" (most efficient) to "E" (least efficient), comparing the real building consumption with the same building under a reference condition. Labels can be obtained for commercial, service, and public buildings (INI-C), and for residential buildings (INI-R). Currently, this is only mandatory for public buildings. The energy consumption calculation is linked to the procedures defined in NBR 15575.

2.4 Chile

The objectives of the Chilean Energy Policy for 2050 include improving the energy performance of buildings, which enables achieving suitable comfort levels, maximizing efficiency, and moving toward "net-zero energy" buildings [23]. In this vein, the Energy Ministry [24] proposed that housing reduces its thermal demand by 30% before 2026. One of the strategies to reach these goals is the Housing Energy Rating (CEV, in Spanish) [25], which through a voluntary tool, rates energy efficiency with labels from "A+" to "G". The "E" label represents the minimum performance demanded by the mandatory thermal regulation [26], which, since 2000, defines insulation standards for housing envelopes considering the climatic location. Apart from evaluating the energy consumption and demand, the PBTD tool of the CEV system allows evaluating the hours per year that the indoor temperature would be above or below the comfort range.

In addition, some other voluntary certification schemes define comfort standards for residential and non-residential buildings. The Sustainable Housing Certification (CVS, in Spanish) [27] defines thermal comfort standards, where it is expected that free-running dwellings manage to stay for a minimum percentage of the year within the adaptive comfort range, promoting passive design strategies. Similarly, the Sustainable Building Certification (CES, in Spanish) [28] defines comfort standards for non-residential buildings, where thermal comfort is based on ASHRAE 55. The Terms of Reference in Energy Efficiency, TDRe in Spanish, of the Ministry of Public Works [29] establish minimum standards that public buildings must comply with in all the environmental comfort dimensions. All these systems promote passive strategies, applying the adaptive thermal comfort model, and defining minimum standards for daylighting and natural ventilation.

Some cities in southern Chile have Environmental Decontamination Plans (PDAs, in Spanish) which incorporate mandatory standards for new homes in terms of thermal insulation, airtightness, ventilation, and the control of solar gains [30].

2.5 Colombia

The Long-Term Climate Strategy of Colombia, E2050 [31] implements the Paris Agreement, setting the goal of carbon neutrality by 2050, and a reduction of 51% of the GHG emissions by 2030. In this vein, the Net-Zero Carbon Buildings Roadmap [32] establishes short-, mid-, and long-term actions for the construction sector, including life cycle and energy efficiency analysis, among others. Decree 1285 [33], and its mandatory Resolution 0549 [34] regulate parameters for sustainable construction and establish guidelines for saving water and energy in buildings. The energy-saving percentages that must be met consider the type of building and the climate zone, varying between 15 and 45%. Comfort is not directly assessed, but some passive and active strategies linked to energy consumption are proposed [35].

At a regulation level, Retilap 2017 [36] establishes the requirements and measurements that lighting systems must comply with, with values required by area and activity, adapted from the ISO 8995 Standard. There are also resolutions associated with acoustics, mainly for noise control and exposure levels [37].

Although there are Colombian Technical Standards (NTC, in Spanish) associated with comfort, these are voluntary and usually are identical copies of international standards. NTC 5316 [38] is an identical translation of ASHRAE 55:2004, NTC 5183 [39] copies ANSI/ASHRAE 62:2001, while NTC 4595 [40] on educational buildings addresses the four parameters of environmental comfort.

At a public policy level, best practices are promoted in the life cycle of construction activities for the different regions using local technical criteria [41]. For this, sustainable construction guidelines and codes are being generated with more detailed and context-specific recommendations [42]. Colombia does not have its own certification system, but the LEED, EDGE, and CASA Colombia certifications are implemented. The domestic roadmap for net-zero carbon buildings promotes voluntary standards, verified by a third party, as a tool to mobilize the market.

2.6 Costa Rica

In Costa Rica, the entity in charge of setting building construction, design, and planning standards is the Institute of Housing and Urban Planning (INVU, in Spanish), through Building Regulations [43]. The latest version of the regulations (2018) mentions temperature as a thermal comfort parameter on three occasions, specifically, article 265 of the section on Health Service Buildings mentions that natural ventilation must ensure air circulation and maintain a temperature between 18 and 24°C. Article 270 of the same section adds that all the air in the rooms must be renewed every hour.

The VII National Energy Plan 2015–2030 [44] outlined, within its specific goals, improving the energy efficiency of buildings (objective 1.2.5), as well as promoting the use and making purchases of efficient equipment, household appliances, water heaters, and lights (objectives 1.2.1 to 1.2.4) more accessible. To date, some progress has been made, such as Directive N° 050-MINAE 2019 [45], which includes 9 sustainability criteria that every public building must comply with. However, the strategies to achieve each one of the criteria do not have metrics that allow monitoring progress.

The private sector has promoted the international LEED and EDGE certifications, among others, while banking entities have opened specific lines of credit for buildings that incorporate sustainability criteria.

The RESET—Requisitos para Edificaciones Sostenibles en el Trópico (Requirements for Sustainable Buildings in the Tropics)—certification was created, which later became the voluntary standard, INTE C170:2020 of INTECO [46]. Criteria 11 of the section on Spatial Well-being and Quality of this Standard refers to comfort, indicating that this is determined considering the activity and clothing of the users. As a reference value to comply with, it indicates that the tolerance limit to temperature and relative humidity for people in the tropics are 28°C and 80%, respectively. This means that all buildings whose thermal conditions are lower than 28°C and 80% (WBT 25.3°C) would comply with the criteria, without indicating the lower tolerance limit.

2.7 Ecuador

As of 2006, Ecuador launched a series of policies, projects, and programs to promote energy efficiency in different economic sectors [47–49]. In 2007, 11 Standards were prepared to foster efficient construction and energy management, along with 23 Technical Requirements on energy efficiency, where the NTE INEN 2506 Energy Efficiency in Buildings stands out [50]. In 2011, a chapter was included in the Ecuadorian Building Standard (NEC, in Spanish), which addresses criteria of thermal and acoustic comfort, as well as ventilation, air quality, and lighting requirements [51].

The National EE Plan 2016–2035 (PLANEE) has concrete goals in the buildings' framework so that Ecuador complies with international initiatives focused on "guaranteeing access to affordable, secure, sustainable, and modern energy" (SDG7), and "doubling the global index of energy efficiency improvements" (SE4ALL) [52]. One of the goals by 2035 is that residential, commercial, and public sector energy consumption is reduced by at least 88.8 Mbep, thanks to the energy efficiency measures implemented.

In 2018, a new regulation applicable to buildings was generated, where the section on EE of NEC-HS includes definitions of Thermal Comfort and Well-being [51], but requirements for indoor conditions are not established. However, in the NEC-HS on Air-conditioning, design humidity and temperatures are established in line with the climate (warm climate temperatures between 23 and 25°C, and RH of 45 to 60%; cold climate temperatures between 20 and 23°C and RH of 40–50%). It promotes natural ventilation for air renewal, establishing minimum flows, mainly based on the ASHRAE 62.1 and ASHRAE 62.2 Standards. For lighting, it establishes minimum values between 50 and 300 lux depending on use, with energy efficiency values of its installation of between 6 and 12 W/m^2.

In 2019, the Organic Energy Efficiency Law [53] was published, a goal outlined in PLANEE 2016–2035, which indicates in Article 17 that there must be a rational use of energy, promoting saving energy without reducing comfort and production.

2.8 Mexico

Mexico is one of the countries in Latin America and the Caribbean that has developed most in energy efficiency-related issues [1, 2], through a broad variety of programs and actions, such as the Energy Efficiency Standardization Program, the Energy Saving Program in the Federal Public Administration, the Green Mortgage Program, and the Sustainable Improvement Program for Existing Housing, among others.

Standardization in energy efficiency has been the most successful cost-benefit public policy in Mexico and has consisted of developing technical specifications that seek to limit energy consumption in equipment and systems, as well as buildings. The issuing of the Official Mexican Standards on Energy Efficiency (NOM-ENER) began in 1995, and to date there are 33 NOM-ENERs, entailing a reduction of 45.9% in residential energy intensity between 1995 and 2015 [54, 55]. In addition, the standardization program has been accompanied by the creation of conformity assessment processes run by laboratories, certification entities, and verification units accredited by the Mexican Accreditation Entity (EMA, in Spanish). NOM-2008-ENER-2021 (energy efficiency in buildings, non-residential building envelope) and NOM-020-ENER-2021 (energy efficiency in buildings, habitational use building envelope) stand out, which it is deemed can entail an improvement compared to the indoor environmental conditions, but that do not set requirements in this regard [56].

In 2019, the NMX-C-7730-ONNCCE-2018 Mexican Standard on "Ergonomics of the thermal environment—analytic determination and interpretation of thermal comfort through the calculation of the VME and PEI indexes and local thermal climate criteria" came into force, an adoption that is identical to ISO 7730:2005 [57]. In 2020, the NMX-577-ONNCCE-2020 Standard was developed, which is currently undergoing consultation. This establishes the parameters, values, documentation, and methodologies to evaluate the indoor environment quality expected of a building, from the design characteristics described in the executive project, to procure occupant comfort and health. Likewise, it allows evaluation of the energy performance of systems that contribute to reaching indoor environmental comfort, to limit energy consumption [58].

Mexico is the only Latin American country that does not have a domestic construction regulation, as each municipality has attributions to issue its own [59]. However, in the state or municipal regulations, no requirements regarding the environmental conditions of spaces are seen.

2.9 Peru

Since 2014, the National Building Regulation (RNE, in Spanish)—Building License includes the management document, EM. 110 Thermal and Light Comfort with Energy Efficiency, which is the first national standard that seeks to improve, from the architectural design, the thermal and light comfort conditions through the energy efficiency of the buildings [60]. The standard establishes and characterizes zones of the Republic of Peru by bioclimatic criteria for construction, and determines technical guidelines and parameters for thermal and light comfort for each zone defined. It is applied for new habitable buildings, along with extensions, remodeling, repair, and/or conditioning. Apart from sources such as ASHRAE or ISO, this standard uses as a reference, the Argentinean, Chilean, and Spanish regulations related to comfort and energy efficiency. With regard to thermal comfort, maximum thermal transmittance limits (U) are established for the roof, wall, and floor, the absence of condensation, and carpentry standards for window permeability. For light comfort, they determine minimum window areas following the calculation method that the standard determines, as well as indicating minimum characteristics that must be obtained from the manufacturer on aspects such as density, thermal conductivity, and solar factor, among others.

Law 3381–2018 CR also exists. This strengthens the attention paid to frosts through improved housing [61]. It rules that the Ministry of Housing, Construction, and Sanitation, through the National Rural Housing Program, must implement improvements under bioclimatic design strategies that improve thermal comfort under extreme weather situations, such as frosts. This law outlines a government policy that has mainly focused on financing rural housing to improve thermal comfort.

2.10 Uruguay

At a national level, Uruguay has developed the Energy Policy 2005–2030 and the National Energy Efficiency Plan 2015–2024 [62, 63], where actions are laid out to move toward the reduction of energy consumption by 2025. Among these actions, the development of a set of technical standards to evaluate the energy performance of buildings stands out. Its goal is to contribute to the development of a building energy efficiency certification program. These standards are mainly adoptions of the international ISO Standards and are voluntary in nature.

As for the residential sector, currently, there is no domestic regulatory framework, though there are uneven requirements between the administrative units and without a direct relationship with climatic zoning [64]. These requirements focus on ventilation and lighting conditions (minimum areas of openings) based on principles of hygiene. Although there are regulations in some administrative units that include sustainability approaches of buildings, energy efficiency, and GHG reduction, in these cases energy efficiency is addressed by the reduction of the energy demand for thermal conditions, establishing minimum energy quality requirements for the envelope (thermal transmittance and solar factors), focusing exclusively on new housing.

A National Building Regulation—Housing Hygiene is under development, which establishes minimum requirements to improve the thermal quality of the envelope, without defining a performance baseline with given comfort levels, or criteria by climatic region or type of building [64]. On the other hand, public housing policies have had demands on the energy quality of the envelope in specific programs since 1999, and since 2011 for the construction of housing with non-traditional construction systems [65].

Although there are no local certifications, the Housing Environmental Sustainability Model (Suamvi, in Spanish), developed at a regional level by the Intendance of Montevideo, stands out. Currently, there are aspirations for the creation of a Suamvi Seal [66]. This model integrates the dimensions of air quality, acoustic comfort, energy quality of the envelope, and the incorporation of renewable energies.

3 Discussion

All the countries revised in this chapter have energy policies or similar initiatives that establish short-, mid-, and long-term actions to reduce greenhouse gas emissions, motivated by the Paris Agreement. In 2020, 136 countries worldwide included actions for addressing building-related emissions or improving energy efficiency [3]. Among them, some of the countries reviewed in this chapter, such as Argentina, Chile, Colombia, Mexico, and Uruguay, are found. One of the main actions is the development of building energy codes, where Latin American countries are quite behind when compared to the countries of the Global North. Among the countries that have building energy codes, these are voluntary, or mandatory for part of the sector (usually the residential sector). This implies a great difference from the countries of the Global North, where building energy codes are mandatory for the entire sector. These codes focus on improving the energy performance of buildings, aiming at reducing energy consumption. In general, occupant comfort goals are not explicitly mentioned, but it is assumed that comfort would be a consequence of improving performance.

In energy label matters, all the countries reviewed have an equipment labeling system, but just Argentina, Brazil, and Chile have energy labeling for buildings, and

Mexico has one for building envelopes. The Province of Santa Fe, in Argentina, which has implemented mandatory labeling for housing, and Brazil, where labeling is mandatory for public buildings, stand out. In other countries, this has been implemented as voluntary, looking to make this a mandatory policy in the future.

For building sustainability certification, the LEED international certification has had a great impact on the countries reviewed. In addition, the EDGE certification, exclusively developed by the World Bank for developing countries, has become quite popular in the region. Only some countries have developed their own certifications, such as the Procel EDIFICA in Brazil, or the CES certification for public use buildings, and CVS for housing in Chile. In addition, the CASA Colombia certification is a local development based on international standards. All of these are voluntary systems.

The regulations for comfort are much scarcer and, in general, replicate international standards, such as the ASHRAE or ISO, to address procedures and standards on thermal comfort, acoustics, air quality, and light comfort. In some isolated cases, comfort standards are included in the building energy codes, such as the Brazilian standard NBR 15575, which establishes thermal comfort requirements to evaluate the thermal performance of buildings under natural ventilation conditions [21]. This initiative is very important, as it promotes the passive behavior of buildings using natural ventilation, alongside adaptive comfort ranges.

In other countries, the ambiguity of thermal comfort regulations is questioned, such as the lack of reference to studies that are based on comfort limit values. These issues have not been a priority in most of the countries reviewed, mainly as buildings traditionally do not use any heating or cooling system, thus consuming very little energy. It is important to consider that Latin American countries have pretty benign or warm template climates, where there is little need for air-conditioning, or there is a high adaptation of the occupants. For example, a study in the city of Cuenca, Ecuador, determined that 65% of the users stated that their home is comfortable, and just 2% said that they use a type of heating, with outdoor temperatures under 18°C most of the year [67]. This is similar to several large cities in the Andean region.

4 Conclusions

This chapter reviews current policy instruments that are relevant in terms of energy and environmental comfort in buildings in ten countries of Latin America. From the review, it can be concluded that there are important differences between countries. Some of them have a strategy articulated by energy policies with short-, mid-, and long-term goals, that include a series of standards and initiatives that would allow reaching the goals as long as their implementation is effective and efficient. However, others are at a fledgling stage.

Some countries have building energy codes that lay down thermal performance requirements, where comfort would be a result of the thermal improvements, but very few define specific requirements for comfort, and certainly not mandatory ones.

Recent economic, environmental, and social changes have increased occupant expectations for comfort, increasing the need to regulate this issue considering the knowledge generated at a local level, including the identification of benchmarks and gaps.

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References

1. World Bank Group (2019) Regulatory indicators for sustainable energy. https://rise.esmap.org/
2. World Bank Group (2020) RISE 2020 regulatory indicators for sustainable energy sustaining the momentum. Washington. www.worldbank.org
3. United Nations Environment Programme (2021) Annual report 2021. Nairobi, Kenya. https://www.unep.org/resources/annual-report-2021
4. Fernández R (2019) Transición Energética 2050. Hacia una visión compartida de la transición energética argentina al 2050. Buenos Aires, Argentina
5. Argentino Instituto, de Normalización y Certificación (1996) IRAM 11605: Acondicionamiento térmico de edificios: condiciones de habitabilidad en edificios: valores máximos de transmitancia térmica en cerramientos opacos. Buenos Aires, Argentina
6. Instituto Argentino de Normalización y Certificación (2001) IRAM 11604: Aislamiento térmico de edifícios: verificación de sus condiciones higrotérmicas. Ahorro de energía en calefacción: coeficiente volumétrico G de pérdidas de calor: cálculos y valores límites. Buenos Aires, Argentina
7. Gobierno de Argentina (2022) Etiquetado de viviendas. https://etiquetadoviviendas.mecon.gob.ar/
8. Instituto Argentino de Normalización y Certificación (2017) IRAM 11.900: Etiqueta de Eficiencia Energética de calefacción para edificios. Buenos Aires, Argentina
9. Kuchen E, Kozak D (2020) Transición energética argentina. El nuevo estándar de eficiencia energética en la evaluación de la vivienda social. Caso de estudio: Barrio Papa Francisco. Revista Hábitat Sustentable 10:44–55. https://doi.org/10.22320/07190700.2020.10.01.04, http://revistas.ubiobio.cl/index.php/RHS/article/view/4015
10. Briano JI, Báez MJ, Moya Morales R (2016) Estado de la eficiencia energética en Bolivia: Identificación de oportunidades. Dirección de Análisis y Estrategia de Energía (DAEE). https://scioteca.caf.com/bitstream/handle/123456789/954/Reporte%20EE%20en%20Bolivia.pdf?sequence=1&isAllowed=y
11. de Hidrocarburos Ministerio, y Energía (2008) DS N°29466: Programa Nacional de Eficiencia Energética. La Paz, Bolivia
12. Boliviano Instituto, de Normalización y Calidad-IBNORCA (2021) NB 87005:2021 Lamparas Led-Especificaciones y Etiquetado. La Paz, Bolivia
13. Boliviano Instituto, de Normalización y Calidad-IBNORCA (2021) NB 87007:2021 Aparatos domésticos de refrigeración-Características y métodos de ensayo. La Paz, Bolivia
14. Boliviano Instituto, de Normalización y Calidad-IBNORCA (2021) NB 87003:2021 Refrigeradores, congeladores de uso doméstico-Clasificación y Etiquetado. La Paz, Bolivia
15. Boliviano Instituto, de Normalización y Calidad-IBNORCA (2021) NB/ISO 9288:2010 Aislamiento térmico-Transmisión de calor por radiación-Magnitudes físicas y definiciones. La Paz, Bolivia
16. Ministerio de Obras Públicas Servicios y Vivienda (2017) Guía Boliviana para Diseño y Presentación de Proyectos. La Paz, Bolivia. www.oopp.gob.bo

17. Gobernación del Municipio de Santa Cruz (2019) Ley departamental de energia N°177. Santa Cruz, Bolivia. https://gacetaoficial.santacruz.gob.bo/verpdf/ley-departamental-177
18. Consejo Municipal de Cochabamba (2017) Ley Municipal de Incentivo a las Edificaciones Sustentables. Ecológicas y Amigables con el Medio Ambiente, Cochabamba, Bolivia
19. Associação Brasileira de Normas Técnicas (2008a) NBR 15220: Desempenho térmico de edificações. Brazil
20. Associação Brasileira de Normas Técnicas (2008b) NBR 16401-2: Instalações de arcondicionado–Sistemas centrai Parte: Parâmetros de conforto térmico. Brazil
21. Associação Brasileira de Normas Técnicas (2013) NBR 15575: Edificações habitacionais: desempenho. Brazil
22. PBE Edifica (2020) O que é a etiqueta pbe edifica? http://www.pbeedifica.com.br/conhecendo-pbe-edifica
23. Ministerio de Energía (2022a) Transición Energética de Chile: Política Energética Nacional. Chile. https://www.energia.gob.cl/sites/default/files/energia_2050_-_politica_energetica_de_chile.pdf
24. Ministerio de Energía (2022b) Plan Nacional de Eficiencia Energética 2022-2026. Chile. https://energia.gob.cl/documentos/plan-nacional-de-eficiencia-energetica-2022-2026
25. Ministerio de Vivienda y Urbanismo (2019) Manual de Procedimientos de Calificación Energética de Viviendas en Chile, 2nd edn. Chile
26. Ministerio de Vivienda y Urbanismo (2022) Ordenanza General de Urbanismo y Construcción. Chile
27. Ministerio de Vivienda y Urbanismo (2021) Manual de Aplicación de la Certificación Vivienda Sustentable. Chile. https://cvschile.cl/downloads/Manual%20CVS%202021.pdf
28. Instituto de la Construcción and Idiem (2014) Manual de Evaluación y Calificación. Sistema Nacional de Certificación de Calidad Ambiental y Eficiencia Energética para Edificios de Uso Público CES. Chile
29. CITEC-UBB (2014) Términos de Referencia Estandarizados con parâmetros de Eficiencia Energética y Confort Ambiental. Chile
30. Ministerio del Medio Ambiente (2022) PPDA—Planes de prevención y/o descontaminación atmosférica. Chile. https://ppda.mma.gob.cl/
31. Gobierno de Colombia (2021) Estrategia climática de largo plazo de Colombia E2050 para cumplir con el Acuerdo de París. Colombia. https://e2050colombia.com/documentos/
32. Consejo Colombiano de Construcción Sostenible (2022) Hoja de ruta nacional de edificaciones neto cero carbono. Colombia
33. Ministerio de Vivienda Ciudad y Territorio (2015a) Decreto 1285 de 2015. Colombia. https://minvivienda.gov.co/normativa/decreto-1285-2015
34. Ministerio de Vivienda Ciudad y Territorio (2015b) Resolución 549 de 2015–Lineamientos y Guía de Construcción Sostenible. Colombia. https://ismd.com.co/wp-content/uploads/2017/03/Resoluci%C3%B3n-549-de-2015.pdf
35. Ministerio de Vivienda Ciudad y Territorio (2015c) ANEXO No. 1–Resolución 549 de 2015: Guía de construcción sostenible para el ahorro de agua y energía en edificaciones. Colombia
36. Ministerio de Minas y Energía (2017) Anexo General: Reglamento Técnico de Iluminación y Alumbrado Público. RETILAP. Colombia. https://www.minenergia.gov.co/documents/3896/080817_py_modifica_cap_4_retilap_030817.pdf
37. Ministerio de Ambiente, Vivienda y Desarrollo Territorial (2006) Resolución Número 627: Por la cual se establece la norma nacional de emisión de ruido y ruido ambiental. Colombia
38. Instituto Colombiano de Normas Técnicas y Certificación (2004) NTC 5316: Condiciones Ambientales Térmicas de Inmuebles para Personas. Colombia
39. Instituto Colombiano de Normas Técnicas y Certificación (2003) NTC 5183: Ventilación para una calidad aceptable del aire en espacios interiores. Colombia
40. Instituto Colombiano de Normas Técnicas y Certificación (2020) NTC 4595: Planeamiento y diseño de instalaciones y ambientes escolares. Colombia

41. Área Metropolitana del Valle de Aburrá, Camacol Antioquia (2018) Implementación de la Política Pública de Construcción Sostenible. https://www.metropol.gov.co/SiteAssets/Paginas/Noticias/conoce-mas-sobre-la-politica-publica-de-construccion-sostenible-del-valle-de-aburra/Implementacio%CC%81n_Poli%CC%81tica_Pu%CC%81blica_Construccio%CC%81n_Sostenible_Valle_de_Aburra%CC%81_2019.pdf
42. Área Metropolitana del Valle de Aburrá (2019) Política publica y guías de construcción sostenible. https://www.metropol.gov.co/noticias/presentamos-la-pol%C3%ADtica-p%C3%BAblica-de-construcci%C3%B3n-sostenible-para-la-regi%C3%B3n-y-entrega-cinco-gu%C3%ADas-metropolitanas
43. Instituto Nacional de Vivienda y Urbanismo (2018) Reglamento de Construcciones. San José, Costa Rica. www.invu.go.cr
44. de Ambiente Ministerio, y Energia MINAE (2015) VII Plan Nacional de Energía 2015–2030. Costa Rica, San Jose
45. de Ambiente Ministerio, y Energía MINAE (2019) Directriz N°050-MINAE Construcción Sostenible en el Sector Público. San José, Costa Rica
46. Instituto de Normas Técnicas de Costa Rica (2020) INTE C170:2020 RESET: Requisitos para Edificaciones Sostenibles en el Trópico. San José, Costa Rica
47. Secretaría Nacional de Planificación y Desarrollo (2009) Plan Nacional para el Buen Vivir 2009–2013. Quito, Ecuador. https://www.planificacion.gob.ec/plan-nacional-para-el-buen-vivir-2009-2013/
48. Secretaría Nacional de Planificación y Desarrollo (2013) Plan Nacional para el Buen Vivir 2013–2017. Quito, Ecuador. https://observatorioplanificacion.cepal.org/sites/default/files/plan/files/Ecuador%20Plan%20Nacional%20del%20Buen%20Vivir.pdf
49. Ministerio de Electricidad y Energía Renovable (2018) Plan Nacional de Energía Renovable y Eficiencia Energética del Ecuador. https://www.undp.org/es/ecuador/publications/plan-nacional-de-energ%C3%ADa-renovable-y-eficiencia-energ%C3%A9tica-del-ecuador-mee
50. Instituto Ecuatoriano de Normalización (2009) NTE INEN 2506: Eficiencia Energética En Edificaciones. Requisitos, Quito, Ecuador
51. Ministerio de Desarrollo Urbano y Vivienda (2018) Capítulos de la NEC (Norma Ecuatoriana de la Construcción). https://www.habitatyvivienda.gob.ec/documentos-normativos-nec-norma-ecuatoriana-de-la-construccion/
52. Asamblea Nacional República de Ecuador (2019a) SUPLEMENTO Año II–Registro Oficial N° 449: Ley Orgánica de Edificencia Energética. www.registroficial.gob.ec
53. Asamblea Nacional República de Ecuador (2019b) Ley Orgánica del Eficiencia Energética. http://extwprlegs1.fao.org/docs/pdf/ecu196087.pdf
54. CEPAL (2018) Informe nacional de monitoreo de la eficiencia energética de México. https://www.cepal.org/es/publicaciones/43612-informe-nacional-monitoreo-la-eficiencia-energetica-mexico-2018
55. Instituto Nacional de Eficiencia Energética y Energías Renovables (2016) Informe Nacional de Monitoreo de la Eficiencia Energética. Mexico
56. Comisión Nacional para el Uso Eficiente de la Energía (2013) Normas oficiales mexicanas en eficiencia energética. https://www.gob.mx/conuee/acciones-y-programas/normas-oficiales-mexicanas-en-eficiencia-energetica-vigentes
57. Diario Oficial de la Federación (2019) Declaratoria de vigencia de la Norma Mexicana NMX-C-7730-ONNCCE-2018. https://dof.gob.mx/nota_detalle.php?codigo=5564192&fecha=26/06/2019#gsc.tab=0
58. Diario Oficial de la Federación (2021) Aviso de consulta pública del proyecto de Norma Mexicana PROY-NMX-C-577-ONNCCE-2020. https://www.dof.gob.mx/nota_detalle.php?codigo=5630816&fecha=24/09/2021#gsc.tab=0
59. Cámara de Diputados del H Congreso de la Union (2021) Constitución política de los Estados Unidos Mexicanos. Mexico. https://www.diputados.gob.mx/LeyesBiblio/pdf/CPEUM.pdf
60. Ministerio de Vivienda Construcción y Saneamiento (2014) Documento de gestión EM.110 Confort Térmico y Lumínico Con Eficiencia Energética. Reglamento Nacional de Edificaciones. Lima, Peru

61. de Vivienda Comisión, y Construcción (2018) Ley 3381–2018/CR: Ley que fortalece la atención ante heladas y friaje a través de viviendas mejoradas y atención médica. Lima, Peru
62. Ministerio de Industria Energía y Minería (2015) Plan Nacional de Eficiencia Energética 2015-2024. Uruguay. http://www.eficienciaenergetica.gub.uy/documents/20182/22654/Plan_Nacional_de_Eficiencia_Energetica.pdf/2e21a8c6-3492-4c7d-b6ba-33b138632a85
63. Ministerio de Industria Energía y Minería (2005) Política Energética 2005–2030. Montevideo, Uruguay. http://www.eficienciaenergetica.gub.uy/politica-energetica
64. Picción A, Sierra P, et al (2021) AD@PTA–Aproximaciones disciplinares para la adaptación de ciudades y edificaciones al cambio y variabilidad climática. Facultad de Arquitectura, Diseño y Urbanismo. Universidad de la República, Montevideo, Uruguay. https://www.gub.uy/ministerio-ambiente/sites/ministerio-ambiente/files/2021-10/ADAPTA_Doc%20S%C3%ADntesis%206M_compressed.pdf
65. Ministerio de Vivienda y Ordenamiento Territorial (2011) Bases del sistema de otorgamiento del Documento de Aptitud Técnica (DAT). https://www.gub.uy/ministerio-vivienda-ordenamiento-territorial/comunicacion/publicaciones/bases-del-sistema-otorgamiento-del-documento-aptitud-tecnica-dat
66. Intendencia de Montevideo (2020) Suamvi: Sustentabilidad Ambiental de la Vivienda. https://montevideo.gub.uy/sites/default/files/biblioteca/modelosuamvi1ra.edicion1.pdf
67. Baquero M, Quesada F (2016) Eficiencia energética en el sector residencial de la ciudad de cuenca, ecuador. MASKANA 7:147–165. https://doi.org/10.18537/MSKN.07.02.11

Multicriteria Design: Optimizing Thermal, Acoustic, and Visual Comfort and Indoor Air Quality in Classrooms

Muriel Diaz, Alex Gonzalez-Caceres, and Shady Attia

Abstract Indoor Environmental Quality (IEQ) is a crucial for ensuring comfortable and healthy indoor spaces, and it is influenced by four primary factors: thermal comfort, acoustic comfort, visual comfort, and air quality. These aspects have a combined influence on the overall perception of comfort, and therefore, need to be assessed with a holistic approach. This chapter presents design strategies that would generate the indoor environmental conditions needed to ensure IEQ in school classrooms in the Global South. First, the design strategies are identified and classified for each aspect of IEQ based on a literature review. Then they are organized, and conflicting design strategies are identified. Finally, a design workflow for the incorporation of passive design strategies in school classrooms is presented.

Keywords Indoor environmental quality · Interactions · Adaptive comfort · Indoor air quality · Acoustic comfort · Visual comfort · School classroom

M. Diaz (✉)
Department of Architectural Design and Theory, Faculty of Architecture, Construction and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: madiaz@uliege.be

A. Gonzalez-Caceres
Department of Architecture and Civil Engineering, Chalmers University of Technology, Göteborg, Sweden
e-mail: alex.gonzalez@chalmers.se

M. Diaz · S. Attia
Sustainable Building Design Lab, Department UEE, Faculty of Applied Sciences, Université de Liège, Liège, Belgium
e-mail: shady.attia@uliege.be

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1 Introduction

Indoor environmental quality is a broad concept that includes thermal, visual, and acoustic comfort as well as indoor air quality. The REVA guidebook [1] proposes that the perception of comfort is dependent on the building's use, outdoor conditions, building design, and the services in place. Recent research has also shown that the personal characteristics of occupants, as well as previous experiences, expectations, and interaction with the building, play a role in the perception of comfort [2].

The quality of indoor environment has well-known impacts on occupants' health and well-being. This is especially relevant in school classrooms where children spend between 799 (elementary school) and 913 hours per year (high school) in OECD countries [3]. The exposure to indoor environment at school as well as their experience at home will shape their comfort expectations for the future.

On the other hand, buildings need to avoid overreliance on energy-consuming strategies to ensure the quality of indoor environment [4]. This is especially true in low-income countries or in buildings serving vulnerable populations. Therefore, there is a need for low-tech solutions that focus on indoor environment quality and energy efficiency. School buildings also have the constraints of low maintenance and operational budgets, and since schools are needed in remote, sometimes inaccessible areas, designers need to consider these constraints.

Passive design proposes strategies that will provide a healthy environment with little to no energy demand. There are many passive design strategies adapted to cool or hot spaces, some to improve light conditions through the use of daylight, some to provide air renewals, and a few on acoustic comfort.

However, there is a lack of knowledge on the impact of these passive design strategies on overall comfort, as well as the effect these strategies have on thermal, visual, and acoustic comfort and indoor air quality. Therefore, this review aims at developing a classification scheme with a holistic multicriteria perspective.

2 Methodology

The research methodology involves two main phases. The first phase is a systematic review of indexed articles and books that present passive design strategies related to thermal, acoustic, and visual comfort along with air quality in educational settings. These publications will be reviewed to retrieve the design strategies used in school classroom design that have a direct impact on IEQ. The second phase will be the classification and cross-examination of the strategies identified to find co-occurrences and how these would interact.

The literature review was limited to the last 20 years and considered thermal, acoustic, and visual comfort, or indoor air quality, related to design strategies applicable to classrooms. The search only considered classrooms as these have specific conditions related to size, occupancy, and period of use, that differentiate them from

Table 1 Keywords used

	Topic	English keyword
1	School classrooms	School building; educational institution; classroom
2	Passive design strategies	Passive design; passive strategy; bioclimatic design; bioclimatic architecture; bioclimatic construction; passive measures; passive system; Architectonic design
3	Indoor environmental quality	Indoor environmental quality; IEQ; environmental ergonomics
4	Thermal comfort	Thermal comfort; thermal sensation; adaptative comfort
5	Acoustic comfort	Acoustic comfort; acoustic design
6	Visual comfort	Visual comfort; light comfort; lighting; natural light
7	Indoor air quality	Indoor air quality; IAQ; outdoor air quality

other buildings. The Scopus database was used to conduct the search. The keywords used are listed in Table 1. The search was defined to include at least one keyword referring to topics 1 and 2, and at least one keyword for topics 3–7.

The selection of papers was made in two steps. First, duplicates were consolidated in the database, then the title and abstract were read to confirm the relevance of the paper for the objective of the review. Papers that were only changing values of the design parameters but not proposing passive design strategies, those that did not consider passive design strategies, were too broad or narrow in scope, or were misclassified by the search engine, were excluded from the review.

In the following step, relevant papers were read and analyzed to extract and identify passive or low-energy consuming design guidelines and architectural solutions, that will provide optimal indoor environmental conditions in classrooms.

3 Results

The review made on the Scopus platform identified 87 documents published between 2012 and 2022. The availability of the authors of 84 articles was established, from all available papers, where 4 were excluded because they were not related to the general research topic; 20 did not study school-level buildings, 4 presented a refurbishment, and 38 presented a case study without passive design strategies. After this step, 15 papers were selected and summarized in Table 2.

All 15 of the reviewed articles included design strategies to improve daylighting and thermal comfort. However, only four of them addressed ventilation, and these primarily focused on heat removal rather than indoor air quality. Additionally, only one article considered acoustic comfort when evaluating the design of a Kinetic adaptive façade [5]. The results of the review are consistent with the idea that passive design aims at improving thermal comfort, while the relevance of the visual aspect in schools makes it relevant to also consider this as part of IEQ. A lack of strategies for indoor air quality and acoustic comfort is identified. This could be related to the predominant use of mechanical ventilation in North America, and the normative requirements for window-sizing in Europe. Acoustic comfort has been a specialist issue, where architects seek expert advice once the initial draft of the architecture is ready.

3.1 Multicriteria Design Recommendations for Comfortable Classrooms or How to Design a Comfortable Classroom

IEQ-related design strategies will have different consequences for each of the four aspects: acoustic, visual, and thermal comfort, as well as indoor air quality. Therefore, the strategies will be presented/classified by their position in the room.

3.1.1 Climate

Climate is of foremost relevance when designing low-tech and low-energy buildings. In the current climate emergency, future climate scenarios should be considered, as schools tend to have a long lifespan. Climate change will affect heating and cooling loads and could also have an impact on rainfall patterns and sky coverage during the year.

Topography, waterbodies, urban heat islands, and vegetation should also be considered as they will characterize a microclimate. This microclimate can also be used in the design to control and change the conditions around the building.

Heating and cooling loads are dependent on the local climate. Tools such as cooling degree days and heating degree days can be used as a first step to assess the climatic conditions but should be complemented with information on pluviometry, daily temperature changes, solar radiation, and sun paths. Humidity, pluviometry, and wind will also affect thermal comfort.

Outside noise is also considered part of the microclimate. Noise sources such as roads, airplane routes, and others should be identified as the building envelope's design needs to be adapted to them.

Wind direction and speed during the year will be especially relevant for design and the use of natural ventilation. Once again microclimate factors such as tall buildings, waterbodies, trees, and others that could affect wind direction and speed need to be considered.

The design incorporating daylighting should consider sky conditions and daylight hours at the location [6]. Tall buildings and other elements that could affect the

Table 2 Design strategies proposed in the identified studies

Ref.		Country	Climate	Classroom type	IEQ aspect(s)	Strategies
1	[6]	Iquique, Santiago and Coyhaique, Chile	BSk, Csa, Cfc	School classroom	Daylighting	–Light shelves –Light shelves and lower blinds –Upper blinds –Light shelf and skylight
2	[7]	Iquique, Santiago and Coyhaique, Chile	BSk, Csa, Cfc	School classroom	Daylighting, Thermal comfort	–Orientation –Infiltration –Glazing area per square meter –Type of glazing –Enhanced walls and roof insulation
3	[8]	Seoul, Korea	Dwa	School building	Daylighting	–Dynamic exterior blinds –Automated artificial lighting –Heat Exchanger (HE)
4	[9]	Taiwan	Cfa	School building	Natural ventilation, Daylight, Avoidance of solar heat gains	–Green roof –Exterior shades –Greenery outside windows –Operable windows and electric overhead fans –Enhanced walls and roof insulation
5	[10]	Tehran, Iran	Csa	School building	Thermal comfort	–Orientation –Wall and roof insulation –Night-time natural ventilation –All-day natural ventilation –Fins and overhangs –Thermal mass
6	[11]	Auckland, New Zealand	Cfb	School building	Energy consumption	–Area to volume ratio –Window area to building volume

(continued)

Table 2 (continued)

Ref.		Country	Climate	Classroom type	IEQ aspect(s)	Strategies
7	[12]	Tianjin, China	Dwa	School building	Heating and cooling demand, Thermal comfort, Daylight	–Orientation –Room depth –Corridor depth and configuration –Window-to-wall ratio –Glazing material –Shading types
8	[13]	Sharjah, UAE	BWh	School building	Thermal comfort, Ventilation	–Open and closed courtyard
9	[14]	Tehran, Iran	Csa	School classroom	Heating and cooling, Daylighting	–Overhang –Blinds –Light shelf
10	[15]	Madurai, India	Aw	University classroom	Thermal comfort, Ventilation	–Vertical and horizontal shading devices
11	[16]	Seoul, Korea	Dwa	School classroom	Daylighting	–Vertical and horizontal shading devices –Outdoor horizontal fins
12	[17]	Kuala Lumpur, Malaysia	Af	School building	Natural ventilation, Daylighting	–Ventilation blocks
13	[18]	Hebron, Palestine	Csa	School classroom	Thermal comfort	–Solar chimney –Solar wall –Underground duct
14	[5]	Ho Chi Minh City, Vietnam	Aw	School classroom	Acoustic comfort	–Kinetic adaptive façade
15	[19]	Biskra, Algeria	BWh	School classroom	Thermal comfort, Daylight	–Window-to- wall ratio –Glazing –Vertical and horizontal shading

availability of light should be considered. Visual comfort also includes views, which should be studied to provide, if possible, views of nature.

Once the climate and site are characterized, passive design strategies can be proposed. Here, an analysis per element is proposed in the classroom envelope setup. The aspects of each element that affect acoustic, visual, and thermal comfort as well as indoor air quality and their interactions are described.

3.1.2 Walls

Walls are the biggest part of the envelope in classrooms. From the inside, these are always visible to students and act as the background for the visual field. From the outside, they are the protective layer, that is in direct contact with the climate.

Wall Insulation

The building's envelope comprises walls, windows, doors, the floor, and the roof. The materials used in walls need to be adapted to the outdoor climate. Choosing proper insulation materials is of the utmost relevance. It is relevant to note that thermal insulation materials can also double as acoustic insulation materials. Each country has its own insulation requirements, but the general approach should be to lower the need for heating and cooling as this will lower operation and maintenance costs.

For acoustic insulation, the rationale is to identify noise sources and design the envelope so that each classroom has a similar level of outdoor noise insulation. Airborne sound insulation of the façade should be used as an indicator for outdoor-facing walls and airborne sound insulation between spaces for indoor-facing ones [20].

Air infiltration should also be considered. Infiltration is the uncontrollable movement of air through cracks and small holes in the envelope. It can also generate interstitial condensation in the walls.

Thermal Mass

Thermal mass can store thermal energy and can be used to lower temperature variation during the day or to store heat during the day. Combined with good ventilation that removes heat through night-time ventilation, this strategy can be used in hot climates. Thermal mass, because of its composition also provides airborne sound insulation.

Finishes

The color, materials, and reflectance will affect the perception of light. The reflectance of walls will affect the perception of glare inside the classroom [21]. It is recommended to use light colors to better distribute luminance by inter-reflection, and avoid high contrast between the window area and the wall.

Color, although not clear, has been linked with thermal perception [22] in experimental settings, where, warm colors make people feel warmer and cold colors colder. There is no clarity about the saturation needed to observe this, or if it would affect thermal perception in a classroom.

The materials used for finishes in classrooms will affect how the voice of the teacher is perceived. It is recommended to include absorbent panels on walls to improve the acoustic quality of the space [23] as a complement to ceiling acoustic absorption.

3.1.3 Windows

Climate will be the first parameter under study when designing windows in a classroom. Outdoor temperatures and wind direction, sky conditions, daytime hours, and pluviometry, should be known in detail for the location of the classroom.

Windows in classrooms are designed mainly to provide daylight as well as providing natural ventilation. In the Global South, most classrooms rely on natural ventilation to provide fresh air [24] to lower operational and maintenance costs. It is also relevant that these systems can work when electricity is scarce or not reliable, making the buildings resilient. The design of windows will also have an impact on thermal comfort and acoustic comfort which should be considered.

Window Orientation

The preferred position of the window in the literature is the façade that does not receive direct sunlight. In the case of the southern hemisphere, this is the south-facing façade. This preference is based on the idea that avoiding direct sunlight will diminish glare and patches of direct solar radiation on the body of the students which would affect their thermal perception. When considering this issue, it is relevant to study not only the orientation of the window, but also if reflective objects on the outside could redirect sunlight into the classroom and if there are obstructing elements that will diminish direct and indirect sunlight. The same principles apply when designing for natural ventilation. Most of the time, the orientation of the building is given beforehand, and the design of the building needs to respond to the constraints of a given site.

It is also relevant to consider that noise could enter the building through the windows. Therefore, windows facing noisy streets or courtyards should be avoided. In this case, one recommendation could be to separate ventilation from lighting.

As stated by Montazami et al. [25], outdoor noise can be detrimental to Indoor Air Quality, because the noise would be more disruptive for the teaching than poor air quality, skewing decision-making toward eliminating noise. When pondering Indoor Air Quality against thermal comfort, research shows that air quality will be neglected in favor of avoiding temperature loss [24].

Ventilation Patterns

Ventilation is the main strategy to provide good indoor air quality by removing contaminants produced inside the classroom. Natural ventilation is the preferred option as it is low-tech, does not require energy, and its maintenance is low. Depending on the characteristics of the climate, different strategies can be used. Ventilation will also remove heat if outdoor air is cooler than indoor air. If the temperature difference is above 2°C, air movement could provide a cooling effect.

Single-side ventilation is the most commonly used option in classrooms, although it is not the most effective strategy. It is reliant on wind pressures on the façade and the stack effect. Due to the high occupancy of classrooms, a more effective ventilation strategy should be preferred.

Cross-ventilation is when two or more windows on different walls are open. The difference in pressure between both sides of the building will cause the removal of indoor air. This strategy will work in narrow buildings, where the distance between windows is less than 5 times the height of the room and less than 15 m. This strategy is dependent on window size and location.

Stack or convective ventilation uses the stratification caused by the air temperature. As the air warms, it becomes less dense and rises. The rising air is removed and replaced by air entering at a lower temperature from outside. This strategy requires openings at the bottom and top of the building or roof operable windows. The main advantage of this strategy is that it is independent of wind speed, therefore, it can be used in climates with low wind velocity or when it is not possible to face prevailing winds.

Solar chimneys are another ventilation strategy comprising three fundamental parts: a solar energy collection area at the top of the chimney, the main ventilation shaft, and air intake and exhaust ducts. Heating the air with solar energy at the top of the chimney increases the temperature difference between the incoming and outgoing air, which in turn increases the velocity at which it moves within the chimney.

Window Size

Window geometry in classrooms is usually defined by the need to provide daylight. Windows should provide natural light, as uniformly as possible to the whole classroom during most of the time in use. Design strategies such as light shelves [14] and high windows could improve light distribution when used correctly.

When deciding the size of the window, glare probability should also be assessed as too much light can be just as detrimental as a lack thereof.

To counteract the possibility of glare, solar protection should be designed. Indoor curtains should not be an afterthought, and if possible, should be specified at the design stage. Indoor and outdoor blinds and louvers could also be designed when needed [15, 16, 19].

To ensure proper ventilation for the removal of indoor pollutants, the size of the operable windows should be considered. It is relevant to consider the orientation of the window and the type of opening as this will determine the efficiency of the system. As stated before, it is possible to uncouple ventilation from lighting if needed as noise from the outside can affect the learning process [26].

Window Materials

The design of windows should consider at least three main aspects: frame, pane, and opening. The frame material and design will affect the thermal conductivity of the window, noise transmission to the frame, air permeability, and the area that is transparent. Frame design varies enormously depending on the available manufacturers and designs; therefore, this will not be further discussed. It is advised to thoroughly review the specifications of several options considering the aforementioned aspects.

Window panes are usually glass. Thermal transmission should be the first aspect to consider using the local regulations and requirements, to better adapt to the climate. Single pane glass will have a transmittance between 5.4 and 5.85 $W/(m^2K)$, and a double pane 1.8 and 3.4 $W/(m^2K)$, depending on the design of the pane and glass. The solar heat gain coefficient (SHGC) is the fraction of solar radiation admitted through a window. The lower the SHGC, the less solar heat it transmits, and the greater its shading ability.

Pane design will also affect acoustic performance. Double-pane glass will have better sound insulation than single-pane. The separation between the panes will also improve sound insulation.

Visible transmittance (VT) is a fraction of the visible spectrum of sunlight that is transmitted through glazing and is expressed as a number between 0 and 1. Glass with a lower VT can be used to reduce glare. Double glazing will have a lower VT than single glazing, but there are other, more effective strategies to control this.

The opening of the window will determine air tightness and ventilation potential. Sliding windows tend to be less airtight than hung and pivoting windows, although this is heavily dependent on the design and quality of the manufacturing process. Ventilation potential should be considered as it will define the available area for natural ventilation. Hung and pivoting windows will account for more ventilation area than sliding windows.

Outside View

Although teachers perceive an outside view as distracting for students, it is also relevant to consider the visual aspect of windows when defining their size. The benefits of visual connection to the outside have been proven, especially when a view of nature is available [27].

A view of nature has been linked to children's well-being [28], while previous studies have found a link between a pleasant view that includes vegetation and better learning outcomes [29]. The current daylighting standard, EN 17037 2018, includes outside views as an indicator that should consider a clear vision outside, a horizontal view from a certain position in the room, and a view that considers more than one layer of information. Kent and Schiavon [27] argue that since nature has a "stronger association with psychological restoration and positive affect", this type of outside view surpasses the minimum requirement, without the need to include more layers of information.

For classrooms, it is relevant to consider the height of the window from the perspective of students sitting and teachers. Younger students will require different windowsill heights than older ones. All students in the classroom should have access to an outside view from their location. Another aspect that interrupts the view is the design of the panes. If too many divisions are made, then the view is segmented. No interactions between the outside view and acoustic, thermal comfort, and indoor air quality have been reported.

Shading and Solar Protection

Solar heat and light can be detrimental to IEQ. Excess heat from unwanted solar gains as well as excess light can be controlled by using shading devices and solar protection. Glare is the most common source of discomfort from daylight in classrooms and should be avoided.

The design of these elements will depend on outdoor temperature, sky conditions, orientation, and location of the windows. Shading can be designed as part of the window or an extension of the roof. This strategy will work better on the façade that receives the sun from a higher position (north façade in the southern hemisphere). When the sun is lower on the horizon, horizontal and vertical louvers will be more effective.

3.1.4 Roof

The fifth façade of the building can also affect the IEQ. The selection of materials should be made considering the climate and microclimate where the school will be located. The need of using thermal mass in roofs should be considered when there are large temperature oscillations during the day.

Roof insulation should be carefully considered based on the characteristics of the climate.

The roof can also double as a learning space. Green roofs can provide extra space for outdoor activities and the restorative benefits related to contact with nature.

Roof Windows

Windows placed on the roof can direct light toward deep-lying spaces. As stated before, daylight penetration has limitations so, when spaces are too deep, additional sources of light are needed. It is advisable to provide indirect light, as direct sunlight from the ceiling would produce overheating and glare.

For ventilation, roof windows, if operable, can provide a stack effect. This type of window is commonly used for night-time ventilation since their operation is safer at night than leaving a window open. Special attention should be given to operable roof windows in climates where rain can be expected.

Noise should be considered if roof windows are operable and there are known sources of outdoor noise such as air traffic or busy street traffic.

If windows have low insulation properties, heat stratification can lead to excess heat loss in winter, affecting thermal comfort.

Finishes

Ceilings should consider acoustic panels to achieve the required sound insulation. Sound, similarly to thermal bridges, can be transmitted if the junction between the vertical and horizontal envelope is not carefully designed. Flanking transmission is the structural transmission of sound energy from one room to another and should be avoided by design. Ideally, the ceiling would be white matt as this provides good light reflectance.

3.1.5 Floor

Floor design will impact thermal comfort, because of radiative temperature and visual comfort, depending on color and finish. Acoustic comfort will be affected by the impact and airborne sound insulation of the floor. Both types of noise can be transmitted vertically between adjacent rooms [23].

The finishing material of the floor should be chosen considering that reflections from direct solar radiation can become glare sources. Although dark colors could be used, the contrast between them and the desk should be considered. Therefore, a low reflectance of the floor is recommended. The specularity of the finish should also be lowered if possible [21].

3.1.6 Furniture

The color and finish of the furniture should be designed for avoiding glare. Highly reflective materials are beneficial to distribute light in the room as long as the surface is not glossy, and has a low specularity. This is especially true for desks but should also be considered for other pieces of furniture such as chairs, bookcases, and windowsills. Dark table colors should not be used to avoid high contrast between the work plane (books and notebooks) and the background.

4 Discussion

The first objective of a school should be to provide a safe space for learning, while also giving the best conditions possible to enhance the experience of children. When approaching the design of a school, the designer and stakeholders need to keep in mind that students will spend more time awake at school than in their own houses. At the same time, if they complete their education in the same building, they would have spent 12 years in it. Probably more than the time any adult will spend in the same work environment. Therefore, it is of the utmost relevance to deliver the best design possible.

School design for indoor environmental quality should be faced from a holistic perspective. In the Global South, a passive design perspective will be especially useful as it will reduce operation costs, energy dependence, and maintenance. At the same time, it will make buildings more resilient to natural disasters [30].

The guidelines proposed in this chapter aim at delineating this holistic approach by presenting the different factors that need to be considered to design a classroom.

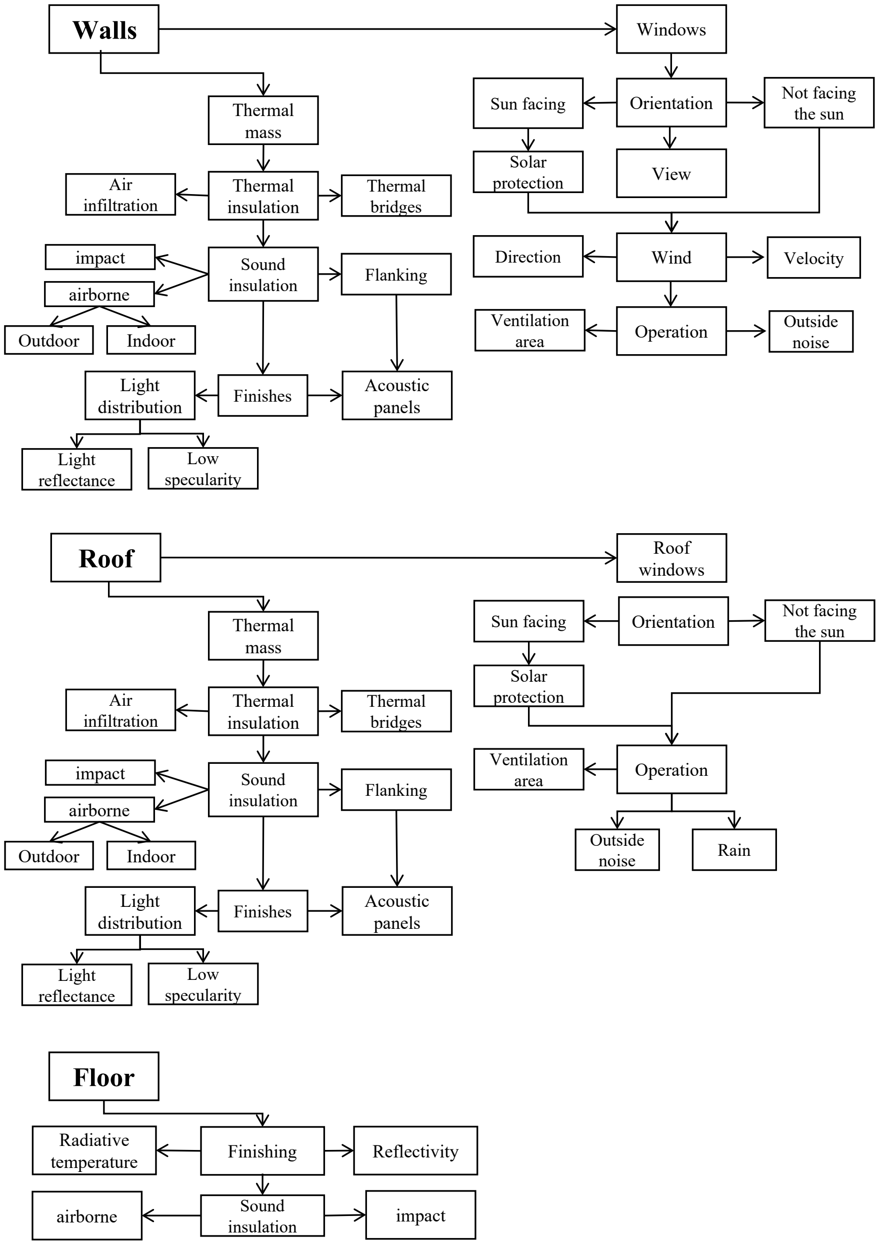

Fig. 1 Design workflow of define passive strategies to achieve IEQ

The design workflow presented in Fig. 1 should work as a guide to achieve safe, healthy, and comfortable classrooms.

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References

1. RHEVA, ISHRAE (2010) Guidebook no 13: Indoor environment and energy efficiency in schools
2. Marín-Restrepo L, Trebilcock M, Porras-Salazar JA (2020) Adaptation by coexistence: Contrasting thermal comfort perception among individual and shared office spaces. Architect Sci Rev 63:235–247. https://doi.org/10.1080/00038628.2019.1708257
3. OECD (2018) Education at a Glance 2018. https://doi.org/10.1787/eag-2018-en
4. Attia S, Shadmanfar N, Ricci F (2020) Developing two benchmark models for nearly zero energy schools. Appl Energy 263:114614. https://doi.org/10.1016/j.apenergy.2020.114614
5. Van TN, Bao LNP, Hung TL (2021) Surveying impacts of adaptive facades on acoustical quality of classrooms. In: AIP conference proceedings, vol 2420. American Institute of Physics Inc. https://doi.org/10.1063/5.0068362
6. Piderit-Moreno MB, Yañez-Labarca C (2015) Methodology for assessing daylighting design strategies in classroom with a climate-based method. Sustainability (Switzerland) 7:880–897. https://doi.org/10.3390/su7010880
7. Trebilcock M, Piderit B, Soto J, Figueroa R (2016) A parametric analysis of simple passive strategies for improving thermal performance of school classrooms in Chile. Architect Sci Rev 59:385–399. https://doi.org/10.1080/00038628.2016.1150251
8. Kang JE, Ahn KU, Park CS, Schuetze T (2015) Assessment of passive vs. active strategies for a school building design. Sustainability (Switzerland) 7:15136–15151. https://doi.org/10.3390/su71115136
9. Huang KT, Huang WP, Lin TP, Hwang RL (2015) Implementation of green building specification credits for better thermal conditions in naturally ventilated school buildings. Build Environ 86:141–150. https://doi.org/10.1016/j.buildenv.2015.01.006
10. Zahiri S, Altan H (2016) The effect of passive design strategies on thermal performance of female secondary school buildings during warm season in a hot and dry climate. Front Built Environ 2. https://doi.org/10.3389/fbuil.2016.00003
11. Su B (2016) Impact of building envelope design on energy consumption of light structure school building. In: Interaction between theory and practice in civil engineering and construction. Proceedings of the First European and Mediterranean Structural Engineering and Construction Conference. ISEC Press, Istanbul, Turkey, May 24-29, pp 641–646
12. Zhang A, Bokel R, van den Dobbelsteen A, Sun Y, Huang Q, Zhang Q (2017) Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China. Energy Build 139:371–384. https://doi.org/10.1016/j.enbuild.2017.01.048
13. Salameh M, Taleb H (2017) Courtyard as passive design solution for school buildings in hot area. In: World Congress on Civil, Structural, and Environmental Engineering. Avestia Publishing, Barcelona, Spain, https://doi.org/10.11159/awspt17.141
14. Balador Z, Imani F, Gjerd M (2017) Evaluation of different shading devices for a Tehran primary school classroom. In: PLEA 2017 Design to thrive, Edinburgh, Scotland
15. Subhashini S, Thirumaran K (2018) A passive design solution to enhance thermal comfort in an educational building in the warm humid climatic zone of Madurai. J Build Eng 18:395–407. https://doi.org/10.1016/j.jobe.2018.04.014

16. Kwon CW, Lee KJ (2018) Article integrated daylighting design by combining passive method with daysim in a classroom. Energies 11. https://doi.org/10.3390/en11113168
17. Nordin N, Ismail MA, Ariffin ARM (2019) Ventilation blocks: Design feature in Malaysia public schools. J Design Built Environ 19:1–12. https://doi.org/10.22452/jdbe.vol19no1.1, https://ejournal.um.edu.my/index.php/jdbe/article/view/17785
18. Monna S, Baba M, Juaidi A, Barlet A, Bruneau D (2019) Improving thermal environment for school buildings in Palestine, the role of passive design. J Phys: Conf Ser 1343:012190. https://doi.org/10.1088/1742-6596/1343/1/012190
19. Lakhdari K, Sriti L, Painter B (2021) Parametric optimization of daylight,thermal and energy performance of middle school classrooms, case of hot and dry regions. https://doi.org/10.1016/j.buildenv.2021.108173
20. Department for Education and Skills (2015) Building bulletin 93–Acoustic design of schools: Performance standards. https://doi.org/10.1016/j.jns.2003.09.014
21. Viula R (2022) Discomfort glare from daylight in classrooms. PhD thesis, Delft University of Technology, Delft, Netherlands, https://doi.org/10.7480/abe.2022.14
22. Wang H, Liu G, Hu S, Liu C (2018) Experimental investigation about thermal effect of colour on thermal sensation and comfort. Energy Build 173:710–718. https://doi.org/10.1016/j.enbuild.2018.06.008
23. IOA, Anc (2015) Acoustics of Schools: a design guide. Institute of Acoustics and Association of Noise Consultants, UK
24. Diaz M, Cools M, Trebilcock M, Piderit-Moreno B, Attia S (2021) Effects of climatic conditions, season and environmental factors on CO_2 concentrations in naturally ventilated primary schools in Chile. Sustainability 13:4139. https://doi.org/10.3390/su13084139
25. Montazami A, Wilson M, Nicol F (2012) Aircraft noise, overheating and poor air quality in classrooms in London primary schools. Build Environ 52:129–141. https://doi.org/10.1016/j.buildenv.2011.11.019
26. Klatte M, Bergström K, Lachmann T (2013) Does noise affect learning? A short review on noise effects on cognitive performance in children. Front Psychol 4. https://doi.org/10.3389/fpsyg.2013.00578
27. Kent MG, Schiavon S (2022) Predicting window view preferences using the environmental information criteria. LEUKOS-J Illum Eng Soc North Am. https://doi.org/10.1080/15502724.2022.2077753
28. Lindemann-Matthies P, Benkowitz D, Hellinger F (2021) Associations between the naturalness of window and interior classroom views, subjective well-being of primary school children and their performance in an attention and concentration test. Landscape Urban Plan 214:104146
29. Mahone H (2002) Re-analysis report
30. Trebilcock M, Soto J, Figueroa R, Piderit-Moreno B (2016) Method for the design of confortable and resilient educational facilities. AUS 70–76. https://doi.org/10.4206/AUS.2016.N20-11

From Comfort to Life Habits. Qualitative Approaches to Comfort Research on Domestic Space in the Colombian Andean Tropics

Ader García-Cardona, Elisabeth Herreño-Téllez, Yury Hernández-Duque, John Arango-Flórez, Laura Andrade Sepúlveda, Carolina Cano Arroyave, Elizabeth Castro Burbano, María José García Vallejo, Luisa María Jaimes Nova, David Orozco Gallo, Cristina Ospina Montoya, and Álvaro Vargas Olmos

Abstract Comfort concept refers to the physical, psychological, and sociological conditions of inhabited space, mainly studied from its physical components with quantitative variables, thereon limiting the scope of qualitative variables from their life habits dimension as an existential circumstance—broad, subjective, continuous, and indeterminate. Traditional approaches to comfort allow partial readings of specific conditions of domestic space, ignoring complex relationships between architecture, culture, and place, specifically in tropical and mountainous contexts, such as the case of the Aburá Valley. This is a qualitative study with a descriptive, analytical, and comparative approach of four dwellings located in the Colombian Andean tropics, looking at comfort and habits of domestic life that allowed understanding the subordination of the former to specific daily situations of life in households, and the latter associated with events woven into a continuous, non-linear network of the domestic day. Particular conditions of each home were identified in their relationships with landscape, climate, and topography, manifested in singular domestic life habits despite their locations within the same territorial entity, while adding an

A. García-Cardona · J. Arango-Flórez · L. Andrade Sepúlveda · C. Cano Arroyave · E. Castro Burbano · L. M. Jaimes Nova · D. Orozco Gallo · C. Ospina Montoya · Á. Vargas Olmos
EMAT Lab, School of Architecture, Architecture Faculty, Universidad Nacional de Colombia, Medellín, Colombia
e-mail: jfarang3@unal.edu.co

A. García-Cardona (✉)
Integrated Arts Faculty, Universidad de San Buenaventura, Bello, Colombia
e-mail: agarcia@unal.edu.co

E. Herreño-Téllez · Y. Hernández-Duque · M. J. García Vallejo
Integrated Arts Faculty, Universidad de San Buenaventura, Medellín, Colombia
e-mail: elisabeth.herreno@usbmed.edu.co

Y. Hernández-Duque
e-mail: yuri.hernandez@tau.usbmed.edu.co

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unprecedented vision to comfort studies in the Andean tropics and/or the conscious decision of inhabitants to renounce comfort in favor of their perceptions of security, identity, or culture.

Keywords Comfort · Habits · Daily life · Domestic space · Andean tropics

1 Introduction

Comfort in the domestic space is an issue that involves analyzing quantitative and qualitative variables with an emphasis on the physical and psychological conditions of people and the bioclimatic factors of spaces based on the climate of the context.

The concept of comfort has a more psychological than physical origin [1]. Its etymology derives from the Latin *"confortare"*: "to soothe or reassure; bring cheer to; console" [2]. But, twentieth-century studies focused instead on physical and quantitative aspects of comfort for architecture implied in a more recent definition of comfort: "a state of ease and satisfaction of bodily wants, with freedom from pain and anxiety" [3].

Correspondingly, studies and the development of thermal comfort in architecture have prevailed over other parameters such as lighting or noise, which influence the physiology and responses of people who use a space. In recent decades, the notion of adaptive thermal comfort introduced the variability of people's responses to certain stimuli or boredom due to an excess of exposure to them [4, 5]. de Dear [6] works on the concept of thermal pleasure, with emphasis on the subjective dimension of people and their relationship with a dynamic time and a fluid space.

However, the technical standards of comfort have focused, from the disciplinary approach of ergonomics, on healthy adults in work environments, excluding other population groups in everyday spaces such as urban or domestic environments [7]. Thus, the static notion of comfort, understood as a state of neutrality, should expand to explore other contexts and other types of situations that include age, gender, culture, place, or prolonged overcrowding.

This variety in the ways of life that produce subjectivities in comfort is reviewed here from the domestic habits, which are space-time units made up of the cyclical repetition of lived experiences within household spaces, acting as mediators between people and their relationship with the world: at home, you learn to socialize through family bonding from all dimensions of life. Domestic space, understood as a lived experience, is inseparable from its inhabitants [8], where time is a crucial dimension [9–12], and as they grow and age, inhabitants transform household spaces generating appropriation [13–16], belonging, and identity through habitual domestic practices.

A practice is an activity named as a verb: to read, to eat, to sleep, and to watch TV [17]. When these refer to living, they are transformed into life actions that are spatialized: habits, "The birth of a habit [...] is the birth of a habitat, of a Space" [18].

In turn, everyday life refers to the world of life, Lebenswelt in the words of Husserl [19, 20], and is composed according to Lefebvre by "space, time, pluralities of meaning, the symbolic, and the practice" [21]. In this sense, the everyday brings dimensions of phenomenal complexity to these domestic activities [22–24]. In contemporary times, life practices are traversed by phenomena that provide novelty, update the ways activities are developed, and also modify their meanings [25, 26].

The intertropical zone of Latin America presents a unique condition in the world: urban structures located in the Andes mountain range. In the case of Colombia, it is divided into three mountain ranges, almost perpendicular radiation, and a hydrographic structure with mighty rivers. The topography, climate, and air humidity are unique variables when approaching the notion of comfort in this part of the world. Under these conditions, conceptual difficulties arise on how to apply technical models to analyze comfort generally considered for seasonal areas of the world and urban settlements on flat lands. On the other hand, living in the mountains in the Andean tropics produces life habits in urban areas associated with landscape, gravity, skyline, urban aerodynamics, or the thermal differential on account of the altitude and not the time of year.

This complexity of everyday life in the tropics proposes the need to identify the role of comfort in the events of domestic life, given that comfort as a quantitative parameter is static and invariable, and is not present during all moments of life at home. This condition offers a hypothesis for this work that defines the everyday as a continuous line while comfort is a point or group of points on that line.

For all these reasons, this chapter aims at understanding the subordination of comfort to daily situations, from habits to domestic life events. It is presented through an analysis of the physical aspects of four houses in the Aburrá Valley, located in the Colombian Andean tropical climate, and of the life habits of the families that inhabit them.

2 Methodology

Descriptive, analytical, and comparative tools were used in a qualitative approach to understand the relationships between daily life and bioclimatic variables of comfort in domestic space (see Fig. 1).

2.1 Context

The Aburrá Valley, located at coordinates 6°15′N and 75°35′W in the central mountain range of the Colombian Andes, is a territorial and physical-spatial structure, with altitude ranges between 1300 and 2800 m above sea level, and an Andean tropical climate with thermal variations between 17 and 28°C at the bottom of the valley and relative humidity between 40 and 70%. Most of its inhabitants live on the eastern and western hillsides bordering a river that flows from south to north.

The topographic configuration and equatorial latitude of Colombia's Andean tropical zones are unique [27], characterized by favoring climatic variability according

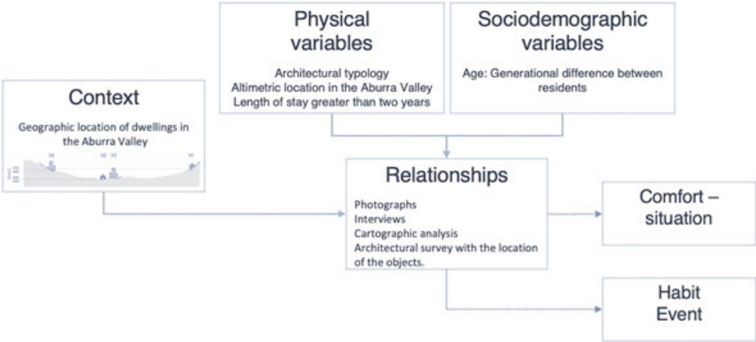

Fig. 1 Methodological flow

to altitude, upward convective flows from riverbeds toward high mountains, and the confluence of trade winds and Pacific Ocean currents, producing particular conditions of temperature, humidity, wind, and microclimatic lighting within the same city, thereby affecting the climatic behavior of households and their inhabitants.

2.2 Case Studies

Four dwellings were selected that would allow contrasting physical and sociodemographic variables with the ways of life of their inhabitants (see Fig. 2) under the following criteria: (a) architectural typology: two individual dwelling units, cases V1 and V2 (houses) and two collective dwelling units, cases V3 and V4 (apartments); (b) altimetric location, a house, and an apartment were defined for both the lower levels of the valley—between 1450 and 1550 m above sea level—and the hillside—between 1700 and 1900 m.a.s.l; (c) (see Fig. 3) family compositions of different generations: inhabitants of the individual dwelling typologies V1 and V2 (houses) are consolidated families with adults and elderly, in contrast to collective dwellings V3 and V4 (apartments) with families made up of adults, teenagers, and children; (d) time of permanence over 2 years in the house, to check on the appropriation of space; and (e) the possibility of access to dwellings, taking into account that the study was conducted during the COVID-19 pandemic.

2.3 Data Collection Analysis

Theories and models covering qualitative and quantitative observations were reviewed to integrate activities of daily living with aspects of environmental comfort. For the qualitative, the following were used as references: the spatial holograms by [28, 29],

Fig. 2 Dwelling typology, sociodemographic information, topographic location, and architectural survey

Fig. 3 Geographic localization of dwellings in Aburrá Valley

the tools of analysis of ways of life by [30, 31], and the interpretation of action sequences in daily habits by [32]. For the quantitative, climatic characteristics of household locations were analyzed, with data from local meteorological stations [33] on average relative humidity and temperature of a day in August, the month with the highest temperatures, and ISO 7730 standard to determine comfort zones [34].

Information on lifestyle habits was captured from photographs, interviews, cartographic analysis, and architectural surveys which included the layout of objects.

Photographs were taken by the inhabitants under the condition of presenting their space to a relative. Photos taken by the researchers looked to obtain details about the inhabitants, daily life, space, and objects.

Interviews with the inhabitants were of the semi-structured type, based on the (a) biographical component of the family (origin, family composition, places of residence); (b) the component of living in the house (time in the house, favorite activities, special places); (c) the objectual component (favorite objects, most used furniture, others); and (d) the COVID-19 pandemic component (effects of confinement, space changes, new activities).

Cartographic analysis was used to determine the households, geographical location in the Aburrá Valley, topography, nearby surroundings, and visuals. An architectural survey was also carried out using drawings of the space, and the location of furniture and objects in the rooms, as shown in Fig. 2.

To determine the temporalities of daily events, a survey was made to the inhabitants of the studied dwellings, where they were asked about the schedules of the activities of getting up, going to bed, getting dressed, undressing, leaving and arriving at the dwelling, the times of eating and socializing, and sociodemographic aspects such as age and gender.

3 From Comfort to Life Habits

The information obtained from the four dwellings was analyzed considering aspects of the context in addition to physical and sociodemographic variables where coincidences of daily life habits associated with the climatic variables of the Aburrá Valley on a domestic day were identified.

The coincidence between habits and weather allowed identifying homogeneous moments in the morning, noon, afternoon, and night and to get up, have lunch, go home, and go to bed, respectively, all connected and juxtaposed in a continuous line of action that we call events (see Fig. 4).

3.1 Comfort Situation

Geographical positions singularize spatial perceptions of the valley; dwellings located on hillsides (V1 and V4) allow visual and landscape control; movements toward and from the households are achieved by going up or down, thereon deter-

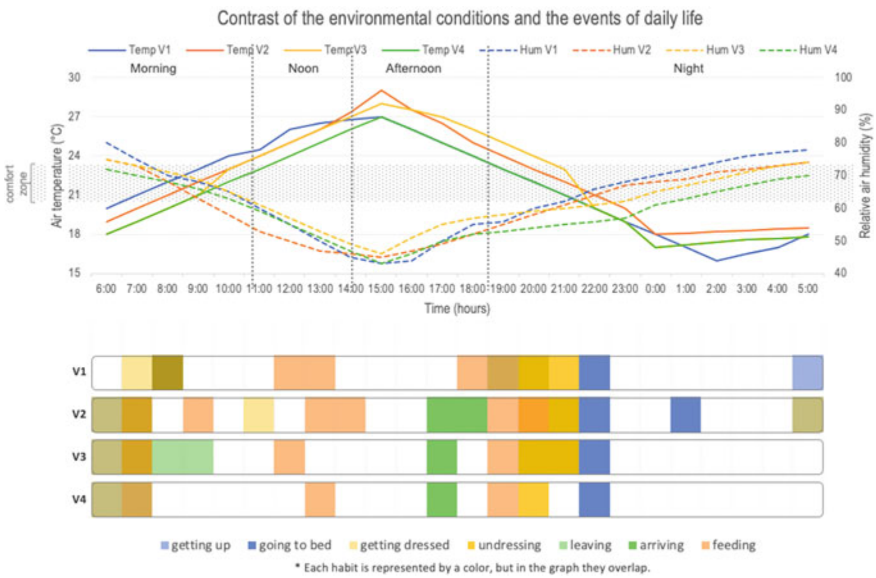

Fig. 4 Contrast of environmental conditions and daily life events in dwellings

mining geospatial routines. On the contrary, dwellings at the bottom of the valley (V2 and V3) establish counterpoint visual relationships with hillside neighborhoods and mountains as a backdrop, with mostly horizontal routes.

Regarding climate, contrasting temporalities between domestic habits and environmental variables allowed visualizing that morning habits are short and follow specific routines (see Fig. 4). At this time of the day, the four houses begin to gain heat, the air loses relative humidity, and outdoor conditions are colder and wetter than indoors. The afternoon is more homogeneous in terms of domestic habits and climate. It is hotter and less humid, a time of day usually used for naps, study, or leisure.

Evening-night habits are not hasty and last longer, routines are unstructured, and leisure is allowed. Greater thermal differences between households are clear during these hours of the day. Those located on the hillside (V1 and V4), have lower temperatures and humidity due to the influx of ascending winds from the bottom of the valley (See Fig. 4), a condition that prompts wearing additional clothing or closing windows and doors to reduce the cold thermal sensation at night. Likewise, in households located on hillsides, a broader skyline provides more daylight during the day and represents fewer artificial light requirements while allowing the use of darker colors for interior finishes and better illuminated partitions.

This is represented in Fig. 4, which superimposes the air temperature and relative humidity data in contrast with the activities carried out in a day in the 4 houses. In addition, the comfort zone is calculated using ISO 7730 standard [34], which for the city of Medellín is between 19 and 23°C.

3.2 Habit Events

The architectural and object analysis showed the axial composition of the houses (V1 and V2) and the presence of a single exterior façade, differing from the apartments (V3 and V4) with diverse axes, and configurations related to more than one façade. This is a difference that defines everyday life trajectories: forward-backward in the former, forward-backward, and left-right in the latter. Common to all four cases, doors define thresholds between private spaces (bedrooms, bathrooms) and the rest of the household, whereas collective spaces (kitchens, dining, and living rooms) have no doors, evidence of an increasingly common variation of domestic space in the case of kitchen configurations in contemporary times.

Light colors for indoor surfaces prevail in the four households. White on walls and ceilings is common, and glossy textures on the floors show the special importance given to domestic hygiene in the Aburra Valley, and despite advancements in gender equality [35], women's association with domestic activities is still present, even in the home with the youngest family (V4).

Regarding household furniture and objects, the dining room table and the living room sofa are key players in family spaces, while the bed is the most significant object-piece of furniture in private spaces for rest and intimacy. Screens have become

Fig. 5 V3 and V4 household interiors

predominant objects both in private and collective spaces, with televisions, computers, tablets, and smartphones, as well as mirrors and reflective surfaces.

A specific space for family entertainment is particularly present in homes with children or adolescents (V3 and V4), including a large TV, a video-game console, artificial lighting, and sound, directly related to the living room. However, a favorite among shared activities in both cases is watching movies as a family in or on the parent's bed. So considerable proportions are required for these beds to accommodate up to six people at a time. Located against the walls, utilitarian furnitures such as cabinets, nightstands, or dressers allow free movement in the four homes (see Fig. 5).

From a sociodemographic point of view, rural origins linked to agriculture jobs were identified as nuclear components in the four families, made clear by indoor and outdoor gardens and ornamental plants. Matriarchy still prevails, and the traditional roles of men and women continue to be clearly defined, even in the youngest family (V4). Each family age group evidenced differences in home perception and appropriation. Family inhabitants in V1 are the oldest, own a much greater number of symbolic objects of memory, and follow almost unchangeable routine patterns. On the contrary, the youngest family that inhabits V4 has more symbolic status objects and their routines become more flexible, especially on weekends.

The interviews showed the presence of a narrative on everyday life that referred to spaces of the house as a collective act, without an explicit reference to the environmental comfort of dwellings. The families narrate their sense of place, indoor-outdoor relationships, and routine, as a sequence of experiences of typical days and schedules established for some activities ("... every day in the morning, on weekends ..."), revealing a space-time condition of the habits of life.

The photographic information showed clear differences in the approaches between residents who took their photos of spaces from angle-views intending to capture everything and not the details, while those of the researchers were descriptive and specifically focused on topics of interest (see Fig. 6).

Living together at home is a combination of different forms of communication. In turn, household spaces transmit messages about their function, hygiene, and climate, which inhabitants know how to interpret. The hermeneutics of the house is built daily from the singular and collective agreement of those who inhabit it. In the

Fig. 6 Analysis of photographs

dwellings studied, the years of stay of its inhabitants reveal a stable communication with every corner of the house, with objects in their rightful place, walls serving to place messages, and windows to indicate the time of day or the weather.

The analysis of results shows that the notion of comfort for inhabitants is subjective and subordinate to habits of daily life, thus allowing the recognition of its value in the spatiality of dwellings as a complement rather than an end. And to explain its presence in the habits of daily domestic life events, these are described in a continuous sequence, like a spiral where everything is related to those that precede and those that follow (Fig. 7). The domestic day is thus understood as a unit of measurement of daily life in its cyclical and non-repetitive condition, and comfort as an instant of daily life, even not conscious in domestic life practices. The most relevant events from this study are described below.

3.2.1 Getting Up and Going to Bed

At dawn, daylight activates the lying body, whose horizontal position defines a spatial perspective where the ceiling becomes predominant, and the floor and the body's sense of gravity disappear. The night, with its darkness and prevailing silence, gives way to the day, with the vertical body that advances, emphasizing values of depth, route, perspective, and point of view, always with the head at the upper part of the space.

This event begins and ends the daily spiral of life, rhythmed by sunlight [36], and usually occurs in the space whose name is taken from its purpose, the *bedroom*,[1] referring to the piece of furniture that defines and structures the space of the room, the bed, which is currently moving from being a refuge of the most sheltered intimacy to becoming a place for work and socializing [38, 39].

In three of the studied families, the action that opens the day is to make the bed, open the curtains, and fresh air is allowed in, regulating the household temperature and humidity, both slightly higher than outside. At night before going to bed, windows are closed again and curtains are drawn, limiting thermal regulation with the outside

[1] The *"habitación"* in Spanish, derived from *"habitar"* [37], to inhabit in Spanish.

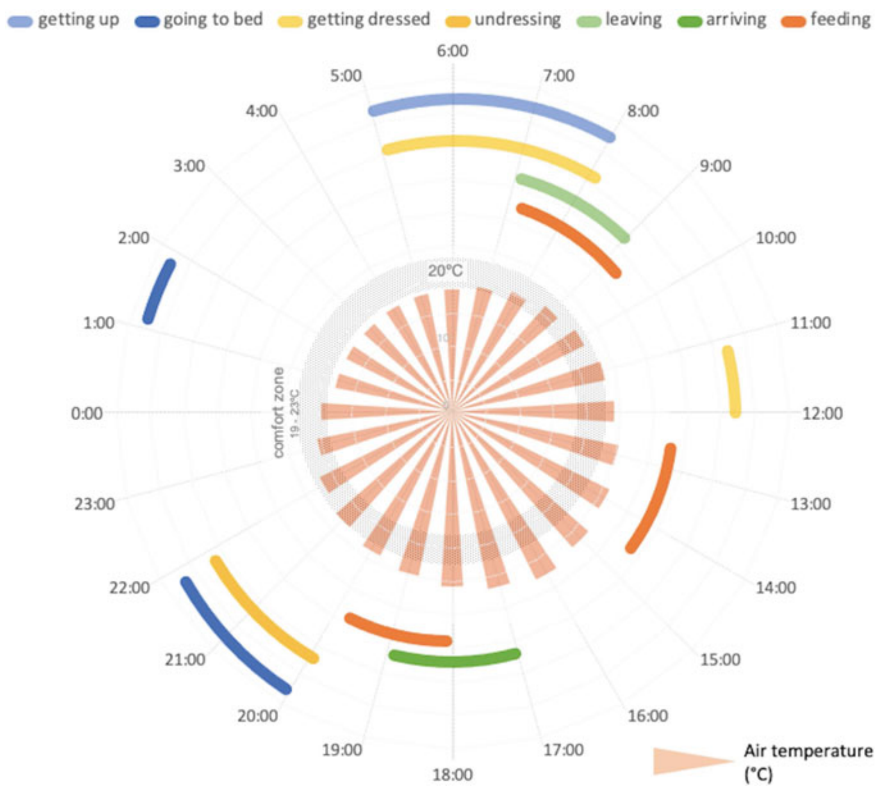

Fig. 7 Domestic day cycle showing the relationship between daily life events and air temperature

in favor of privacy, especially in those apartments (V3 and V4) with windows to the outside in each room.

In the four houses, the bed is moved away from the view of the street, the room is to look at, not to be looked at, and the location of the beds is oriented toward the door, which can be interpreted as a search for a sensation of control, security, and protection, even if the rooms are dark and poorly ventilated. However, this condition seems to have no relevance for the inhabitants, as in the case of V1 where the intimacy and habits that take place inside these spaces seem to override the comfort provided by daylighting or ventilation. It is possible that the event, getting up-lying down, requires remote spaces of the house and the use of the outside environment mediated by the openings is not that important.

3.2.2 Dressing and Undressing in Spaces

In everyday life, there is a permanent dialectic between body and space. The body that inhabits while it perceives, touching space [40], skins of organic and architectural bodies are covered and discovered in an almost-erotic relationship between surfaces of contact [41]. Thus, dressing and undressing always imply an act of intimacy of two, where spaces and inhabitants are reflected on each other [42, 43].

The mild climate of the Aburrá Valley allows sleeping naked or barely covered by delicate fabrics. Clothing to start and end the day is light, and the clothes worn at home are often called comfortable, because they are associated with the thermal regulation of the body and freedom of movement, unlike clothing to go out. Dressing and undressing involve activities associated with both public life and the most private of all-bodily hygiene. Inhabitants in the four houses bathe daily in the morning or even twice on warm days, a frequent practice in the Colombian Andean tropics.

The bathroom as a space for nudity is used 15 min a day on average in the studied households. Despite being poorly ventilated and daylit, inhabitants manifested their satisfaction with these conditions in favor of avoiding exposure to their intimacy. Thus, dressing/undressing is associated with spatial devices such as dressing rooms and dressing tables, where nudity expressed in the mirrors allows self-recognition, and the relationship with water as an element of physical and spiritual purification is permanent.

The common practice of displaying washed clothes on the facades of the apartments is rejected, and many joint properties expressly prohibit it, which leads to clothes piling up in rooms where the air required for drying cannot be moved. However, none of the inhabitants of the four houses had a problem photographing their hanging clothes or their closet with open doors.

3.2.3 Leaving and Arriving Home

Establishing a connection between the inside and outside of the house occurs every day. The daily act of walking through the door marks the limit between the family's private and social life, but leaving the house is also a daily routine action linked to returning. The first one usually occurs in the morning. It is a premeditated and prepared action that requires the readiness of the body that has risen. The heat of the room is left to undress in the bathroom and then get dressed and eat before leaving home.

The door is the binding element and the first testimony of the day, anticipating the outside brightness and temperature. It is observed that in the two houses (V1 and V2), the doors operate as witnesses to the outside climate, the topography, and the time of year, configuring a different landscape in each case. The situation in the two apartments (V3 and V4) is another story, with its doors and the collective circulation spaces that delay the experience of reaching the street. The families in V3 and V4 are raised high up and must go down to the street, a section that modulates the climatic and light connection with the outside.

The return home occurs at another climatic moment of the day, close to sunset and darkness, presenting greater climatic variability between the bottom of the valley and the slope. For that reason, V1, located on the western side at 250 m from the bottom, has more ventilation and daylight and a lower temperature. V2 has less altitude from the bottom of the valley (40 m), and its door is located to the west. It has the most sunlight hours, and artificial lighting can be delayed. In the apartments (V3 and V4), the building's hallways are dark and artificially lit in advance of the arrival of inhabitants. Returning home happens under much more varied conditions than those in the morning. Leaving with daylight and returning at night are done in very different ways for each case, additionally considering activities, age, and means of transportation.

3.2.4 Feeding the Body and Spirit

The preparation of food activates the temperature of the kitchen and the bond of the family, which is generated in the encounter with others, in sharing and giving, which is also an encounter with oneself.

Feeding activates household items: household goods, tools, and surfaces, among others, which are significant elements that reveal tastes, traditions, and roots, a reflection of individuals' experiences in building their nuclear family. Some domestic objects are exhibited as memories of the inhabitant's past, they are inherited. Others are collected, feed the spirit, and remain over time. Others are hidden, they are useful as time goes by and help in transforming food for the body.

The four families have similar cooking routines, breakfast in the morning, between 7:00 and 8:00 a.m.; lunch at noon, between 12:00 and 2:00 p.m.; and dinner in the evening between 6:00 and 9:00 p.m.

Breakfast is associated with hot food, temperature evaporates liquids in the cooking process, altering air conditions, raising temperature and humidity while spreading aromas of coffee, hot chocolate, *arepa*, and fruits, identified with the beginning of a daily journey.

At lunch, there are three characteristic moments: preparation, family time, and consumption. In V1 and V2, more time and objects are required because preparations are often slow and traditional. The kitchen space is located at the back of the house, an area with limited air renewal capacity. Indoor air is thus filled with smells that whet the appetite for the moment of sharing with the family. On the other hand, inhabitants in V3 and V4 prepare lighter meals that are only heated or have small transformations, while lunch is usually an individual act or not done at home. These kitchens have better ventilation that avoids the concentration of scents.

Finally, evening meals are light to benefit sleep, done individually, and often in front of the TV.

Although the four families declare that the moment of collective meals is especially meaningful, these are increasingly unusual during a typical week. Current morning rushes no longer allow a leisurely meeting at breakfast, lunch is in places of study or work, and dinner occurs in the private space of the bedroom. However, special dates, such as birthdays, anniversaries, and Christmas, are still celebrated with family meals, sometimes in the household dining room or outside in a restaurant. So, family food continues to have an important symbolic value, although more uncommon and less domestic.

Human actions related to cooking must be analyzed from the vertical position of the body, activating the visual-motor system that needs lighting to visualize the surfaces where food is transformed. In this sense, although the kitchens in V3 and V4 have good daylighting, artificial lighting is still used when cooking, even during the day, to the benefit of visual ergonomics and the detriment of energy consumption.

From the spiritual point of view, all the families interviewed profess some faith and express it in their spiritual routines and the objects that represent them. Sacred images (V1) and oratories (V2 and V4) are located in private places with silence and darkness. Family memories and objects that left their mark over time are collected and exhibited in social spaces of homes. In V1 and V2, the collections of family photographs and symbolic elements of memory predominate, evoking the past. Inhabitants in these households are older, with fully formed families, while in V4, the inhabitants are young and starting their family. Symbolic objects of status and future projection—tech devices—predominate in this household.

4 Strengths, Limitations, and Prospects

The COVID-19 pandemic limited the study, forcing daily activities to move into households, thereby affecting domestic life behaviors. Consequently, data is limited and perhaps biased, and some information gathering could not be carried out in situ.

Despite limitations during this part of the study, findings already suggest future research possibilities that allow digging into ways of inhabiting domestic space, derived from relationships with climate and topographic configurations, thus triggering phenomenological differences under family sociodemographic and housing typologies.

The experience of collective construction with a transdisciplinary approach, integrating the gaze of stakeholders and experts, as well as that of inhabitants of various genders, ages, and social groups, fosters a break with the old-school knowledge of comfort models (static and adaptive), opening new doors to research in contexts with conditions other than a controlled space or a laboratory. The evidence of such ruptures appears in the contrasting views between the researchers (analytical) and those of the inhabitants, holistic and integrated, arising from their daily experience of space.

5 Conclusions

Comfort is subordinate to domestic life habits. Despite the insistence from architecture to design with bioclimatic comfort standards based on quantitative measurements that define stable ideals, the inhabitants make appropriation decisions of their spaces that contradict these principles, in favor of qualities related to psychological or phenomenal situations of space. Inhabitants of the four houses manifested their preference for closed, dark, and poorly ventilated spaces in favor of a sense of intimacy and isolation.

A domestic day is configured as a space-time measurement unit of everyday life. Current studies on comfort in domestic spaces focus on isolated activities of daily life, without a date or specific duration. On the contrary, the registered experience is a continuum with no beginning or end, where both the activities and their connections, as well as the space-time when they occur, are relevant.

Topographic configurations in the Andean tropics modify the climatic and landscape conditions of homes within the same territorial entity, affecting particular aspects of domestic life habits. This unique situation has scarcely been studied in the technical literature.

This chapter brought to light an unprecedented perspective to comfort studies of domestic space in the Andean tropics, derived from a better understanding of the core role played by qualitative aspects of life exposed by daily habits and physical perceptions of space. Global South countries could be contexts for further studies.

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References

1. Rybczynski W (1986) Home, a short history of an idea. Viking Penguin Inc., New York
2. WordReference (2021) English dictionary. Accesed 24 Sept 2021, from https://www.wordreference.com/
3. Getty Trust JP (2004) Art and architecture thesaurus full record display (Getty Research). Accessed 24 Sept 2021, from http://vocab.getty.edu/page/aat/300158836
4. Cabanac M (1999) Pleasure and joy, and their role in human life. In: Creating the Productive Workplace, CRC Press, pp 40–50. https://doi.org/10.4324/9780203027813.ch4
5. Giraldo Vásquez N, Rupp RF (2021) Confort térmico en el ambiente construido: Una breve introducción a la teoría analítica y adaptativa. In: Herreño Téllez E, García Cardona A (eds) Experiencias escenciales sobre el hábitat contemporáneo. Ser humano, hábitat y ambiente. Editorial Bonaventuriana, Medellín, Colombia, pp 14–25
6. de Dear R (2010) Thermal comfort in natural ventilation–a neurophysiological hypothesis. In: Windsor conference 2010: Adapting to change: New thinking on comfort, Windsor, UK
7. Salazar Trujillo JH (2010) Uso y apropiación de los espacios públicos. Universidad Nacional de Colombia, Medellín, Colombia
8. Moore J (2000) Placing home in context. J Environ Psychol 20:207–217. https://doi.org/10.1006/jevp.2000.0178

9. Hägerstrand T (1970) Qué hay acerca de las personas en la ciencia regional? Traducción de “What about people in regional science?” In: Ninth European Congress of the Regional Science Association–Papers of the Regional Science Association, vol. XXIV, vol 24, pp 7–21
10. May J, Thrift N (2011) Timespace: Geographies of temporality. Taylor & Francis, London, UK
11. Thrift N (1997) An introduction to time geography. In: Concepts and techniques in modern geography, vol 13, Institute of British Geographers, pp 1–37
12. Sabaté Martínez A, Díaz Muñoz M, Rodríguez Moya JM (1995) Mujeres, espacio y sociedad: Hacia una geografía del género. Editorial Síntesis, Madrid, Spain
13. Amérigo M, Aragonés JI (1997) A theoretical and metodological approach to the study of residential satisfaction. J Environ Psychol 17:47–57. https://doi.org/10.1006/jevp.1996.0038
14. Aragonés JI, Amérigo M, Pérez-López R (2010) Perception of personal identity at home. Psicothema 22:872–879
15. Aragonés JI, Pérez-López R (2009) Personalización del dormitorio: Descripción, sentimientos y conductas 1. Medio Ambient Comportamiento Humano 10:287–301
16. Pérez López R (2011) La vivienda como símbolo de identidad personal y social. Un estudio sobre la personalización de los dormitorios como facilitadora de inferencias. PhD thesis, Universidad de Castilla-La Mancha, Spain, https://ruidera.uclm.es/xmlui/handle/10578/2320
17. Pallasmaa J (2016) Habitar, 1st edn. Gustavo Gili, Barcelona, Spain
18. Pardo JL (1991) Sobre los espacios pintar, escribir, pensar. Ediciones del Serbal, Barcelona, Spain
19. Husserl E (2006) Investigaciones Lógicas 2. Alianza Editorial, Madrid, Spain
20. Husserl E (2006) Investigaciones Lógicas 1, vol 1. Alianza Editorial, Madrid, Spain
21. Lindón A (2004) Las huellas de Lefebvre sobre la vida cotidiana. Veredas, Revista del pensamiento, pp 39–60, https://veredasojs.xoc.uam.mx/index.php/veredas/article/view/83
22. de Certeau M (2000) La invención de lo cotidiano I. Artes de hacer, vol 1. Universidad Iberoamericana, México
23. de Certeau M, Giard L, Mayol P (1999) La invención de lo cotidiano 2. Habitar, cocinar, 1st edn. Universidad Iberoamericana, México
24. Heller A (1994) Sociologia de La Vida Cotidiana. Península, Barcelona, Spain
25. Han BC (2016) La sociedad de la transparencia. Herder, Barcelona, Spain
26. Han BC (2018) La sociedad del cansancio. Herder, Barcelona, Spain
27. Carrizosa Umaña J (2014) Colombia compleja. Jardín Botánico de Bogotá José Celestino Mutis. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Bogotá, Colombia, http://hdl.handle.net/20.500.11761/32548
28. Lindón A (2007) El constructivismo geográfico y las aproximaciones cualitativas. Revista de geografía Norte Grande 21:5–21. https://doi.org/10.4067/S0718-34022007000100001
29. Lindón A (2007) Los imaginarios urbanos y el constructivismo geográfico: Los hologramas espaciales. EURE (Santiago) 33:31–46. https://doi.org/10.4067/S0250-71612007000200004
30. Evans R (2005) Traducciones. Pre-Textos, Girona, Spain
31. Moles A, Rohmer E (1983) Teoría de los actos. Trillas, Madrid, Spain
32. Romero Ayuso DM (2007) Actividades de la vida diaria. Anales de Psicología/Ann Psychol 23:264–271. https://revistas.um.es/analesps/article/view/22291
33. SIATA (2021) Sistema de alerta temprana del valle de Aburrá. Accessed 24 Sept 2021, from https://siata.gov.co/siata_nuevo/
34. ISO (2006) ISO-7730:2005. Ergonomía del ambiente térmico. Determinación analítica e interpretación del bienestar térmico mediante el cálculo de los índices PMV y PPD y los criterios de bienestar térmico local
35. Thomas F (1998) Habitar. En otras palabras. Mujeres y espacios urbanos 5:92–95
36. Le Corbusier, de Pierrefeu F (1979) La casa del hombre. Poseidón, Barcelona, Spain
37. Monteys X (2014) La habitación. Gustavo Gili, Barcelona, Spain
38. Colomina B (2018) Privacidad y publicidad en la era de las redes sociales. ARQ, Santiago, Chile
39. Arango-Flórez J, Pérez-Orrego N (2022) Habitar nuestro tiempo, superposiciones entre espacios físicos y virtuales. In: Duque Cañas J (ed) Arquitectura Temas y Reflexiones. Editorial Universidad Nacional de Colombia, Medellín, Colombia, pp 59–78

40. Vélez Ortiz C (2021) De los ojos a las manos: tocar el espacio. Universidad Nacional de Colombia, Medellín
41. Mesa C (2019) Superficies de contacto. Adentro en el espacio, Mesa Estandar, Medellín, Colombia
42. Pardo JL (1996) La Intimidad. Pre-Textos, Valencia, Spain
43. Sloterdijk P (2003) Esferas I. Siruela, Madrid, Spain

The Paradigm of Environmental Comfort in the Global South: Unattainable Goal or Design Tool?

Jorge Hernán Salazar Trujillo and Lucas Arango-Díaz

Abstract This chapter offers a reflection on how comfort is perceived in the Global South, specifically in tropical countries, considering economic and technological constraints. International standards do not fit well within the climatic diversity of the places located in the equatorial zone, such as Colombia. This raises the question of whether tropical climates do not allow comfort, or simply do not provide what others want. The bioclimatic architecture paradigm of the last century assigned comfort the status of goal, but in this climatic and socio-cultural context, an attempt has been made to use it as a work tool. The calculation of the environmental performance of spaces, empirically valued as adequate or inadequate for specific conditions, indirectly provides knowledge about the typical tolerance thresholds of a place.

Keywords Environmental comfort · Bioclimatic architecture · Tropics

1 Introduction

We are all comfortable with something different. We may have different expectations and preferences. Partly because of our culture, which conditions us to prefer the socially assimilated to the foreign. Partly due to our life history, because habitual

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J. H. Salazar Trujillo (✉)
EMAT Research Group, School of Architecture, Universidad Nacional de Colombia, Medellín, Colombia
e-mail: jhsalaza@unal.edu.co

L. Arango-Díaz
Facultad de Artes Integradas, Universidad de San Buenaventura, Medellín, Colombia
e-mail: lucas.arango@usbmed.edu.co

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interaction with any stimulus normalises it and, therefore, reduces our capacity for amazement concerning stimuli that others might consider impossible to ignore. It is worth mentioning that our perceptions of a stimulus are linked to the immediate spatial and temporal context [1]. No longer the life history, but the immediately preceding instant, the immediately adjacent environment.

Our sense organs are not objective and absolute measurers as are, for example, thermometers, lux meters or sonometers. It is easy to forget, but our perception of the world relies on a permanent process of comparison with the temporal and spatial environment in which a stimulus is framed. What was happening just a while ago, determines exactly what is beautiful, dark, bright or dazzling [2]. Our preferences are conditioned by the real context: the history of what we have recently perceived, together with the illusory context: the campaign of prior expectations of a new stimulus and the memory of previous similar experiences. The physical parameters of our environment are certainly objective, quantifiable and–many of them–predictable, but our reactions to these objective parameters are far from being objective. It is the purest subjectivity, yet expressed in degrees Celsius (°C), in Lux (lx), in Decibels (dB). It is easy to get confused.

The progressive recognition of the relevance of the local simply confirms how distant objective parameters are from local preferences. Over the past few decades, the scientific discourse on thermal comfort has evolved from the "comfort range" that we once believed to be predetermined by the metabolic particularities of our species to discussions on acclimatisation, desirability, and preferences [3, 4]. A similar process is happening in the field of visual comfort, where the physical parameters of lighting are being complemented and enriched with "soft" magnitudes that are impossible to measure with devices such as luxmeters and luminance meters [1].

Recognising this other dimension of every physical phenomenon is resulting in a "softening" of the limits of comfort. At first, cautious warnings were made about the validity ranges of a model, pointing out that the supposed comfort ranges were valid only for specific types of persons, wearing specific types of clothing, under specific health situations, with certain postural motions and performing particular tasks. There were so many cautions about the circumstances that made a range of stimuli desirable that they eventually raised questions about the appropriateness of defining ranges with absolute numbers [5, 6].

We already know that the adaptive model of thermal comfort occasionally falls short of addressing the thermal complexity of our environments: acclimatisation and accommodation keep providing evidence that it is not feasible to fit all of humanity into a single range. These two concepts, acclimatisation and accommodation, understood as the product of our ability to adapt to different unpredictable conditions are evidence of our own evolutionary capacity to modify our comfort ranges so that we can feel comfortable in circumstances where other people, under the same conditions, would not [1, 7].

The adaptable ability refined over millions of years of evolution has been overlooked by comfort models framed as a design target, along with user preferences and specific design intentions outside the conventional parameters of comfort. To enhance academic or professional productivity in work environments, it has been decided to place the whole burden of ensuring that thermal, lighting or acoustic conditions remain as long as possible within a pre-set and typically static range on the building [8, 9].

It is not a matter of abdicating numerical models or predictive approximations. It is not possible to measure what does not yet exist. That is the reason why future well-being will necessarily have to be estimated during the design phase. Although numerical models for predicting comfort, pleasure or personal preferences will continue to be necessary, the nuance is that the condition of desirable well-being is now a point of departure rather than an end state. Today we know that the reliability of any comfort model is limited. Supported by all the valuable contributions of the past decades, we are now busy trying to assess how experiential history and individual particularities influence our environment's assessments [10–15]. So, in the plural, also discovered how unreliable a purportedly original recipe might be.

This chapter aims to discuss what is understood by environmental comfort in the Global South, specifically in the intertropical belt, as well as to present a methodological approach to address it. It is a discussion piece about methods for environmental comfort in the Global South rather than a research report.

2 Comfort Models in the Global South

The term Global South refers to a group of countries that share economic, political and sometimes historically similar realities across the globe. Surprisingly, a classification that does not obey geographical or climatic criteria displays so many latitudinal and life zone co-occurrences that become evident when the classification is plotted on a map. That wavy line in Fig. 1, which we might call the "Equator of Inequity", separates the globe into regions where people consume and those where they survive.

One is tempted to provide an explanation given the latitudinal coincidence with the 30°N parallel, but that is not the intention here. The Brandt Line, as recognised by the International Commission on Development Issues in 1980 [16], is derived from the analysis of economic circumstances. However, it is used here to refer to the Global South, as the concept can be extended since it also gathers regions with environmentally similar circumstances.

There are clear indications that the applicability of imported comfort models has to be reviewed in this particular zone. For most sites in the Equatorial Zone, it is frequently impossible to guarantee that a building never overheats when it comes to air temperature. Passive architecture dances with external environmental oscillations. When these changes are abrupt and extreme, this severity is manifested inside in proportion to the level of insulation that delimits it. The absence of insulation leaves the interior space vulnerable to the climatic rigours of the exterior environment, yet, notably, excessive insulation suppresses the very diversity that constitutes its richness.

Applying thermal comfort models to equatorial locations reveals that these climates are frequently not "comfortable", simply because they do not resemble what

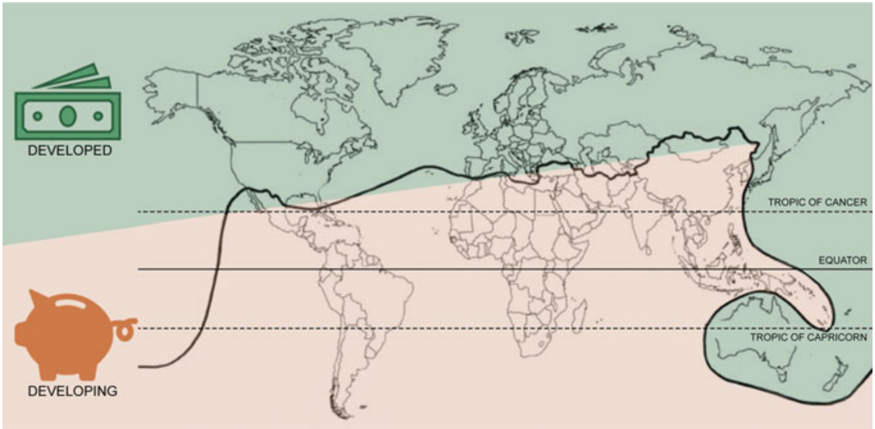

Fig. 1 Brandt line. Elaborated using the original image from Jovan.gec–Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=48725194

others want them to be. In these cases, experience with the site and knowledge of its climatology are often better advisors than the best comfort models. In this highly biodiverse part of the world, it does not seem too risky to estimate that such generalisations of human comfort do not always apply and can sometimes even be problematic.

In the Andean tropics, for example, the abrupt altitudinal changes result in marked contrasts. With the diversity of climates and microclimates in this part of the world, where Colombia and other countries are located, international standards often do not fit well because these regions and cities are too hot, too humid, too tropical, too poor, too unequal, too remote and inaccessible. Finally, very unique. Like any other place on the planet, they all have their dose of uniqueness, except that in Colombia uniqueness can mean just a few kilometres away. It is worth highlighting the problem involved in this mismatch between the climatic and socio-cultural context: regulations aimed at standardising comfort conditions can easily end up going against what people want. The city of Medellín, for example, extends over three thermal floors, but urban regulation instruments do not manage to reach this level of detail, and the administrative effort required to prevent this from happening would be considerable.

While many people do not need air conditioning, many others cannot afford this luxury. As a result, Colombia has a large population accustomed to heat or cold, in other words, to "discomfort". One example is enough: in the words of many Europeans, the climate in Bogotá and the surrounding area calls for heated homes. However, heating is rare there. Since most Colombians have become accustomed to their surroundings, they have more modest expectations for the environmental performance of their buildings. This can be explained by a largely rural and agrarian history, of people who spend much of the day outdoors; people from excluded communities who do not perceive the severe energy and technological shortages where they live because they simply do not have anything to compare with. This is not an apology for poverty, but the truth is that many Colombians are still happy with the climate and environment that surround them. They accept that every place comes with its own climate peculiarities, but they also know that it is environmentally irresponsible to try to change it.

This reality is identical to what is felt in other climatic and socio-cultural environments south of the Tropic of Cancer, as well as in the Global South more broadly: Clothing and food, not heating, are the solutions to cold in Ecuador, southern Brazil, and the entire Bolivian altiplano. In Brazil, the breeze, the beach, and lots of liquids help to combat the heat. Numerous coastal cities, including those in the Caribbean, have clearly marked time slots where only tourists roam the streets. Fans are more common than central heating, and steam barriers are a constructional sophistication even in places as cold and damp as Río de la Plata.

The truth is that the South is not the land of cheap and abundant energy. In many places, there is not even energy or food security. However, there is abundant natural light all year round, and fortunately for many, space is not in short supply. What is tight by Southern standards is a large flat by European standards. Our buildings, except for urban, industrialised, massive and high-rise housing projects, are still generous in porches, corridors, patios, foyers, entrance halls, front gardens and a wide repertoire of transitional spaces with no clearly designated function, which operate as climatic buffers.

The history of the South is one of contingency. These are regions where solutions have always been developed with the current state of affairs in mind, rather than an idealised future. It is similar to a geographical disease: we have learned to mistrust grandiose plans, long-term goals and major socio-cultural transformations. It seems that the routes of the South are those of the interstice, of building and rebuilding with what is available. The idea of a large-scale endeavour to provide lighting, thermal comfort or any other kind of standardised comfort sounds utopian. It makes more sense to start with a project to settle into daily life, then move toward becoming a little bit more comfortable from there. The starting point for a continental comfort project is our current reality, not the idealised future.

3 Methodological Proposal

For instance, rural schools in Colombia face more urgent problems than guaranteeing a certain percentage of Useful Daylight Illuminances (UDI) [17, 18] o Spatial Daylight Autonomy (sDA) [19], even if there were a large number of experts in the country capable of designing buildings based on these metrics. For this reason, rather than predicting how long a hypothetical architectural object remains in its comfort zone, it is more effective to characterise the environmental performance of what is available, and then classify it as desirable or undesirable based on tolerance thresholds drawn from the actual experience of living in that or a similar building, and not based on a standard drawn from the availability of outdoor light in a geographical location with marked seasons.

The comfort-oriented approach leads us to accept an imported response and a performance gamut that is assumed to work equally for all. The counter-proposal is to identify ways to improve what exists or to build something superior to what has regularly been built. Instead of a previously "agreed"–and thus-imposed endpoint, it is merely a little step, a differential route. Avoiding the comfort zone as a starting point makes it possible to incorporate into the analysis process the unfeasibility of completely solving everything from the beginning. This translates into an alternative methodological choice, aimed at differentiating the architectural possibilities being considered to select the most convenient one, even if it is not the greatest possible one.

Comfort conditions often go unnoticed precisely because they free the mind to focus on other things. The opposite is true for discomfort thresholds when one begins to sense that discomfort is approaching, and it is time to take action. Therefore, instead of imposing pre-defined answers and standardised ranges, here we propose to observe occupancy patterns in occupied and functioning buildings and places, to observe people, and try to answer questions such as How much glare can be tolerated? How many hours of overheating are permissible? What activities/postures are common at that time of day in that place?

From this point of view, comfort is not approached from the "target" but from its borders: the limits of tolerance, the threshold of discomfort, and the transition where the resident is at the mercy of their resilience. Assuming that there will always be some gaps between ideal and estimated performance, the focus of interest is not to invest efforts in predicting comfort but to predict the performance of openings, building envelopes, and ultimately, buildings. Working to reduce these gaps is the way to bring building performance closer to the limit of acceptability.

Nevertheless, calculating performance is a useless task if there are no prior reference values to assess it, and this requires a lot of research still to be done. There is a need to define the performance thresholds required to differentiate environmental conditions as desirable/good/bad/tolerable, and for this purpose, the observation of people and the analysis of the performance of what is already built provide valuable elements to identify these limits. It is essential to observe the conditions under which a user changes position, makes a complaint, leaves an enclosure, or begins to express dissatisfaction. Obviously, these are thresholds with very local validity. They depend on specific climatic and environmental conditions and are associated with cultural preferences and habits, yet the fact that they are values that are difficult to generalise does not constitute a nuisance; their strength resides therein.

The list of manifestations of discomfort is longer than the typical comfort survey. It is therefore easier to obtain evidence of discomfort than evidence of comfort. The metrics for this need not differ from those commonly used in architecture, what changes is the approach to using them. For instance, identifying the use of curtains and artificial light based on latitude is sufficient to determine glare tolerance or low light levels [20]. Empty benches in a public space, as well as the time when they start to be reoccupied, may be useful for estimating acceptable insolation levels in Public Space [21]. Observing where people sit in a park allowed the identification of the solar permeability thresholds of a tree canopy for a particular climate [22]. We have learned that patterns of use and occupation of space are also manifested in the metrics and systems of representation of environmental phenomena, we just need to concentrate on looking in that direction.

Decades ago, the computational resources for calculating metrics such as Daylight Autonomy (DA) [23], Annual Sunlight Exposure (ASE) [19], Daylight Glare Probability [24] and UDI were not available and yet then, the question was still the same as today: which of the two windows is preferable in terms of lighting? One can make the most of computational and statistical means to answer this question, but one can also look for two similar windows, already built, and observe those who use them. Again, an example is appropriate: there are countless school infrastructures and in them, classrooms with windows in all possible orientations. It is enough to look at the way the chairs are arranged at the end of the day and you can find indications of the levels of sunlight that are tolerable for that location [25]. It is very easy to move a chair to “adjust” to a particular solar condition, but once the adjustment has happened and the class is over, the empty chair remains as a testimony of a satisfactory location for that time of the year.

A few years ago, we were still working without Typical Meteorological Year (TMY) or similar concepts. Complete weather series were hard to find, and weather stations were at airports, not in cities, but none of this prevented good projects from being carried out at that time as well. It is important to keep in mind that improved projects do not always result from the advancement of technological tools for environmental analysis. Predicting comfort is a relatively recent trend now that we have the resources to do so, but it should not be forgotten that comfort is a working tool, not a design target.

A Low-Tech approach is timely today. Any successful architectural project aims to foster specific occupations, certain types of activities and the retention of individuals because when people are comfortable, they prefer to stay rather than go. Calculating and sometimes measuring the environmental performance of enclosures, hollows or enclosures that are proven to be suitable for a particular use and location may be a sufficient exercise. Copying the performance of what is known to be good is the most inexpensive way to provide knowledge about a place/culture’s performance thresholds. It is preferable to adopt a performance parameter that has been shown to be successful and implement it in a new project rather than replicating a form or constructive solution. The idea can be repeated in its negative version: once the parameter that explains an adverse condition has been identified, it is sufficient to prevent the same parameter from occurring in a new project. We are constantly on the lookout for comfort; thus, our surroundings are more likely to provide it than our books. It is not ground-breaking; it is the same strategy of the vernacular: you only copy what is good.

This alternative way of approaching comfort without the need to standardise or attempt to measure it is an effective strategy since all performance thresholds are experiential. They are observed in everyday reality and, therefore, the threshold of performance for a location, a culture, a climate or a specific destination might be determined through ethnographic research, which is often unsystematic. Jean Gehl’s early work is inspiring in demonstrating how careful observation can yield valuable lessons. Reducing the relative importance of such an active research topic as comfort may sound quite unscientific, but it is crucial to emphasise that in architecture, smart decisions are what matter the most.

4 Final Considerations

Conducting a study to understand local comfort in the Equatorial Zone involves major investment. Characterising what is preferred and desired in the middle of the two tropics is an immense endeavour. In the northern hemisphere, companies and associations interested in standardising artificial climate control paid for it, but now that there is so much sensitivity to the issue and reasonable doubt about it, we are very interested in not repeating the mistakes made over the Tropic of Cancer. The other half of the earth cannot be air-conditioned artificially, but there does not seem to be any interest in funding efforts to standardise passive air conditioning.

The pursuit of comfort does not result in comfort; rather, it encourages us to explore the architectures that are possible in our contexts. The absence of discomfort or the constant comfort are two equally unrealistic extremes, they are legitimate to be used as starting points, though. Finding a representative parameter that compares one architectural approach's suitability to another is crucial, but for this to work, it is critical to understand how the known adequate performances reflect in the metrics and representation systems that are used to make decisions.

With this technique, the maximum difference between two images or two numerical metrics—one indicating the performance of what is known as good and the other reflecting the performance of the yet-to-be-built item—is always the subject of discussion. The rationale is simple: anything with a comparable environmental performance will likewise have a comparable representation. This task implies a certain level of familiarity with how desirability "registers" in an abstract performance rating system.

In conclusion, uncertainty increases when thresholds and performances are both the products of a simulation process. Thus, thresholds should be derived from reality and model performances. In fact, the emphasis on thresholds is arguably more important than the method, model or tool used to estimate performances.

5 Conclusions

Colombian buildings are not as High Tech as some people dream. Even if they are new, we use outdated materials and technologies since industrialisation is not happening on this side of the globe. Buildings that are unique in terms of their materiality and technology are not from this country either, and when they are imported, they are still exceptional examples. The Northern route went through climate analysis [26], the formulation of climate mitigation strategies [27], as well as the thermal comfort zone [28]. The starting points in that hemisphere were first the scarcity of energy resources, and then an idealised but practical situation of comfort. As a result, there is much more active architecture, a remarkable sophistication of architectural envelopes, and strict regulations in the production and assembly processes of building components, among others. Other results are also present: a generation that declares itself distant from the natural environment and, therefore, individuals who are less tolerant to the natural variability of environmental stimuli, people who are accustomed to the constant, permanent circumstances of interior settings requiring higher consumption of energy. Millions of us in the Global South have had a totally different experience. In this part of the globe, we have been focused on minimising thermal discomfort and, if you will, maximising the benefit derived from a design choice that is admittedly insufficient but viable in the context of our limitations. The route that has brought us here is a different one, and it certainly makes sense to consider that our starting points for the production of architectural forms may be different.

The challenge of the 1960s and 1970s was to materialise this paradigm, but as environmental evidence gradually disproves it, it is becoming increasingly obvious that the task facing our generation is to overcome such a paradigm. The "Route of the South" might be viewed as a journey through the management of discomfort, concentrating on the potential for improvement of an architectural idea opposed to inaction. Recognising the technological challenges of ensuring constant comfort and working within the constraints of thermal, energy or lighting advancements is more productive than attempting to implement solutions and methods from different contexts and times.

We need other regulations, different explorations and different methodological strategies. For instance, there are parts of Colombia that are inhabited, habitable and magnificent but that, from the standpoint of comfort standards developed in the North, should be abandoned. The goal is quite simple: by taking daily life as a starting point and making a commitment to enhancing the performance of what we currently have, we may better "accommodate" ourselves to the realities of our climate as well as to the limitations of our economy and technology. It sounds like an invitation to manage discomfort to adapt to the irremediable, it sounds like a renunciation of comfort. The truth is that we unintentionally chose to start with human factors rather than putting the comfort we couldn't afford as a priority; that we had no resources with which to measure, we couldn't simulate; but still, make good design decisions.

Illustrating the practical implications of what is proposed, we suggest a course of action that should be consolidated in the light of the ideas already presented: technological adaptations tend to be much more fertile when transplanted horizontally as changes in geographical longitude are often accompanied by minor climatic changes. The life zones of the southern Colombian Pacific Coast (latitude 1.8, longitude –78.75) and the southern coast of Singapore (latitude 1.35, longitude 103.82) are very similar despite the large distance between them. On the contrary, technological adaptations between locations at different latitudes are often difficult or unfeasible. For example, vapour barriers make perfect sense in New Jersey, USA, and not in Tumaco, Colombia, even though they are coastal locations of almost equal length.

For this reason, academic and scientific alliances should be less centred on the North and more focused on the left and right. Ultimately, useful solutions are more likely to be found in contexts where problems similar to the ones to be solved are experienced.

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References

1. Arango-Díaz L (2021) Nueva métrica dinámica de luz natural:relación entre la percepción de suficiencia lumínica y la disponibilidad lumínica exterior. PhD thesis, Universidad del Bío-Bío, Concepción, Chile, https://doi.org/10.6084/m9.figshare.21277719.v1
2. Alonso C, López J, Coch H, Serra R (2012) Visual adaptability in architecture: A physical and psychological approach. In: PLEA2012–28th conference, opportunities, limits & needs towards an environmentally responsible architecture, Lima, Perú
3. Nicol F, Humphreys M, Roaf S (2012) Adaptive thermal comfort: Principles and practice, 1st edn. Routledge, London. https://doi.org/10.4324/9780203123010
4. Sun C, Lian Z (2016) Sensitive physiological indicators for human visual comfort evaluation. Light Res Technol 48:726–741. https://doi.org/10.1177/1477153515624266
5. Rupp RF, Giraldo Vásquez N (2021) Confort térmico en el ambiente construido: Factores humanos y ambientales. In: Herreño Téllez E, García Cardona AA (eds) Experiencias esenciales sobre el hábitat contemporaneo. Ser Humano, Hábitat y Ambiente, Editorial Bonaventuriana, Medellín, Colombia
6. Vásquez NG, Pereira FOR, Kuhnen A (2018) Preferências visuais das crianças em salas de aula de educação infantil: Uma aproximação experimental. Ambiente Construído 18:11–28. https://doi.org/10.1590/s1678-86212018000300265
7. Maier J, Zierke O, Hoermann HJ, Windemut I (2017) Subjectivity of lighting perception and comfort: The role of preferences and expectations. Environ Behav 49:1105–1127. https://doi.org/10.1177/0013916516678905
8. Porras-Salazar JA, Wyon DP, Piderit-Moreno B, Contreras-Espinoza S, Wargocki P (2018) Reducing classroom temperature in a tropical climate improved the thermal comfort and the performance of elementary school pupils. Indoor Air 28:892–904. https://doi.org/10.1111/ina.12501
9. Porras-Salazar JA, Schiavon S, Wargocki P, Cheung T, Tham KW (2021) Meta-analysis of 35 studies examining the effect of indoor temperature on office work performance. Build Environ 203:108037. https://doi.org/10.1016/j.buildenv.2021.108037
10. Altomonte S, Allen J, Bluyssen PM, Brager G, Heschong L, Loder A, Schiavon S, Veitch JA, Wang L, Wargocki P (2020) Ten questions concerning well-being in the built environment. Build Environ 180:106949. https://doi.org/10.1016/j.buildenv.2020.106949
11. Schweiker M, Huebner GM, Kingma BRM, Kramer R, Pallubinsky H (2018) Drivers of diversity in human thermal perception-A review for holistic comfort models. Temperature 5:308–342. https://doi.org/10.1080/23328940.2018.1534490
12. Parkinson T, de Dear R (2016) Thermal pleasure in built environments: spatial alliesthesia from contact heating. Build Res Inf 44:248–262. https://doi.org/10.1080/09613218.2015.1082334
13. Pereira FO, Fonseca RW, Moraes LN (2012) Iluminação natural: Comparação entre percepção visual e medidas dinâmicas de avaliação. In: Encontro Nacional de Conforto no Ambiente Construído, Brazil, pp 1–9
14. Shafavi NS, Tahsildoost M, Zomorodian ZS (2020) Investigation of illuminance-based metrics in predicting occupants' visual comfort (case study: Architecture design studios). Solar Energy 197:111–125. https://doi.org/10.1016/j.solener.2019.12.051

15. Bellia L, Fragliasso F, Stefanizzi E (2017) Daylit offices: A comparison between measured parameters assessing light quality and users' opinions. Build Environ 113:92–106. https://doi.org/10.1016/j.buildenv.2016.08.014
16. Lees N (2021) The brandt line after forty years: The more North-South relations change, the more they stay the same? 47:85–106. https://doi.org/10.1017/S026021052000039X
17. Nabil A, Mardaljevic J (2006) Useful daylight illuminances: A replacement for daylight factors. Energy Build 38:905–913. https://doi.org/10.1016/j.enbuild.2006.03.013
18. Mardaljevic J, Andersen M, Roy N, Christoffersen J (2012) Daylighting metrics: Is there a relation between useful daylight illuminance and daylight glare probability? Ibpsa-England Bso 12:189–196
19. IESNA–The Daylight Metric Committee (2012) IES LM-83-12. Aproved method: IES Spatial Daylight Authonomy (sDA) and Annual Sunlight Exposure (ASE). Illuminating Engineering Society of North America, New York, USA
20. Arango-Díaz L, Hernandez YA, Gallego HW, Piderit-Moreno MB (2022) Differences in perception of daylighting sufficiency related to the geographical location in the context of university classrooms. J Green Build 17:181–209. https://doi.org/10.3992/jgb.17.2.181
21. Waldron JA, Salazar JH (2013) Calculation of areas of permanence in public spaces, according to solar radiation simulated conditions. In: Marcus A (ed) Design, user experience, and usability. User experience in novel technological environments, Springer, Berlin, pp 215–223. https://doi.org/10.1007/978-3-642-39238-2_24
22. Salazar JH (2009) Sombra vegetal las huellas de sombra. In: X Encontro Nacional e VI Encontro Latinoamericano de Confort no No Ambiente Construido, pp 1753–1762
23. Reinhart CF, Mardaljevic J, Rogers Z (2006) Dynamic daylight performance metrics for sustainable building design. LEUKOS 3:7–31. https://doi.org/10.1582/LEUKOS.2006.03.01.001
24. Wienold J (2010) Daylight glare in offices
25. Salazar Trujillo JH (2015) Openwork walls and their solar applicability range. J Civil Eng Architect 9:373-383. https://doi.org/10.17265/1934-7359/2015.04.001
26. Givoni B (1969) Man. Elsevier, Climate and Architecture
27. Szokolay S (1980) World solar architecture. Architectural Press, London, UK
28. Olgyay V (2008) Arquitectura y Clima. GG

Concluding Remarks and Future Outlook

Laura Marín-Restrepo, Jesús Pulido-Arcas, and Alexis Pérez-Fargallo

Abstract This chapter comments on the main points addressed in the book, showing how barriers can be removed and paths are drawn for future research and progress, with a local perspective that is appropriate to the climatic and sociocultural context of the countries in the Global South.

Keywords Environmental comfort · Global south · Tropical climates · Southern hemisphere

1 Introduction

As was said in Chap. 1, roughly 100 years have gone by since air-conditioning became available for the general public in The United States, and it was the 1960s and 1970s that would see seminal studies on thermal comfort for humans started in Denmark, with a pool of around 1300 subjects brought from Denmark, the US, and a group of "people from the tropics" (sic). These would give rise to current thermal

L. Marín-Restrepo (✉)
Architecture et Climat, Louvain Research Institute for Landscape, Architecture, Built environment, Université catholique de Louvain, Louvain-la-Neuve, Belgium
e-mail: laura.marinrestrepo@uclouvain.be

J. Pulido-Arcas
Center for Research and Development of Higher Education, The University of Tokyo, Tokyo, Japan
e-mail: jpulido@g.ecc.u-tokyo.ac.jp

A. Pérez-Fargallo
Department of Building Science, Faculty of Architecture, Construction, and Design, Universidad del Bío-Bío, Concepción, Chile
e-mail: aperezf@ubiobio.cl

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comfort standards and their inherent cultural bias, favoring inhabitants of northern colder countries.

However, over recent decades, countries from the Global South, en masse, have followed this imported knowledge and technology that underrepresents their populations and is not always suited to their geography, demography, or sociocultural background. Sometimes, this has even meant ignoring their own cultural background and traditional building knowledge, which to some extent, already addressed these issues.

The successive turning points in our recent history, such as the oil crisis in 1973, and climate change in recent years, have always brought uncertainty at first, and then a strong will to overcome difficulties by exchanging scientific knowledge across countries. It is not only the authors' belief, but also their certainty, that countries in the Global South are now in the position to take the lead and raise their voices to show that it is only through common efforts that we can make our buildings more sustainable, more comfortable, and more resilient.

In this vein, this book showcases a variety of perspectives from different countries in the Global South for environmental comfort inside buildings. The authors' contributions make it clear that, in a world facing crucial challenges, such as climate change and energy shortages, these countries, which legitimately aspire to improve their living standards, can no longer rely on imported technology and scientific knowledge from the so-called developed countries, but rather they should find their own ways of doing things, based on concepts such as sustainability, resilience, self-management, and a culturally conscious perspective.

This chapter summarizes the main findings, from a global perspective, and concludes with some remarks to summarize this book.

2 Removing Barriers to Environmental Comfort in the Global South

Climatic conditions in the Global South and even within countries include great diversity. Deserts, coasts, mountains, forests, jungles, and paramos, etc., sometimes even conditions unknown to people in the Global North, such as large cities located at high altitudes in the mountains, almost constant temperatures throughout the year, the sun at the zenith, and no seasons in the tropics. Research on thermal comfort, addressed in Part I, to remove the "barrier" of specific climatic conditions, different from how comfort has traditionally been studied and where the established models came from, explores climate-conscious solutions.

The chapters show how buildings can effectively become a third skin for humans and modulate local climate variations to a point where indoor comfort conditions are, albeit not ideal, still acceptable. The interaction between occupants and buildings becomes the cornerstone of understanding this approach and includes the use of local materials, adaptive comfort standards, passive design techniques, and bioclimatic strategies. These chapters have shown that it is more than evident that current thermal comfort standards do not represent the conditions and needs of people in these countries.

At the same time, they provide insights on how these standards can be amended and improved to consider aspects traditionally disregarded in the theory of thermal comfort: the role of ventilation and relative humidity, occupants' satisfaction with tailored comfort standards, and the role of passive design. In this sense, the chapters also highlight solutions that are not only local but also low-cost. In these contexts, major technological interventions or automation are often not only unfeasible but unnecessary.

Building on this, to face the challenge of lack of knowledge on behalf of built environment practitioners who may consider comfort is achieved after construction, that there are no suitable strategies for the Global South, that they are expensive, that there are no design tools, or they do not apply to their contexts, Part II explored the forever controversial aspects of design, between architectural design and building engineering. Strategies for layout and building design, considering occupant satisfaction and thermal comfort, are explored and discussed. It is acknowledged that there are challenges around the implementation of such initiatives, needing the creation of mechanisms to ensure adequate knowledge transfer to policies and legislation, and improving the competencies of practitioners and institutional legal frameworks.

Addressing the barrier that, in some contexts, it may not be possible to meet indoor thermal comfort standards, without large amounts of energy, a change of approach is suggested: taking advantage of the adaptive behavior of occupants to achieve their comfort. Flexibility and personal adaptation are key.

This also answers the housing deficit challenge, by seeking comfortable but affordable buildings that reduce energy poverty or energy dependence. In this sense, the availability of tools that help designers to incorporate passive design strategies in the early stages of projects, where the decisions made can have the greatest impact, is crucial. For this reason, existing tools are discussed, and new tools are proposed with a local twist. A variety of local solutions applied in the early design stages of buildings provide a hands-on guide, useful not just for experts but also for readers with little practical experience in bioclimatic design.

Regarding Indoor Air Quality, it has been identified that there is a lack of understanding about the problems caused by poor air quality. This is aggravated by a prevalence of fuel poverty. Currently, there is little or no regulation in many Latin American countries and the Global South to ensure acceptable IAQ in new and existing buildings, even when poor IAQ has an unavoidable impact on government health care, social care, and social security spending.

On the other hand, in south-cold climates, there is a widespread use of heating with fuels and systems with high indoor pollutant emissions. In addition, the lack of airtightness associated with self-construction, low standards, and generally low construction quality allows pollutants to enter from outside. All-in-all, the need for IAQ regulation is acknowledged, whose implementation requires public and private investment, awareness campaigns, stakeholder agreements, legislation, verification, and control processes, requiring, in essence, a political commitment.

To overcome these barriers, Part III described how contaminants might be controlled and regulated to minimize their impact on a population's health and well-being. It also presents a low-cost, responsive air-renewal system considering the increasing need for indoor air quality control, particularly in hot countries.

Visual comfort and daylight also have an important place in this book, considering that the amount and quality of available solar radiation radically differ depending on the latitude and climate considered. To meet the challenge that standardized metrics are based on the preferences of building users from the Global North and that visual comfort perception depends on the availability of light, local metrics and passive strategies for daylight are analyzed and proposed, and the circadian stimulus on spaces which rely only on artificial lighting is explored. Part IV presents evidence from these studies highlighting the importance of finding a balance between a human-centered design and the need for reducing energy consumption in buildings, showing that when considering daylight metrics, designers should consider the particularities of the place and adapt the thresholds and metrics, for instance, adapting them for the tropics, as has been mentioned in one of the chapters.

The book also shows the need for residential and educational environments with good acoustical quality, which is an aspect usually disregarded in an integrated design, and the least addressed factor of environmental comfort. To remove the barrier to noise pollution and the need for indoor spaces that protect people and guarantee sound quality, Part V proposed design strategies and discussed acoustic regulations. Apart from this, high-density, multi-residential buildings, exposed to different noise levels but where ventilation is also a priority, could prevent sleep disturbance by integrating design strategies for noise control and acoustic comfort. Meanwhile, a careful choice of materials and finishings is deemed necessary to improve the acoustical quality of interior spaces. It is also highlighted that how new learning methods may clash with the regulatory framework for educational establishments, therefore showing the need for a careful design for future educational spaces.

Part VI focuses the effort towards showing the progress of research on energy use and energy efficiency in the Global South. The chapters in this section address the barrier to studying energy use in contexts where in most cases, the problem is not the energy consumption itself but a lack of comfort and resources to cover energy consumption. In this sense, finding a balance between comfort and energy is also highlighted as a challenge. These contributions adopt a human-centered approach, based on the interaction between users and buildings through the adaptive comfort models, aligned with a pressing issue such as climate change. The main conclusion from these contributions is that energy efficiency not only pertains to the technical aspects of a building but also its occupants' sociocultural context. Moreover, this aspect is crucial in mild warm climates where thermal adaptation can bring substantial energy savings without the need for economic investment. Furthermore, it is proposed that in some scenarios, energy use may not be an adequate metric for building performance, but the users' time in comfort would be a better fit. On the other hand, the high-rise re-densification that is taking place in many cities in the Global South is creating new barriers, related to a lack of solar access, increasing lighting demand, and energy costs, potentially affecting well-being, and further worsening energy poverty.

In this sense, the findings in these chapters serve as a key input to the development of new energy policies that should involve comfort and economic indicators rather than only energy use. The inclusion of local use profiles would also help for a better definition of thresholds and to reduce the performance gap. In this sense, residential heating use profiles in Central-Southern Chile have been included in Part VI. Local constructive solutions to optimize thermal comfort and energy efficiency in low-income housing are also proposed, as well as a multi-objective optimization tool that could be replicated in other contexts to select design strategies.

The last part of the book, Part VII, includes a series of reflections and gives hints at the path that countries from the Global South may follow in the future, to respond to one of the biggest barriers: the lack of a definition and approach to environmental comfort. These contributions highlight the importance of the relationship between architecture, culture, and place to develop energy tools and comfort models specifically adapted to the sociocultural background of these countries. Rather than relying on imported models and scientific knowledge, or trying to achieve unachievable standards from other contexts, these countries should strive to develop a locally brewed scientific ecosystem. The final goal should be, in this way, to find their own way of improving comfort standards and abating energy consumption in a sustainable and resilient way. Namely, relying on local knowledge and resources while being sensitive to the local culture and socioeconomic background.

As a final conclusion, in a time of uncertainty, when climate change and the scarcity and affordability of energy are challenging our beliefs about the role of architecture, scientific knowledge can reassure us that there is a way to design, build, and operate buildings that can provide us with acceptable levels of comfort while not being a burden to the natural environment. This book has shown that countries in the Global South have amassed a solid body of scientific knowledge to start making their own reflections about the true meaning of environmental comfort. It is our sincerest hope that the contributions in this book can help to open the path to exchange information between countries, to identify new references and common work, and to walk together towards a future of common prosperity in harmony with the environment.

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