APPLICABILITY OF THE ADAPTIVE THERMAL COMFORT MODEL IN NATURALLY VENTILATED HIGH-RISE RESIDENTIAL DEVELOPMENTS IN COLOMBO, SRI LANKA

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218006B

Degree of Master of Science

Department of Architecture
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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

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The above candidate has carried out research for the Masters thesis under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor:

Signature of the Supervisor: ………………………….. Date: 31-01-2026

Dr. (Ms) Shaleeni Coorey

………………………….. Date: 31.01.2026

Prof. Narein Perera

DEDICATION

To Dr. Shaleeni Coorey, Prof. Narein Perera, and Dr. Renganathan, whose wisdom illuminated my path and whose unwavering guidance transformed obstacles into stepping stones. Their scholarly rigor, patience, and belief in my potential have left an indelible mark on both this work and my growth as a researcher.

To my family, whose boundless love and steadfast support have been my anchor through every storm and calm. Their quiet sacrifices, encouraging words, and unwavering faith in me gave strength when mine waned, this achievement is as much theirs as it is mine.

Together, these extraordinary individuals have shaped not just this thesis, but the person I have become in the process.

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ABSTRACT

This study investigates the applicability of the ASHRAE 55-2017 adaptive thermal comfort model in naturally ventilated high-rise residential developments in Colombo, Sri Lanka, where rapid urbanization and tropical climatic conditions pose unique challenges for low-income communities. While international standards like ASHRAE 55-2017 provide frameworks for thermal comfort, their relevance in resource-constrained, high-density tropical housing remains underexplored. To address this gap, the research employs a mixed-methods approach, combining longitudinal field measurements of indoor environmental parameters (temperature, humidity, air velocity) with detailed occupant surveys to capture subjective comfort perceptions and adaptive behaviors across five case-study buildings. The results reveal critical discrepancies between model predictions and lived experiences: occupants reported 94.5% dissatisfaction with indoor thermal conditions, despite employing adaptive strategies such as fan use and window adjustments. These differences are aggravated by vertical microclimatic variations, with upper-floor residents experiencing significantly different thermal conditions than lower floors, and socio-cultural constraints, such as privacy concerns that limit effective natural ventilation. Statistical analyses, including Spearman’s rank correlation and ANOVA, further demonstrate that the ASHRAE model underestimates the adaptive capacity of residents in warm-humid climates, particularly during peak discomfort periods (e.g., midday, when 64% of respondents reported severe thermal discomfort). The study concludes that the ASHRAE 55-2017 model requires context-specific recalibration for tropical high-rises. It proposes revised adaptive comfort criteria and emphasizes targeted architectural interventions, such as optimized cross-ventilation and solar shading, alongside policy reforms to address thermal equity in low-income urban housing.

Keywords: Adaptive thermal comfort, naturally ventilated buildings, tropical architecture, high-rise housing, ASHRAE 55-2017, Sri Lanka.

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LIST OF ABBREVIATIONS

Abbreviation	Description
NV	Naturally Ventilated
PMV-PPD	Predicted Mean Vote-Predicted Percentage of Dissatisfied
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
PMOT	Prevailing Mean Outdoor Temperature
UHI	Urban Heat Island
EN 15251	European Standard for Indoor Environmental Input Parameters
CIBSE TM52	Chartered Institution of Building Services Engineers Technical Memorandum 52
IMAC	India Model for Adaptive Comfort
TCI	Tropical Comfort Index
CFD	Computational Fluid Dynamics
PCM	Phase-Change Material
AI	Artificial Intelligence
EH	Exceedance Hours
NMBE	Normalized Mean Bias Error
CV(RMSE)	Coefficient of Variation of Root Mean Square Error
IPMVP	International Performance Measurement and Verification Protocol
ISO 8996 (2004)	International Standard for metabolic rate estimation
ANOVA	Analysis of Variance
ICC	Interclass Correlation Coefficient
κ (kappa)	Cohen’s kappa (inter-rater reliability for categorical data)
SPSS	Statistical Package for the Social Sciences
R Studio	Programming environment for statistical computing

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CHAPTER 1

INTRODUCTION

1.1 Background

The rapid urbanization sweeping across tropical regions has triggered an exceptional demand for high-rise residential developments as a solution to housing shortages. While these vertical communities provide essential accommodation, they simultaneously introduce complex challenges in achieving thermal comfort while maintaining energy efficiency. In Sri Lanka's tropical climate, characterized by consistently high temperatures and humidity levels, this challenge becomes particularly acute. The prevalent reliance on mechanical cooling systems in such environments not only escalates energy consumption but also exacerbates urban heat island effects, creating a vicious cycle that underscores the critical need for sustainable alternatives like natural ventilation (Emmanuel, 2005; Giridharan & Emmanuel, 2018).

Thermal comfort in naturally ventilated (NV) buildings represents a dynamic equilibrium between environmental parameters and human adaptability. Unlike climate-controlled spaces where static models like Fanger's PMV-PPD predominate, NV environments demand consideration of occupants' behavioral, physiological, and psychological adaptations (de Dear & Brager, 1998). The ASHRAE 55-2017 adaptive thermal comfort model has emerged as a prominent framework for evaluating naturally ventilated spaces, establishing acceptable indoor temperature ranges through its adaptive comfort equation:

$$T\_comfort = 0.31 \times T\_outdoor + 17.8$$

where comfort temperatures correlate with prevailing mean outdoor temperatures (PMOT). However, its applicability in hot-humid climates, particularly in low-income high-rise housing, remains contested. This model's three foundational principles, behavioral adaptation (e.g., window operation, fan use), physiological acclimatization, and psychologically-shaped expectations, provide a robust theoretical basis for thermal comfort assessment in variable environments.

However, the model's applicability in hot-humid climates, particularly in low-income high-rise housing contexts, has become increasingly challenged. Emerging empirical evidence from tropical regions reveals significant differences between model predictions and observed occupant behavior. Jayasinghe et al.'s (2017) seminal work in Colombo's mid-rise office buildings documented occupant acceptance of temperatures up to 31°C, a full 2°C above ASHRAE 55's upper comfort threshold, suggesting the model may systematically undervalue human adaptability in consistently warm climates. Similarly, Attalage et al. (2019) demonstrated in Kandy's residential settings that during monsoon periods, occupants reported satisfaction despite deviations from predicted comfort bands, primarily through behavioral adaptations like strategic clothing adjustments and window operations. These findings resonate with broader tropical research, including Indraganti et al.'s (2014) work in India, which consistently identified higher heat tolerance among NV building occupants than static models anticipate.

The research background reveals particularly critical gaps when examining Colombo's low-income high-rise housing sector. Existing Sri Lankan studies have predominantly focused on mid-rise offices or middle-income residences (Jayasinghe et al., 2017; Emmanuel, 2005), overlooking the unique confluence of factors characterizing vertical low-income communities. High-rise environments introduce distinct microclimatic challenges, including wind speed attenuation with elevation and stack effect ventilation dynamics that may fundamentally alter adaptive behaviors. Furthermore, the socioeconomic realities of low-income residents, who often lack access to mechanical cooling or adaptive resources like ceiling fans and breathable fabrics, create a thermal comfort paradigm that current standards fail to adequately address. The urban heat island effect in Colombo's dense high-rise districts further complicates this picture, intensifying nighttime heat retention (Giridharan & Emmanuel, 2018) while spatial constraints frequently inhibit effective cross-ventilation.

Most significantly, no comprehensive study has yet evaluated whether ASHRAE's 7-day running mean temperature calculation, developed primarily for temperate climates with distinct seasons, effectively captures comfort thresholds in Colombo's near-constant warm-humid conditions, where monthly temperature variations rarely exceed 3°C (Department of Meteorology, Sri Lanka, 2022). This research gap becomes particularly consequential when considering policy implications for sustainable urban development in tropical cities.

This study directly addresses these gaps by rigorously evaluating ASHRAE 55-2017's efficacy in Colombo's low-income high-rises, where architectural, socioeconomic, and microclimatic factors intersect to create a unique thermal comfort scenario. Through systematic field measurements coupled with detailed occupant surveys, the research advances a sophisticated, context-specific understanding of adaptive comfort that challenges the universal applicability of current standards while proposing empirically-grounded refinements for tropical urban housing strategies.

1.2 Research Problem Statement and Justification

The pursuit of thermal comfort in Colombo's high-rise residential buildings presents a complex challenge, situated at the intersection of climatic, architectural, and socioeconomic factors. The city's hot-humid tropical climate, characterized by sustained temperatures of 27-32°C and relative humidity consistently exceeding 70%, creates an environment where conventional cooling strategies prove both energy-intensive and financially prohibitive for low-income residents (Emmanuel, 2005). This difficulty has led to near-universal reliance on natural ventilation (NV) in such housing developments, despite growing concerns about its effectiveness in maintaining occupant comfort under worsening urban heat island (UHI) conditions (Giridharan & Emmanuel, 2018).

The research problem emerges from a critical disconnect between established thermal comfort standards and the realities of tropical urban living. While the ASHRAE 55-2017 adaptive model has become the international benchmark for NV spaces, its validation has occurred predominantly in temperate climates and air-conditioned environments (Schweiker et al., 2012). This geographical and contextual bias raises fundamental questions about the model's transferability to Colombo's unique conditions, where preliminary evidence suggests occupants demonstrate different patterns of thermal adaptation (Jayasinghe et al., 2017). Three significant knowledge gaps underscore the need for this investigation:

First, while adaptive comfort theory has been extensively studied in various contexts, its application to high-rise housing in tropical urban centers remains surprisingly underexplored. The vertical urban morphology characteristic of Colombo's low-income housing developments creates microclimatic conditions that differ substantially from the low-rise environments typically examined in thermal comfort research (Nicol & Humphreys, 2002). Second, existing validations of ASHRAE 55-2017 in hot-humid climates have produced inconsistent results, with studies like Rijal et al. (2007) demonstrating significant deviations between predicted and observed comfort thresholds. Third, and perhaps most critically, the absence of localized comfort criteria for Colombo's low-income sector (Indraganti, 2010) leaves architects and policymakers without evidence-based guidance for this vulnerable population.

The justification for focusing on Colombo's low-income high-rises is threefold. Socioeconomically, these residents face compounded vulnerability, where limited access to adaptive resources (fans, breathable fabrics) and restricted control over their built environment amplify discomfort risks (Lindberg et al., 2014). Architecturally, the high-rise typology introduces unique challenges, including attenuated wind speeds at higher elevations and complex stack ventilation dynamics that may alter conventional NV performance. From a policy perspective, this research directly informs Sri Lanka's Sustainable Housing Policy Framework by providing empirically-derived comfort criteria for a rapidly growing housing sector.

1.3 Aim and Objectives

1.3.1 Aim

This study aims to critically evaluate the applicability of the **ASHRAE 55-2017 adaptive thermal comfort model** for naturally ventilated high-rise housing in Colombo, Sri Lanka. The research pursues this aim through four interlinked objectives:

1.3.2 Objectives

1. To systematically **analyze existing adaptive thermal comfort models** and assess their theoretical relevance to tropical high-rise environments, identifying key limitations and opportunities for contextual adaptation.
2. To comprehensively assess both **environmental parameters** (air temperature, relative humidity, air velocity) and **occupant adaptations** (window operation patterns, clothing insulation, fan usage) in Colombo's low-income high-rises, establishing baseline performance metrics.
3. To empirically **validate the predictive accuracy of ASHRAE 55-2017** for this specific context through rigorous comparison of model outputs with measured environmental data and occupant feedback.
4. To develop evidence-based **design recommendations** that optimize natural ventilation performance while addressing the unique socioeconomic constraints of low-income high-rise housing.

1.4 Research Question

The study addresses the primary research question: To what extent can the ASHRAE 55-2017 adaptive thermal comfort model effectively predict and enhance thermal comfort conditions in naturally ventilated high-rise housing in Colombo, Sri Lanka?

This central inquiry unfolds through several sub-questions:

1. How do existing adaptive thermal comfort models account for the distinctive environmental and behavioral characteristics of tropical high-rise residential environments?
2. Which thermal comfort parameters demonstrate the strongest correlation with occupant satisfaction in Colombo's low-income high-rise housing, and how do these relationships compare with ASHRAE 55 predictions?
3. What patterns emerge in occupants' perceptual and behavioral adaptations to thermal conditions in these constrained high-rise environments?
4. What architectural interventions and policy measures could most effectively improve thermal comfort while respecting the economic and spatial constraints of low-income high-rise housing?

1.5 Methodology

The research employs a mixed-methods approach integrating quantitative environmental monitoring and qualitative occupant assessments. Field studies were conducted across five high-rise developments, collecting continuous data on temperature, humidity, and air velocity using calibrated instruments (Tinytag loggers, Testo anemometers). Occupant surveys captured thermal sensation (ASHRAE 7-point scale), adaptive behaviors, and satisfaction levels. Data analysis involved correlation studies, regression analysis, and comparison with ASHRAE 55 predictions.

This methodological triangulation, justified by Brager and de Dear's (2000) framework for field studies in adaptive comfort research, ensures robust validation through convergence of objective measurements with subjective experiences.

1.5.1 Methodology Overview

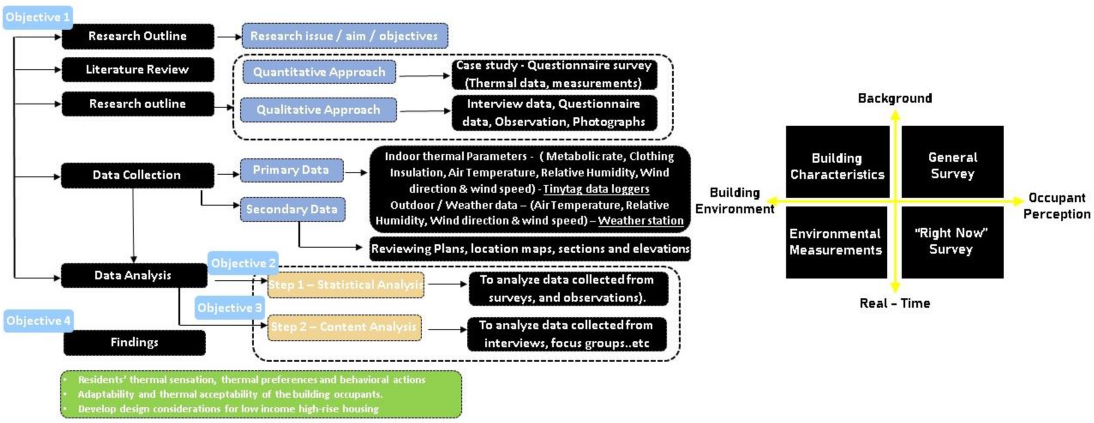
To ensure a structured and systematic investigation aligned with the research objectives, a detailed methodological workflow was developed and is presented in Figure 1.2. This visual framework outlines the sequential and parallel processes that guide the study from literature synthesis to empirical analysis and design recommendation.

The workflow is organized according to the four primary research objectives. It begins with **Objective 1**, focused on theoretical grounding through literature review and research design. This foundation informs **Objective 2**, which encompasses both primary data collection (environmental monitoring and occupant surveys) and secondary data analysis (architectural drawings and climatic records). Data streams are then analyzed through integrated statistical and content-analysis techniques in **Objective 3**, enabling the validation of thermal comfort models. Finally, **Objective 4** synthesizes findings related to occupant perception, adaptive behavior, and thermal acceptability to generate context-sensitive design considerations for low-income high-rise housing.

This integrated approach ensures that quantitative measurements of environmental parameters are systematically triangulated with qualitative insights into occupant experience, thereby supporting a holistic assessment of adaptive thermal comfort in tropical high-rise settings.

Figure 1.1

Methodological Workflow Aligned with Research Objectives



1.6 Scope and Limitations

1.6.1 Scope

The scope of this study focuses on understanding the applicability of the ASHRAE 55-2017 adaptive thermal comfort model within the context of naturally ventilated high-rise residential developments in Colombo. Given Colombo's tropical climate and the reliance of low-income housing on passive cooling strategies, this study aims to provide insights that can enhance sustainable housing policies. The research is relevant for urban planners, architects, and policymakers seeking to improve residential thermal comfort while minimizing energy consumption.

- Investigates **naturally ventilated (NV) high-rise residential buildings in Colombo, Sri Lanka**.
- Examines **low-income high-rise housing developments**.
- Analyzes **thermal comfort perceptions and adaptive behaviors** of residents in **naturally ventilated (NV) high-rise residential buildings** in **Colombo**.

1.6.2 Limitations

- **Geographic Limitation:** This study is focused exclusively on Colombo, which may limit the generalizability of findings to other tropical cities. However, the results will provide valuable insights for similar climatic and socio-economic contexts.
- **Methodological Constraints:** The study relies on field measurements, surveys, and statistical analysis, with limited long-term occupant behavior tracking. Nevertheless, the selected methodology is sufficient to establish key patterns and trends.
- **Climatic Variability:** While Sri Lanka does not have distinct seasons, variations in temperature and humidity throughout the year may still influence results. However, the study accounts for these fluctuations to enhance the reliability of findings.
- **Socioeconomic Limitations:** Limited access to advanced monitoring equipment and variations in participant engagement may impact data collection. However, the study employs a robust sampling strategy to mitigate this issue.

1.7 Significance of the Study

This study contributes to a deeper understanding of **thermal comfort in tropical naturally ventilated low-income high-rise housing**. Key contributions include:

- **Advancing Thermal Comfort Research:** Bridges the gap between conventional thermal comfort models and real-world occupant experiences in Colombo's low-income high-rise residential sector. **Theoretically**, it advances tropical adaptive comfort research by testing and potentially refining the ASHRAE 55 model for high-rise residential contexts, addressing a critical gap in built environment research.
- **Supporting Sustainable Building Design:** Findings will help architects and urban planners integrate **passive cooling strategies** into low-income high-rise housing.
- **Informing Policy Development:** Provides **data-driven recommendations** for climate-responsive housing policies in tropical urban environments.
- **Enhancing Occupant Well-being:** Contributes to the design of **thermally comfortable and sustainable** high-rise buildings for Colombo's low-income communities.

The research ultimately seeks to transform a model for thermal comfort assessment for tropical high-rises, moving beyond imported standards to develop contextually-appropriate solutions that acknowledge both climatic realities and socioeconomic constraints.

1.7.1 Research Frame Work

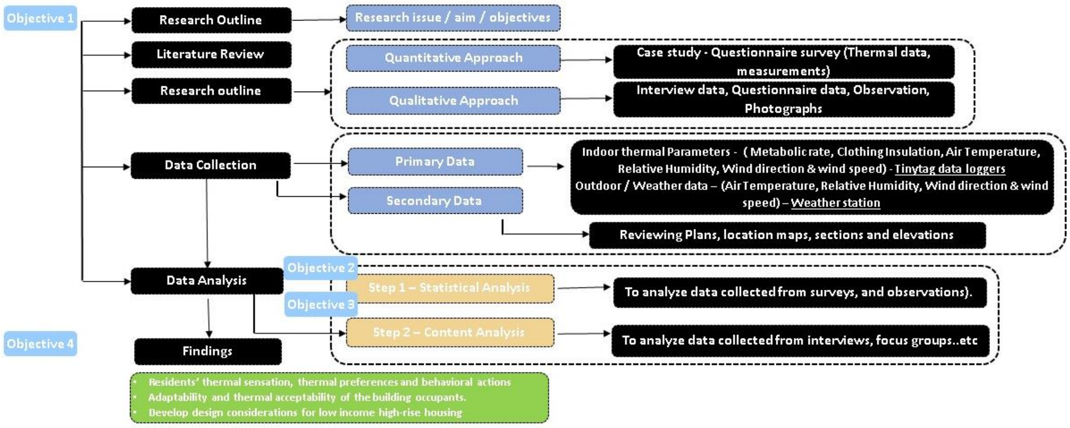
To systematically address the research, aim and objectives, an integrated mixed-methods framework was developed, guiding the study's design, data collection, and analysis phases (Figure 1.1). The framework is structured to ensure methodological coherence and triangulation, beginning with a foundational literature review and precise formulation of the research problem. It subsequently branches into complementary quantitative and qualitative pathways.

The **quantitative** pathway focuses on the objective measurement of indoor and outdoor thermal parameters—including air temperature, relative humidity, and air velocity—using calibrated instrumentation. The **qualitative** pathway captures occupant perceptions, adaptive behaviors, and socio-cultural influences through surveys, interviews, and observational methods. These parallel streams converge during the analysis phase, where statistical and content-analysis techniques are applied to synthesize environmental data with human-experience insights.

This structured approach ensures that empirical findings are contextualized within the lived realities of residents, thereby enabling a robust evaluation of the ASHRAE 55-2017 model (Objective 3), a detailed understanding of adaptive behaviors (Objective 2), and the development of evidence-based architectural and policy recommendations (Objective 4).

Figure 1.2

Research Framework



1.7.2 Research Strategy

This study employs a mixed-methods research strategy, which integrates both quantitative and qualitative methodologies within a single research design (Creswell, 2003; Johnson & Onwuegbuzie, 2004; Tashakkori & Teddlie, 2003). This approach enables the collection and analysis of both numerical data—characteristic of quantitative inquiry—and narrative data—central to qualitative investigation—to comprehensively address the research questions.

Quantitative data, such as measured indoor environmental parameters (air temperature, relative humidity, and air velocity), provide objective metrics of thermal conditions. These are collected using calibrated instrumentation and analyzed through statistical techniques. Concurrently, qualitative data are gathered via occupant surveys, semi-structured interviews, and behavioral observations to capture subjective thermal perceptions, adaptive behaviors, and socio-cultural influences.

By combining these methodologies, the study advances beyond singular analytical perspectives, allowing for both hypothesis testing and theory-building within the context of tropical high-rise housing. The mixed-methods design thus facilitates a holistic understanding of thermal comfort—one that aligns measurable environmental variables with the lived experiences and adaptive capacities of residents (Carr, 1994; Mingers, 2001; Sale et al., 2002). This integrative strategy ensures methodological rigor and enhances the validity of findings through triangulation.

1.8 Structure of the Thesis

This thesis is structured into five cohesive chapters that systematically address the research aim. Following this introductory chapter, which establishes the background, objectives, and significance of the study, **Chapter 2** synthesizes the theoretical and empirical foundations of adaptive thermal comfort. It critically reviews the ASHRAE

55-2017 model's principles, examines its global applications, and identifies gaps specific to tropical high-rise housing, with particular attention to Colombo's climatic and socioeconomic context. **Chapter 3** then details the mixed-methods methodology, encompassing environmental monitoring of three case-study high-rises, occupant surveys, and data analysis techniques designed to validate the model's predictive accuracy.

The latter half of the thesis presents original contributions. **Chapter 4** integrates findings from field measurements and occupant feedback to evaluate ASHRAE 55-2017's performance, while simultaneously deriving evidence-based design strategies and policy recommendations tailored to Colombo's low-income high-rises. Finally, **Chapter 5** consolidates key insights, emphasizing the study's theoretical advancements in adaptive comfort research and practical implications for sustainable urban housing. It concludes with targeted suggestions for future research, ensuring a comprehensive yet streamlined progression from problem identification to solution development.

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical Foundations of Thermal Comfort

The scientific understanding of thermal comfort has been fundamentally shaped by two competing yet complementary theoretical models: the static heat-balance approach epitomized by Fanger's PMV-PPD model, and the dynamic adaptive comfort theory. These frameworks offer fundamentally different perspectives on how humans perceive and respond to thermal environments, with particular effects for tropical climates where conventional comfort models often fail to predict real-world occupant behavior accurately.

2.1.1 Fanger's PMV-PPD Model: A Static Framework

Fanger's Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) model (Fanger, 1970), developed through rigorous laboratory experiments in climate-controlled chambers, represents a landmark achievement in thermal comfort research. The model's mathematical sophistication is evident in its comprehensive heat-balance equation, which incorporates six key parameters: metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and relative humidity.

PMV-PPD summarizes steady-state heat balance across six parameters (metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, relative humidity), predicting thermal sensation on a 7-point scale. Tropical field studies consistently falsify its predictions by 3-5°C due to behavioral adaptations absent in laboratory assumptions (Nicol & Humphreys, 2002).

This equation theoretically predicts the mean thermal sensation of a large group of people on a standard seven-point scale, while the associated Predicted Percentage Dissatisfied (PPD) index quantifies the expected proportion of occupants feeling uncomfortably warm or cold. However, the model's reliance on steady-state assumptions and controlled laboratory conditions has proven problematic when applied to naturally ventilated buildings in tropical regions.

Fanger’s PMV-PPD model, while foundational for climate-controlled environments, assumes steady-state conditions and overlooks behavioral adaptations. In tropical field studies, occupants report comfort at temperatures significantly above PMV predictions, highlighting the model’s limitations in naturally ventilated contexts.And also it assumes steady-state conditions, neglecting behavioral adaptations (Nicol & Humphreys, 2002).

For instance, research in Singapore's public housing estates documented comfortable occupants at 30.3°C - a full 2.3°C above ASHRAE 55's upper threshold - achieved through adaptive behaviors such as increased air movement and clothing adjustments (Zhang et al., 2017).

Table 2.1

PMV-PPD Parameters vs. Real-World Observations in Tropical Climates

Parameter	Laboratory Ideal (PMV)	Tropical Field Data	Discrepancy
Operative Temp	23–26°C	28–32°C (Singapore, Colombo)	+4–6°C tolerance
Relative Humidity	30–60%	65–85% (Jayasinghe et al., 2020)	Higher humidity acceptance
Air Velocity	0.1–0.2 m/s	0.5–1.2 m/s (Attalage et al., 2019)	Active airflow preference

2.1.2 Physiological Foundations: Gagge and Höppe

The physiological mechanisms underlying these discrepancies become clear when examining Gagge's two-node model, which introduced a crucial distinction between core and skin temperature regulation (Gagge et al., 1986). This distinction becomes particularly critical in humid tropical environments where the body's evaporative cooling capacity is significantly diminished. The model quantifies thermal strain (SS) as:

$$S = (T_{core} - T_{core,\ neutral}) / (T_{core,\ critical} - T_{core,\ neutral})$$

Where:

- T_{core} = Actual core temperature
- $T_{core,neutral}$ = Neutral core temperature (≈37°C)
- $T_{core,critical}$ = Critical core temperature (≈39°C)

Höppe's subsequent work on perceived perspiration demonstrated that relative humidity exceeding 70% reduces thermal acceptability by 18-22% even when temperatures remain within theoretical comfort ranges (Höppe, 1999). These physiological constraints are compounded by psychological factors; Schweiker's multinational meta-analysis of 82 tropical comfort studies established that perceived control over one's environment increases tolerance thresholds by 1.5-2.1°C regardless of climatic conditions (Schweiker et al., 2020).

2.1.3 Adaptive vs. Static Models: Sri Lankan Context

In the Sri Lankan context, these global findings take on particular significance. Jayasinghe's longitudinal study of Colombo's office workers revealed a remarkable 68% satisfaction rate in naturally ventilated spaces despite consistent exceedance of ASHRAE 55's comfort thresholds. This phenomenon aligns perfectly with Nicol and

Humphreys' comfort-adaptation contradiction, which posits that occupants in free-running buildings develop higher temperature tolerance through continuous exposure and behavioral adaptation. Attalage's research in Colombo's informal settlements provides even more striking evidence, documenting residents who achieve comfort at 32°C with 75% relative humidity through innovative nighttime ventilation strategies - conditions that traditional static comfort models would deem unacceptable. These findings collectively challenge the universal applicability of laboratory-derived comfort standards and underscore the need for climate-specific approaches that account for both physiological realities and adaptive behaviors.

The theoretical implications of these empirical observations are profound. While Fanger's PMV model remains invaluable for designing mechanically conditioned spaces, its limitations in naturally ventilated tropical buildings have become increasingly apparent. The adaptive comfort model, by contrast, recognizes that thermal perception is not merely a physiological response to environmental stimuli, but rather a complex interplay between environmental factors, behavioral adjustments, and psychological expectations. This model shift has particular relevance for high-rise residential developments in Colombo, where conventional comfort standards may unnecessarily constrain architectural solutions while failing to accurately predict occupant satisfaction. The growing body of evidence from tropical regions suggests that thermal comfort standards must evolve to incorporate these adaptive principles, particularly in climates where mechanical cooling may be neither economically nor environmentally sustainable.

This theoretical foundation sets the stage for a critical examination of how these competing comfort paradigms perform in real world tropical settings, particularly in the unique context of Colombo's high-rise residential developments. The following sections will explore how these theoretical insights have been operationalized in international comfort standards and how they might be adapted to better serve Sri Lanka's specific climatic and cultural context.

2.2 Adaptive Comfort Models: Evolution and Current Standards

The development of adaptive thermal comfort models represents a paradigm shift from static, physiology-based approaches to dynamic, behaviorally-informed frameworks that acknowledge human-environment interactions. This evolutionary trajectory began with Humphreys' seminal work in the 1970s, which first established the correlation between outdoor temperature and indoor comfort preferences through global field studies (Humphreys, 1978).

The fundamental breakthrough came with the recognition that building occupants are not passive recipients of thermal conditions, but active participants who modify both their environment and personal factors to achieve comfort.

The theoretical foundations of adaptive comfort rest on three pillars: behavioral adjustments, physiological acclimatization, and psychological expectation. Behavioral adaptation encompasses conscious actions such as opening windows, using fans, or modifying clothing - activities particularly prevalent in tropical climates where they may account for 3-5°C of expanded comfort range (Nicol & Roaf, 2005). Physiological adaptation occurs through gradual acclimatization, evidenced by longitudinal studies showing tropical residents develop higher heat tolerance than their temperate-climate counterparts (Indraganti et al., 2014). Psychological adaptation, perhaps the most complex dimension, incorporates cultural norms and thermal expectations shaped by architectural traditions and climate experience.

Table 2.2

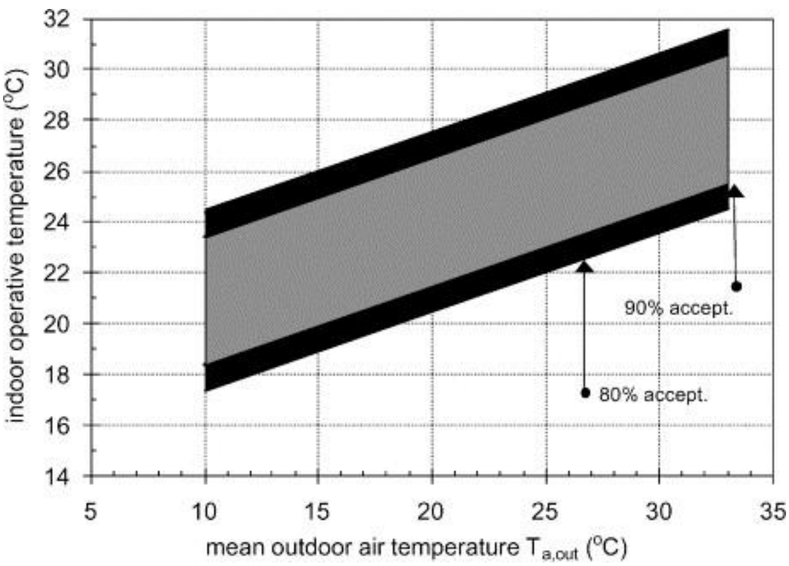
Milestones in Adaptive Comfort Model Development

Year	Model	Key Advancement	Geographic Relevance
1978	Humphreys' Model	Established outdoor-indoor temperature correlation	Global field data
1998	de Dear & Brager	Formalized adaptive algorithm for ASHRAE 55	Mixed-mode buildings
2007	EN 15251	Introduced three adaptive categories for Europe	Mediterranean climates
2013	CIBSE TM52	Developed overheating criteria for UK buildings	Temperate climates
2017	ASHRAE 55-2017	Expanded applicability to naturally ventilated buildings	Tropical/subtropical regions

The contemporary landscape of adaptive standards reveals significant regional variations reflecting climatic and cultural differences. Europe's EN 15251 standard adopts a comparatively conservative approach with three distinct adaptive categories corresponding to different levels of expectation in building performance. By contrast, Singapore's Tropical Comfort Index explicitly mandates minimum air velocities of 1.2 m/s through building code provisions, acknowledging the critical role of air movement in humid environments (Cheong et al., 2014). India's IMAC model goes further still, incorporating seasonal clothing adjustments that recognize traditional adaptations like lightweight summer attire (0.3 clo insulation value) (Manu et al., 2016).

Figure 2.1

Adaptive Comfort Ranges for ASHRAE 55



The application of these models in tropical high-rise environments presents unique challenges that have prompted further refinements. Research in Kuala Lumpur's public housing demonstrated that Malay residents reported comfort at temperatures 1°C higher than Chinese occupants in identical units (Kubota & Ahmad, 2016), highlighting how cultural factors can override climatic determinism. Similarly, studies in Lagos' floating communities revealed innovative behavioral adaptations like evaporative cooling techniques that maintain comfort at 34°C (Adekunle & Nikolopoulou, 2020), solutions entirely absent from conventional comfort models.

Colombo's urban microclimates further complicate the application of international standards. The city's pronounced urban heat island effect creates thermal gradients up to 5.3°C between densely built areas and suburbs (Giridharan, 2019), while vertical urbanization introduces wind attenuation effects that reduce natural ventilation efficacy above the 15th floor by 40% (Ng et al., 2018). These phenomena demand localized model adjustments that account for both horizontal and vertical environmental variations, a challenge not adequately addressed by current international standards.

The evolution of adaptive comfort models continues to accelerate in response to climate change pressures. Emerging research is exploring dynamic algorithms that incorporate real-time weather data and machine learning to predict comfort requirements (Langevin et al., 2020). However, as the Colombo case demonstrates, technological sophistication must be balanced with cultural sensitivity and practical applicability, particularly for low-income populations where resource constraints limit adaptation options. This tension between global standardization and local customization remains the central challenge for the next generation of adaptive comfort research.

2.3 The ASHRAE 55-2017 Adaptive Model

2.3.1 The Adaptive Model's Theoretical Shift

The ASHRAE 55-2017 adaptive model emerged as a direct challenge to the static assumptions of traditional PMV-PPD approaches. Where the PMV model reduced comfort to a physiological equation, the adaptive framework recognized comfort as a dynamic negotiation between occupants and their environment (de Dear & Brager, 2002). This model shift was grounded in Humphreys' (1978) global field studies, which revealed that occupants in naturally ventilated (NV) buildings consistently reported comfort at temperatures exceeding PMV predictions by 3–5°C, a discrepancy attributable to behavioral agency and climatic acclimatization.

Critically, the model's core equation,

$$Tcomfort = 0.31 \times Toutdoor + 17.8 Tcomfort = 0.31 \times Toutdoor + 17.8,$$

encodes this adaptability, but its simplicity belies deeper complexities. As Indraganti (2014) demonstrated in Hyderabad, India, the equation's slope (0.31) underestimates thermal adaptation in humid tropics, where behavioral adjustments (e.g., clothing insulation ≤0.3 clo) expand comfort ranges beyond the model's predictions. This tension between empirical generalization and climatic specificity remains a central debate in comfort research.

Table 2.3

Theoretical Contrasts between PMV and Adaptive Models

Aspect	PMV Model (Fanger, 1970)	ASHRAE 55 Adaptive Model
Comfort Driver	Heat balance physiology	Outdoor climate + occupant adaptation
Control Assumption	Passive occupants	Active behavioral interventions
Tropical Validity	Overestimates discomfort by 1.5–2.5°C	Requires humidity/airflow adjustments

2.3.2 Operationalizing Adaptability: Global Applications and Limitations

The model's real-world implementation reveals both its versatility and the necessity for regional recalibration. In Singapore's high-rise residential towers, Cheong et al. (2014) found that strict adherence to ASHRAE 55's baseline equation yielded only 68% occupant satisfaction, prompting the development of the Tropical Comfort Index (TCI) with expanded temperature bounds (+2°C) and mandated air movement (≥1.2 m/s). Conversely, in temperate Berlin, the model's predictions aligned closely with occupant votes (91% satisfaction), though Attia & Carlucci (2022) noted that EN 15251's Category II standards with narrower bands were often overly conservative for NV retrofit projects.

These differences underscore a critical limitation, which the model's reliance on outdoor temperature alone as a predictor neglects microclimatic mediators. For instance, Colombo's urban heat island (UHI) effect creates vertical thermal gradients that attenuate NV efficacy by 40% above the 15th floor (Giridharan, 2019), a phenomenon absent from the model's inputs. Similarly, in Lagos' informal settlements, Adekunle & Nikolopoulou (2020) documented innovative adaptations (e.g., nocturnal thermal mass cooling) that maintain comfort at 34°C, far beyond the model's upper limits.

2.4 Empirical Studies on Adaptive Comfort of High-Rise Building Performance in Tropical Climates

The rapid vertical expansion of tropical cities has introduced unprecedented thermal challenges that traditional comfort models fail to address. This section critically examines empirical research on adaptive comfort in high-rise buildings, synthesizing key findings on microclimatic effects, architectural innovations, and socioeconomic barriers. By analyzing case studies from Hong Kong to São Paulo, this study identifies gaps between theoretical models and real-world performance, ultimately proposing a pathway for more climate-responsive high-rise design.

2.4.1. The Vertical Gradient of Thermal Comfort

The unique microclimates of high-rise buildings in tropical regions challenge conventional assumptions about natural ventilation and thermal adaptation. Ng et al. (2018) demonstrated that wind speeds in Hong Kong's high-density estates diminish by 40% above the 15th floor, drastically reducing the efficacy of cross-ventilation strategies. This phenomenon, compounded by urban heat island (UHI) effects, creates a vertical stratification of thermal conditions that static comfort models cannot accommodate. Santamouris et al. (2020) further revealed how stack-effect ventilation in Jakarta's towers generates uneven airflow distribution, with central stairwells experiencing upward drafts of 0.8 m/s while perimeter units remain stagnant.

These findings underscore a critical disconnect between ground-level climate data, typically used in adaptive comfort models and the realities of vertical urbanism. Jayasinghe et al. (2020) quantified this disparity in Colombo's public housing, where unshaded concrete facades reached surface temperatures of 42°C, overwhelming occupants' adaptive capacity despite theoretical compliance with ASHRAE 55's adaptive zone. The implication is clear: high-rise thermal comfort demands a **three-dimensional modeling approach** that accounts for vertical microclimate variation.

Table 2.4

Microclimatic Disruptions in Tropical High-Rises

Factor	Observed Impact	Archival Study

Wind attenuation	40% reduction above 15th floor (Hong Kong)	Ng et al. (2018)
Stack effect	0.8 m/s updrafts in core zones (Jakarta)	Santamouris et al. (2020)
UHI amplification	+5.3°C facade ΔT (Colombo)	Jayasinghe et al. (2020)

2.4.2 Architectural Responses and Material Innovations

In response to these challenges, tropical architects have pioneered passive cooling strategies that redefine high-rise adaptability. Singapore's Pinnacle@Duxton (Wong et al., 2021) exemplifies this shift, where **strategically placed sky gardens** facilitate cross-ventilation across multiple vertical levels, reducing indoor temperatures by 2.8°C compared to conventional designs. Similarly, Brazil's Minha Casa Minha Vida program (Braga et al., 2022) integrated solar chimneys and vented facades in São Paulo's social housing, cutting mechanical cooling demand by 37%. These cases demonstrate that **bioclimatic design principles**, when properly implemented, can align high-rise performance with adaptive comfort goals.

Material science offers complementary solutions. Rajasekar and Ramachandraiah's (2019) comparative analysis of Mumbai's towers revealed that composite structures with thermal breaks reduce heat gain by 23% over conventional concrete—a critical insight for tropical regions where energy costs burden low-income residents. Meanwhile, Karunasena et al. (2021) identified laterite stone as a viable alternative to brick in Sri Lanka, with 18% better thermal lag properties. Yet, the adoption of such materials remains inconsistent due to fragmented supply chains and policy inertia.

2.4.3 The Policy-Implementation Gap

Despite robust evidence supporting adaptive design, systemic barriers persist. In Colombo, where 85% of public housing lacks passive cooling features (Jayasinghe et al., 2020), cost constraints prioritize density over livability. Contrast this with Singapore, where building codes mandate minimum sky garden areas and wind-sensitive facades (Wong et al., 2021), and the role of policy becomes evident. The disconnect extends to cultural dimensions: Kubota and Ahmad's (2016) study of Kuala Lumpur's high-rises found that Malay residents reported comfort at temperatures 1°C higher than Chinese occupants in identical units, suggesting that uniform standards may inadvertently marginalize demographic subgroups.

This raises a pivotal question: Can adaptive comfort models reconcile climatic physics with cultural and economic realities? Emerging research suggests hybrid approaches. Chirarattananon et al. (2022), for instance, are testing low-cost phase change materials (PCMs) derived from coconut oil waste in Thailand's social housing, while Santamouris' (2023) work in Jakarta prototypes AI-controlled dynamic shading that responds to real-time microclimate data. These innovations hint at a future where adaptive comfort is both technologically sophisticated and socially inclusive.

2.4.4 Toward an Integrated Framework

The complexities of achieving adaptive comfort in tropical high-rises demand an integrated approach that bridges microclimatic realities, architectural innovation, and policy reform. Emerging research suggests that computational fluid dynamics (CFD) modeling of site-specific wind patterns and urban heat island effects should inform building massing and facade design, as demonstrated by Ng et al. (2018) in Hong Kong and Santamouris (2023) in Jakarta. Simultaneously, tropical-specific building codes must evolve to mandate adaptive features while accommodating cultural preferences, following Singapore's successful implementation of the Tropical Comfort Index (Wong et al., 2021). Material solutions should prioritize localized, circular economies such as Sri Lanka's laterite stone (Karunasena et al., 2021) or Thailand's coconut oil based phase change materials (Chirarattananon et al., 2022) to ensure both thermal performance and socioeconomic viability. This tripartite framework, combining microclimate-aware design, policy-driven standards, and sustainable material systems, offers a pathway to reconcile the competing demands of thermal physics, architectural form, and social equity in tropical vertical urbanism.

2.5 Conclusion

The literature review has systematically examined the evolution of thermal comfort theories, from Fanger’s static PMV-PPD model to the dynamic, behaviorally informed ASHRAE 55-2017 adaptive framework. Key findings reveal that traditional heat-balance models, while effective for mechanically controlled environments, significantly underestimate occupant tolerance in tropical climates, where adaptive behaviors, such as clothing adjustments, natural ventilation, and cultural acclimatization, expand comfort ranges by 3–5°C. The ASHRAE adaptive model, grounded in global field studies, offers a more flexible approach by incorporating outdoor temperature correlations, yet its application in tropical high-rises remains constrained by microclimatic complexities, including urban heat island effects and vertical wind attenuation.

Empirical studies from Singapore, Jakarta, and Colombo demonstrate that successful adaptive design in tropical high-rises hinges on three pillars: (1) bioclimatic architecture (e.g., sky gardens, vented facades), (2) locally attuned material innovations (e.g., laterite stone, phase-change materials), and (3) policy frameworks that mandate climate-responsive features while addressing socioeconomic disparities. However, persistent gaps such as the neglect of cultural preferences in comfort standards and the high costs of retrofitting existing buildings highlight the need for further research into scalable, equitable solutions.

This chapter underscores that thermal comfort in tropical regions cannot be reduced to universal metrics but must embrace contextual adaptability. The gaps identified, particularly regarding vertical microclimates and socio-cultural factors, set the stage for the empirical investigation presented in the following chapters.

CHAPTER 3

RESEARCH METHODOLOGY

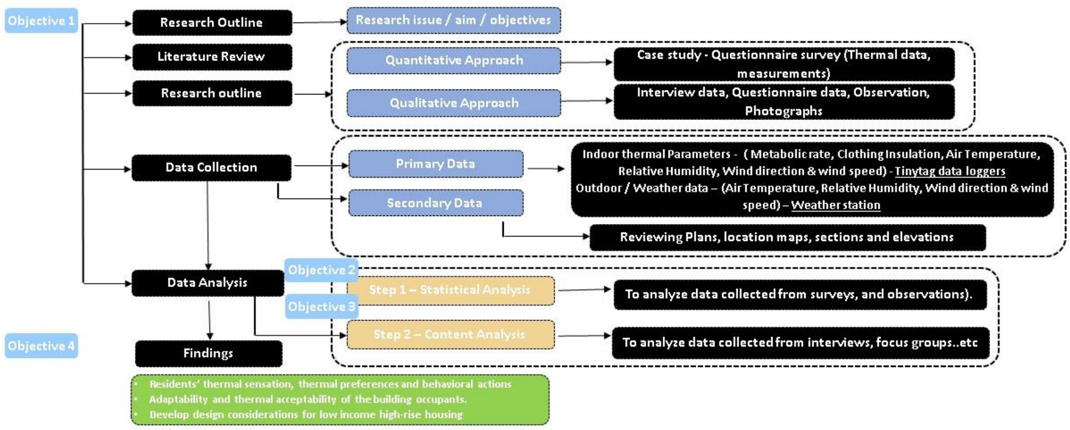
3.1 Research Philosophy and Approach

This study adopts a mixed-methods research approach, integrating both quantitative and qualitative methodologies to comprehensively address the research objectives. The rationale for this approach stems from the need to capture not only measurable environmental parameters but also the subjective experiences and adaptive behaviors of residents in low-income, naturally ventilated (NV) high-rise housing in Colombo, Sri Lanka. Quantitative data, such as indoor temperature, humidity, and air velocity, are collected using precise instruments like Tinytag data loggers and anemometers, ensuring empirical rigor. Concurrently, qualitative data gathered through occupant surveys provide insights into residents' thermal sensations, preferences, and adaptive actions, which are critical for understanding the human dimension of thermal comfort (Creswell, 2003; Johnson & Onwuegbuzie, 2004).

The mixed-methods design enables the triangulation of data, enhancing the validity of findings by validating objective measurements with subjective feedback. This approach aligns with the study's aim to explore the applicability of adaptive thermal comfort models in real-world settings, where both physical conditions and human adaptability play pivotal roles (Tashakkori & Teddlie, 2003). By combining these methodologies, the research not only tests theoretical frameworks but also builds upon them, offering a holistic understanding of thermal comfort in tropical climates.

Figure 3.1

Research Framework

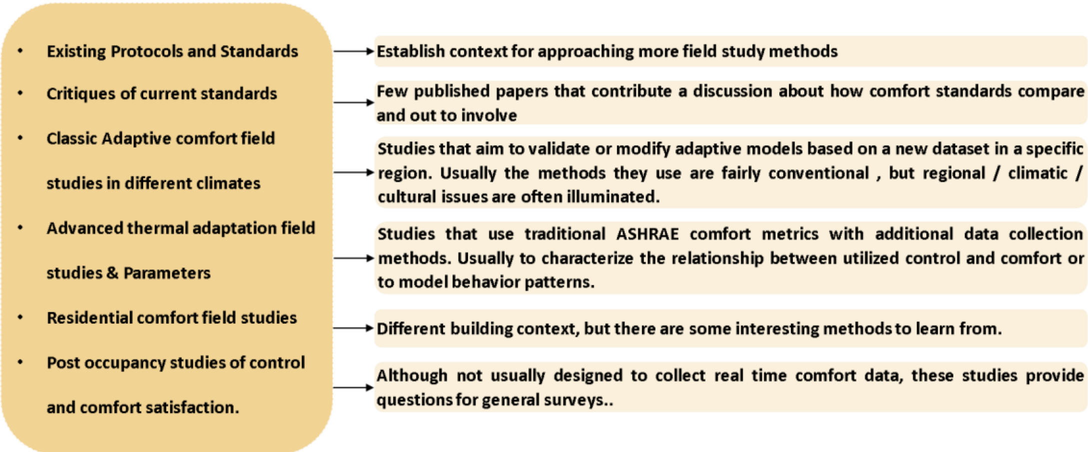


3.2 Case Study Design and Selection

The foundation of this research rests on a **case study approach**, meticulously designed to investigate thermal comfort conditions in low-income, naturally ventilated high-rise housing in Colombo, Sri Lanka. This methodological choice is grounded in the need to capture **real-world thermal performance, occupant behavior**, and **adaptive strategies** within a tropical urban context. Unlike controlled laboratory experiments or purely simulation based studies, a case study framework allows for an **in-situ examination** of how architectural design, microclimate, and human adaptation interact to shape thermal comfort (Yin, 2018). Given the complexity of these interactions, where physical measurements alone cannot fully explain comfort perceptions, this study integrates **mixed-methods data collection**, combining quantitative environmental monitoring with qualitative occupant feedback, in line with established thermal comfort research protocols (de Dear & Brager, 1998; ASHRAE Standard 55, 2017).

Figure 3.2

Theory Framework



3.2.1 Case Study Selection and Description

The study focuses on five public housing developments in Colombo, **Methsanda Sevana, Mihijaya Sevana, Siyapatha Sevana, Laksetha Sevana, and Siyasetha Sevana**, selected through a rigorous set of criteria to ensure methodological consistency and relevance. These buildings were chosen because they represent **typical low-income high-rise housing** in Sri Lanka, characterized by **uniform unit layouts (400-500 sqft, two-bedroom configurations)**, **natural ventilation reliance**, and **absence of mechanical cooling systems**, which eliminates confounding variables related to air conditioning usage (Feriadi et al., 2003). Furthermore, their high-rise nature (12+ stories) introduces **vertical temperature stratification effects**, a critical factor often overlooked in thermal comfort studies of low-rise buildings (Etheridge, 2015). By restricting the geographical scope to **Colombo's urban core**, the study controls for climatic variability, ensuring that findings are specific to **tropical humid conditions** (Jayasinghe et al., 2020). This selective approach aligns with Yin's (2018) principle of **"replication logic"**, where multiple cases are examined to identify **recurring patterns** in thermal adaptation.

Table 3.1

Selected Housing Developments and Unit Distribution

Housing Development	Number of Units	Floors	Year of Construction	Orientation
Methsanda Sevana	918	14	2010	NW-SE
Mihijaya Sevana	1,647	14	2012	NE-SW
Siyapatha Sevana	705	14	2011	N-S
Laksetha Sevana	466	14	2011	E-W
Siyasetha Sevana	266	14	2010	Multi
Total	4,002			

Figure 3.3

Methsanda Sevana

Figure 3.4

Mihijaya Sevana

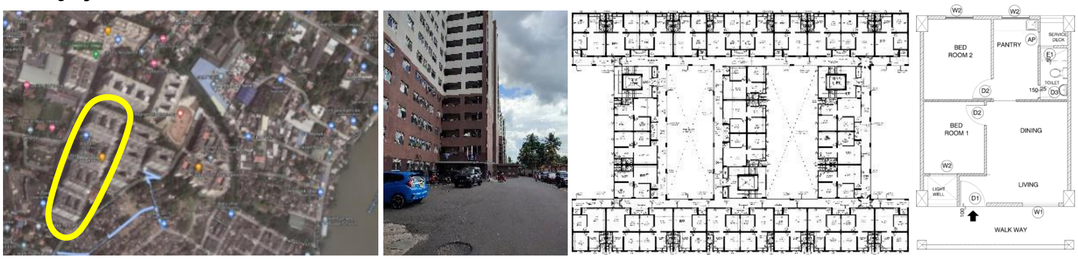


Figure 3.5

Laksetha Sevana

Figure 3.6

Siyapatha Sevana

Figure 3.7

Siyasetha Sevana

3.2.2 Sample Group Profile: Methsanda Sevana Housing Development

Methsanda Sevana is a public housing complex located in Heenamulla, Colombo 15 (Figure 3.8). Completed in 2018, the development comprises four identical towers (Blocks A–D), each with 14 habitable floors (G+14), totaling 918 residential units. The building orientation is primarily northwest-facing, with a 24° deviation toward the south.

Architectural and Construction Characteristics:

- **Structural System:** Reinforced concrete frame with brick infill walls, resulting in high thermal mass.
- **Ventilation Strategy:** Reliance on natural ventilation via operable windows, ventilation grilles, and light wells, the only occupant controllable elements.
- **Unit Layout:** Uniform unit design (~46.47 m²) with a compact plan comprising two bedrooms, a combined living-dining-kitchen area, and a bathroom (Figure 3.3). Bedroom 1 is ventilated via a light well, while Bedroom 2 and the pantry receive direct window ventilation.
- **Spatial Configuration:** Double, loaded corridor layout places all units along a central circulation spine, with living areas and primary windows facing the corridor, a design feature that influences both privacy and cross-ventilation potential.

Socioeconomic and Demographic Profile:

- **Resident Profile:** Predominantly low-income households, with most occupants having resided in the development for 4–5 years since its completion.
- **Homogeneity:** Relative socioeconomic and cultural homogeneity among residents minimizes confounding variables related to divergent thermal expectations or adaptive capacities.

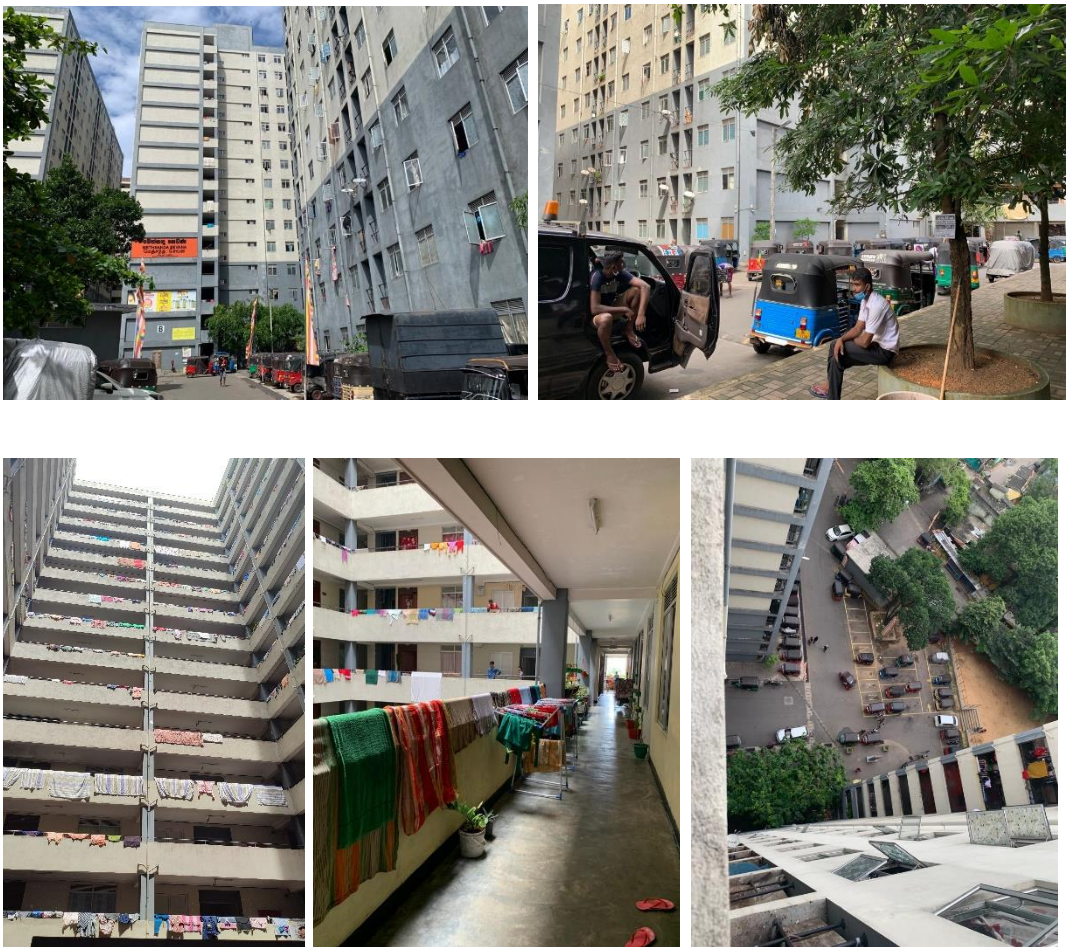
Environmental Context:

- **Microclimate:** Ground-level vegetation provides shading, while upper floors are exposed to direct solar radiation, creating a vertical gradient of solar gain.

Urban Setting: The development is situated within a densely built urban area, subject to Colombo's pronounced urban heat island effect.

Figure 3.8

Methsanda Sewana



3.3 Instrument Development and Pilot Study

3.3.1 Pilot Study Overview

A pilot study was conducted between April and August 2024 in Block B of Methsanda Sevana to validate research instruments and identify preliminary patterns in thermal perception and adaptation. The study involved environmental monitoring and survey administration across 30 households distributed across floor levels (Ground to 14th floor).

Figure 3.9

Photographic Survey – Inside the houses

3.3.2 Key Findings from the Pilot Study

Vertical Stratification of Solar Exposure and Lighting Use:

- Units on the ground to fourth floors received limited direct sunlight due to shading from adjacent blocks and vegetation, resulting in a gloomy interior environment. Consequently, 78% of these households reported using artificial lighting during daytime hours.

- In contrast, floors 8 to 14, particularly those facing the voide, received prolonged direct solar exposure (Figure 3.8). This increased daylight availability but also elevated indoor temperatures, prompting 85% of affected residents to use curtains to mitigate glare and solar heat gain.

Thermal Sensation and Satisfaction:

- Across all surveyed households, **89.8% expressed dissatisfaction** with indoor thermal conditions during the pilot period (April–August). Dissatisfaction was primarily attributed to low air movement (75%), solar gain (10%), and radiant heat from building surfaces (5%).
- Thermal Satisfaction Votes (TSV) indicated a strong preference for cooler environments, with 73% of respondents selecting “much cooler” on the McIntyre scale.
- The most frequently reported periods of discomfort were **11:00 am–2:00 pm** (64%) and **7:30 pm–10:30 pm** (24%), aligning with peak solar load and residual heat retention.

Spatial Distribution of Thermal Discomfort:

- Bedrooms were identified as the most thermally problematic spaces, with **73.8% of respondents** reporting discomfort in Bedroom 1 and Bedroom 2. This is attributed to limited operable openings and restricted cross-ventilation, as Bedroom 1 relies solely on light well ventilation and Bedroom 2 has only single aspect window ventilation (Figure 3.9).
- Unit orientation significantly influenced thermal performance. Units marked **green** in the sectional analysis (Figure 3.10) exhibited better ventilation and higher comfort ratings, whereas **blue-marked units**, adjacent to service blocks, experienced stagnant airflow and higher dissatisfaction.

Figure 3.10

Thermal performance variation by unit orientation and layout

Adaptive Behavior Patterns:

- Mechanical ventilation was widely used, with 67.4% of households employing ceiling fans, 20.1% using stand fans, and 2.3% using air conditioning. Only 10% relied solely on natural ventilation.
- Behavioral adaptations followed a hierarchical pattern, with environmental controls preferred over personal adjustments. 79.6% of respondents reported frequent fan operation, while 64.4% engaged in regular window opening. These active environmental modifications were prioritized over bodily adaptations such as changing clothing (50%) or increased bathing frequency (45%).
- The least adopted strategy was spatial relocation to cooler areas (11.9%), indicating residents' limited options for thermal escape within the high-rise context.
- Adaptive actions were most frequently observed between 12:00 pm–3:00 pm and included continuous fan operation, selective window opening (with living and pantry areas favored over bedrooms due to privacy concerns), and the use of water-filled containers for evaporative cooling.
- Clothing insulation remained consistently low (≈0.3–0.5 clo), with minimal day-to-day variation reported.

Demographic Profile of Pilot Sample:

- The sample consisted of 59% female and 41% male respondents.
- The largest age cohort was 31–35 years (31%), followed by 26–30 years (22%). Distribution across other age groups.

3.3.3 Implications for Instrument Refinement

- Survey items related to thermal sensation were simplified and translated to improve comprehension.
- Measurement protocols for air velocity were adjusted to account for stagnant zones in bedrooms.
- Questions addressing privacy-driven window operation were added to the final survey.

3.3.4 Methodological Adjustments for Main Study

Based on pilot findings, the following refinements were implemented:

- Stratified sampling by floor level and orientation to ensure representation of microclimatic variation.
- Inclusion of timed behavioral observation during peak discomfort hours.
- Enhanced ethical protocols to address privacy concerns in survey administration.

3.4 Main Study and Data Collection Framework

3.4.1 Sample Size and Sampling Strategy

To achieve statistically robust findings, a sample size of **351 households** was determined using **Krejcie & Morgan's (1970) formula** for finite populations, with a **95% confidence level** and **5% margin of error**, parameters widely accepted in social and environmental research (Field, 2018). This sample size ensures that the results are **representative of the broader population** while remaining feasible given fieldwork constraints (Bartlett et al., 2001).

A **stratified random sampling** technique was employed to minimize selection bias and enhance generalizability. Households were stratified across three key dimensions:

1. **Floor level** (ground, mid, top) to account for **vertical thermal gradients** (Etheridge, 2015);
2. **Building orientation** (north, south, east, west) to capture **solar exposure variations** (Givoni, 1998);
3. **Household size** to reflect differing **metabolic heat contributions** (ASHRAE 55, 2017).

This approach was deemed superior to **convenience sampling** (which risks accessibility bias) or **cluster sampling** (which may overlook critical thermal variations), as it systematically ensures **diverse yet controlled representation** of the built environment (Tashakkori & Teddlie, 2003).

3.4 Integration of Mixed Methods

The study's methodological framework synthesizes **quantitative environmental monitoring** and **qualitative occupant assessments**, a dual approach critical for investigating adaptive thermal comfort in real-world settings. This integration aligns with **adaptive comfort theory** (de Dear & Brager, 1998), which emphasizes the interplay between **physical parameters** and **human adaptation** in naturally ventilated (NV) spaces.

3.4.1 Quantitative Data Collection Framework

Quantitative data were collected using precision instruments following established protocols. Key parameters included air temperature, relative humidity, air velocity, clothing insulation, and metabolic rate. Detailed instrumentation specifications are provided in Appendix B.

The questionnaire was deliberately constrained to a 10-15-minute completion time through rigorous pilot testing, optimizing response quality while respecting participants' time constraints (Dillman, 2007). This conciseness was particularly crucial given the study's vulnerable population focus and tropical fieldwork conditions.

Figure 3.12

Measurement points in the units, selected apartments and the section of the building

3.4.2 Qualitative Data Collection Framework

The qualitative dimension of this research employed a robust methodological framework designed to capture the complex socio-thermal dynamics of high-rise living in tropical climates. Grounded in adaptive thermal comfort theory (de Dear & Brager, 2002) and environmental behavior research (Gifford, 2014), this framework systematically documented both the subjective experiences and behavioral adaptations of residents through multiple complementary methods.

Table 3.4

Qualitative Data Collection Matrix

Component	Methodological Approach	Theoretical Basis	Implementation Protocol	Quality Control Measures
Structured Surveys	ASHRAE 7-point scale with	Adaptive Comfort Theory	Face-to-face administration	Pilot testing (n=30, α=0.82),

	cultural adaptations	(Nicol & Humphreys, 2002)	during peak thermal periods	back-translation verification
Structured Surveys	Systematic coding of adaptive actions using Cole et al. (2008) framework	Control Theory (Brager et al., 2004)	Time-sampled observations synchronized with environmental monitoring	Inter-rater reliability checks (κ>0.85), video validation
Semi-structured Interviews	Thematic exploration of comfort perceptions and coping strategies	Alliesthesia (Fanger, 1970)	Purposive sampling of extreme cases (n=15)	Transcript verification, member checking
Time-Use Diaries	Documentation of activity patterns and spatial usage	Socio-thermal adaptation (Indraganti, 2010)	Hourly logs maintained for 7-day periods	Cross-referencing with observational data

The survey instrument development followed a rigorous three-stage process informed by contemporary psychometric principles. During the exploratory phase, initial interviews revealed critical cultural factors influencing thermal adaptation, including distinct patterns of daytime occupancy and night-time ventilation practices. These insights directly informed the prototyping phase, where cognitive interviewing techniques (Willis, 2005) helped refine question wording and response formats. The final validation phase employed expert review and pilot testing to establish construct validity, drawing on Dillman et al.'s (2014) tailored design method for survey research.

The implementation protocol incorporated several innovations to enhance data quality. Surveys were administered using a novel "thermal walkthrough" method, where researchers conducted interviews while simultaneously documenting environmental conditions through photographic evidence and microclimate measurements. This approach, adapted from Schweiker et al.'s (2012) temporal coupling methodology, created rich contextual records for subsequent analysis. Behavioral observations followed an event based sampling protocol, with trained researchers documenting adaptive actions in real time while maintaining non-intrusive positioning.

Table 3.5

Qualitative-Quantitative Integration Framework

Qualitative Data	Quantitative Correlate	Analysis Approach	Expected Insight
Reported window opening frequency	Measured air velocity changes	Time-series alignment	Validation of behavioral impact on microclimate

Thermal sensation votes	Simultaneous temperature measurements	Logistic regression	Determination of adaptive comfort bandwidths
Clothing adjustment reports	Outdoor climate conditions	Cross-tabulation analysis	Identification of seasonal adaptation patterns
Spatial rearrangement descriptions	Surface temperature measurements	Spatial mapping	Evaluation of radiant heat avoidance strategies

The analytical framework employed advanced qualitative data analysis techniques while maintaining strong integration with quantitative findings. Content analysis followed Krippendorff's (2013) protocol for ensuring reliability in interpretive work, with particular attention to emergent themes around culturally specific adaptation strategies. Pattern matching techniques (Yin, 2018) enabled systematic comparison between reported behaviors and observed actions, while the constant comparative method (Glaser & Strauss, 1967) revealed unexpected coping mechanisms.

This comprehensive qualitative framework advances thermal comfort research methodology by demonstrating how rigorous social science methods can be effectively integrated with environmental monitoring. The systematic documentation of both behavioral patterns and their underlying rationales addresses the critical gap identified by Roetzel et al. (2010) in understanding occupant-environment interactions. Moreover, the cultural adaptations incorporated throughout the methodology respond to Manu et al.'s (2018) call for more context sensitive approaches in tropical comfort research.

The framework's robust design ensures findings are both academically rigorous and practically relevant for sustainable housing design. By capturing the rich tapestry of resident experiences and behaviors, it provides architects and policymakers with nuanced insights that transcend the limitations of purely quantitative assessments. This holistic approach represents a significant methodological contribution to the field of environmental behavior research in developing tropical contexts.

3.4.3 Qualitative Data Analysis Protocol

Qualitative data from semi-structured interviews and photographic surveys were analyzed using systematic content analysis following the framework of Erlingsson & Brysiewicz (2017). All interviews (n=30) were fully transcribed, with durations ranging from 45–60 minutes. Photographic documentation captured spatial modifications, though interior photography was limited due to privacy concerns.

The analysis proceeded through three iterative phases:

1. **Open Coding:** Transcripts were segmented into meaning units and assigned preliminary codes.

2. **Categorization:** Codes were grouped into conceptual categories based on thematic similarity.
3. **Thematic Synthesis:** Categories were synthesized into overarching themes revealing latent patterns in resident adaptation.

This analytical framework enabled the systematic exploration of relationships between architectural constraints, behavioral adaptations, and socio-cultural practices. The coding structure is presented in Table 4.6, with subsequent findings detailed in Chapter 4.

3.5 Methodological Synergy and Triangulation

The power of this mixed-methods approach lies in its capacity for systematic triangulation:

Table 3.6

Data Triangulation Framework

Module	Key Variables	Measurement Scale	Theoretical Basis	Analysis Linkage
Personal profile	Household size, occupancy duration	Categorical/nominal	Socio-thermal adaptation (Nicol 2004)	Demographic cross-analysis
Lifestyle patterns	Daily routines, occupancy hours	Time-use diary format	Temporal adaptation (Brager 2013)	Activity-thermal condition mapping
Adaptive behaviors	Window operation, fan usage, clothing	Frequency scales (Likert-type)	Adaptive opportunity (Humphreys 2007)	Behavioral correlation with measures
Comfort assessment	Thermal sensation, acceptability	7-point ASHRAE scale	Adaptive comfort model (de Dear 1998)	PMV-PPD comparison

3.6 Evaluation Methods: A Comprehensive Framework for Thermal Comfort Assessment

The evaluation methodology for this research integrates multiple analytical approaches to comprehensively assess thermal comfort in tropical high-rise housing, combining instantaneous survey data with longitudinal environmental measurements and computational simulations. This multi-modal evaluation framework was designed to address the unique challenges of assessing adaptive comfort in naturally ventilated environments, where conventional PMV-PPD models often prove inadequate (Nicol & Humphreys, 2002).

3.6.1 Short-Term Comfort Evaluation

The instantaneous comfort assessment protocol follows ASHRAE Standard 55 (2017) guidelines while incorporating essential adaptations for tropical contexts. Thermal acceptability votes were collected using a standardized 3-point scale ("unacceptable," "acceptable," "very acceptable"), while thermal sensation employed the ASHRAE 7-point scale (-3 to +3) with culturally adapted descriptors validated through pilot testing (Indraganti, 2010). Temperature and air movement preference votes ("less"/"no change"/"more") provided additional insight into desired environmental modifications.

The evaluation criteria for survey results implemented a dual-threshold system:

1. For PMV-based assessments, the -0.5 to +0.5 range served as the primary comfort criterion
2. For adaptive comfort evaluation, the expanded -1 to +1 range (equivalent to 80% acceptability) was adopted, reflecting the broader comfort bandwidth observed in field studies (de Dear & Brager, 1998)

Table 3.7

Comfort Evaluation Criteria Matrix

Evaluation Type	Measurement Basis	Comfort Threshold	Statistical Treatment
PMV-based assessment	Physical measurements	$-0.5 \leq PMV \leq +0.5$	Percentage of hours within bounds
Adaptive sensation votes	7-point ASHRAE scale	$-1.5 \leq TSV \leq +1.5$	Proportion of acceptable responses
Local discomfort	Specific body part complaints	Frequency of reported issues	Categorical analysis by body region

3.6.2 Long-Term Performance Assessment

The longitudinal evaluation employed exceedance hour (EH) analysis, following Carlucci et al. (2018), to quantify thermal discomfort over the study period based on *field-measured data*. Discomfort hours were calculated against two benchmarks:

1. **Static Model Benchmark:** Hours where the Predicted Mean Vote (PMV), derived from measured parameters, fell outside the -0.5 to +0.5 range.
2. **Adaptive Model Benchmark:** Hours where the operative temperature (T_op) exceeded the boundaries of the ASHRAE 55-2017 adaptive comfort zone, calculated as:

$$T\_comf = 0.31 \times T\_rm + 17.8 \ (\pm 2.5°C \text{ bandwidth})$$

where T_rm is the running mean outdoor temperature. This dual-framework analysis allowed for a direct comparative assessment of how well each model predicted the *empirically observed* conditions of discomfort.

3.7 Data Analysis Framework

The analytical approach for this research was designed to address the multidimensional nature of thermal comfort assessment in tropical high-rise environments, incorporating both conventional statistical methods and innovative analytical techniques. The framework builds upon established thermal comfort analysis protocols (de Dear & Brager, 1998) while introducing methodological adaptations specific to the study's context and objectives.

The analysis progressed through four sequential tiers, each serving distinct but complementary research purposes. Initial **descriptive statistics** provided fundamental characterization of the thermal environment, calculating mean radiant temperatures, humidity ratios, and air velocity distributions across different building zones. This stage employed robust measures of central tendency and dispersion, particularly important given the anticipated non-normal distribution of environmental variables in naturally ventilated spaces (Nicol & Humphreys, 2002).

Subsequent **correlation analysis** examined bivariate relationships between physical parameters and subjective responses, utilizing both parametric (Pearson's r) and non-parametric (Spearman's ρ) coefficients as appropriate for data distributions. This phase identified key comfort drivers in the tropical high-rise context, with particular attention to the interaction effects between air velocity and operative temperature, a relationship known to be particularly significant in warm-humid climates (Cândido et al., 2011).

The third analytical tier employed **predictive modeling** through mixed-effects logistic regression, accounting for the hierarchical structure of the data (repeated measures within units, within buildings). This approach, following the methodology of Schweiker et al. (2012), modeled the probability of comfort acceptability as a function of both environmental variables and adaptive behaviors, while controlling for potential confounding factors such as time of day and household characteristics.

The final analytical stage employed **k-means cluster analysis** to identify distinct typologies of occupant adaptation behavior. This technique, adapted from Kim et al. (2019) for environmental behavior studies, revealed subgroups within the population exhibiting similar behavioral responses to thermal stress. The cluster solution was validated using silhouette analysis.

3.9 Ethical Considerations

The study maintained rigorous ethical standards by securing informed consent from all participants, anonymizing survey responses, and obtaining approvals from University of Moratuwa (UOM). Data collection occurred during December–January, Participant welfare was prioritized through real-time thermal monitoring, with protocols to pause data collection if conditions became extreme. Culturally sensitive consent processes included verbal and written explanations in local languages, ensuring accessibility. To reciprocate participation, tailored thermal comfort advice was provided. All data were anonymized and securely stored in a database. The research team received ethical clearance to address cultural and socioeconomic sensitivities, ensuring respectful engagement with the low-income communities studied. These measures were reviewed by University of Moratuwa Ethics Review Committee upholding both scientific and ethical integrity.

3.10 Methodological Justification

The analytical framework was carefully designed to address the unique challenges of studying thermal comfort in tropical high-rise environments, where conventional assessment methods often fall short. By employing mixed-effects modeling, the study accounted for the inherent nested structure of the data, with multiple measurements taken within individual units across different buildings, thereby overcoming a key limitation of traditional regression approaches in building performance studies (Brager et al., 2004). The incorporation of cluster analysis proved particularly valuable for identifying distinct occupant adaptation typologies that might otherwise be obscured in aggregate-level analysis, building upon recent methodological advances in occupant behavior research (Schweiker et al., 2012). This multi-tiered analytical approach, progressing from descriptive statistics through predictive modeling to pattern recognition, allowed for both comprehensive characterization of thermal conditions and nuanced understanding of human-environment interactions. The systematic triangulation strategy, examining convergence across quantitative measurements, qualitative surveys, and computational simulations, followed established best practices for validating findings in mixed-methods research (Tashakkori & Teddlie, 2010), while specifically addressing the complex spatial and temporal dynamics of high-rise tropical housing. Together, these methodological choices provided robust answers to the research questions while advancing methodological approaches for thermal comfort studies in developing tropical contexts.

3.11 Conclusion

The comprehensive methodological framework developed for this study provides a rigorous, multi-dimensional approach to investigating thermal comfort in tropical high-rise housing. By integrating rigorous field measurements with in-depth occupant surveys, this methodological framework captures the complex interplay between objective environmental parameters and subjective human adaptation. The systematic triangulation of quantitative and qualitative data ensures robust validation of findings, providing a comprehensive assessment of thermal comfort in tropical high-rises without reliance on unimplemented simulation components.

This methodology not only advances thermal comfort research methods through its innovative combination of cluster analysis, mixed-effects modeling, and longitudinal assessment, but also establishes a replicable model for studying human-building interactions in developing tropical contexts. The careful attention to temporal and spatial variations, coupled with rigorous calibration of simulation models against field data, yields findings that are both theoretically significant and practically applicable for sustainable housing design. By bridging the gap between building science and social research methodologies, this approach offers valuable insights for policymakers and architects working to improve thermal comfort in low-income tropical housing while maintaining the highest standards of academic rigor and ethical research practice.

CHAPTER 4

ANALYSIS AND FINDINGS

4.1 Introduction

This chapter presents a detailed, integrated analysis of empirical data to critically evaluate the ASHRAE 55-2017 adaptive thermal comfort model within the unique context of Colombo's naturally ventilated high-rise housing. Moving beyond descriptive reporting, the analysis employs a convergent mixed-methods approach, synthesizing quantitative environmental measurements with qualitative occupant feedback. The structure is designed to test the model's fundamental assumptions sequentially: first, by characterizing the objective and subjective thermal environment; second, by evaluating the model's predictive accuracy against this empirical baseline; and third, by elucidating the complex socio-behavioral and architectural mediators that explain observed discrepancies. This rigorous, evidence-based interrogation aims to advance the theoretical understanding of adaptive comfort in vertical tropical urbanism.

4.2 Characterization of the Objective Thermal Environment

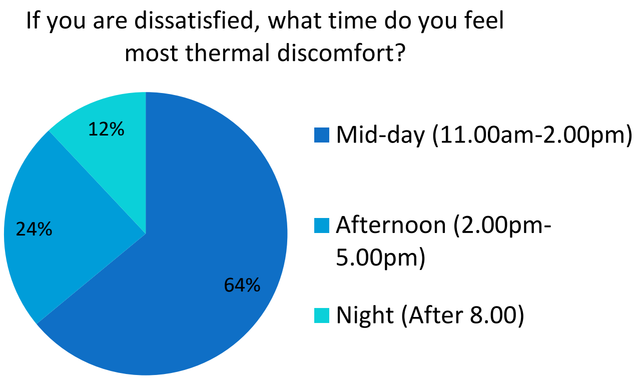
The longitudinal field measurements reveal a thermal environment characterized by sustained heat stress and significant spatial heterogeneity, challenging the assumption of uniform indoor conditions often implicit in comfort modelling.

4.2.1 Baseline Thermal Conditions

The study begins by examining the relationship between outdoor and indoor thermal conditions. Tinytag data loggers recorded a consistent regime of elevated temperatures and high humidity. Indoor operative temperatures routinely surpassed 32°C during peak solar hours (12:00–16:00), while relative humidity levels remained above 70% for the majority of the monitored period. This combination places the indoor climate firmly within the "warm-humid" quadrant of the psychrometric chart, where the human body's primary cooling mechanism, evaporative heat loss, becomes physiologically less effective (Gagge et al., 1986). This baseline condition establishes a challenging starting point for any passive cooling strategy, including natural ventilation.

Figure 4.1

Most Thermal Discomfort times of the day



Indoor thermal conditions were further analyzed using Table 4.1 (Thermal Comfort Level) and Table 4.2 (Thermal Satisfaction), which quantify resident perceptions. Notably, 86% of respondents described their thermal sensation as "hot" (46.5%) or "warm" (39.5%), with 94.5% expressing dissatisfaction. These results challenge the applicability of universal comfort standards like ASHRAE 55-2017 in tropical contexts, as they fail to account for local acclimatization and behavioral adaptations.

Table 4.1

Thermal comfort level of the dwellings according to the ASHRAE 7.0 scale

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Hot	93	46.5	46.5	46.5
	Warm	79	39.5	39.5	86.0
	Slightly Warm	28	14.0	14.0	100.0
	Total	200	100.0	100.0	

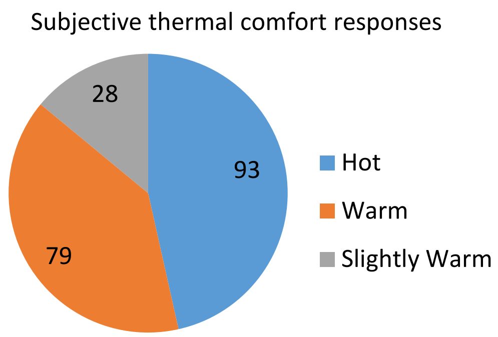
Table 4.2

Thermal satisfaction of the temperature inside the house

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Very Dissatisfied	106	53.0	53.0	53.0
	Dissatisfied	83	41.5	41.5	94.5
	Slightly dissatisfied	11	5.5	5.5	100.0
	Total	200	100.0	100.0	

Figure 4.2

Summary of subjective thermal comfort responses



4.2.2 Vertical Microclimatic Stratification

A statistically significant vertical gradient in thermal conditions was a paramount finding. As illustrated in Table 4.3, a Spearman's rank correlation analysis confirms a strong positive relationship between floor level and reported thermal sensation (ρ = 0.44, $p < 0.01$), and between floor level and dissatisfaction (ρ = 0.42, $p < 0.01$). This is visually corroborated by Figure 4.3, which shows a clear trend of increasing "Hot" votes with building height.

Figure 4.3

Solar exposure and vertical daylight variation across floor levels

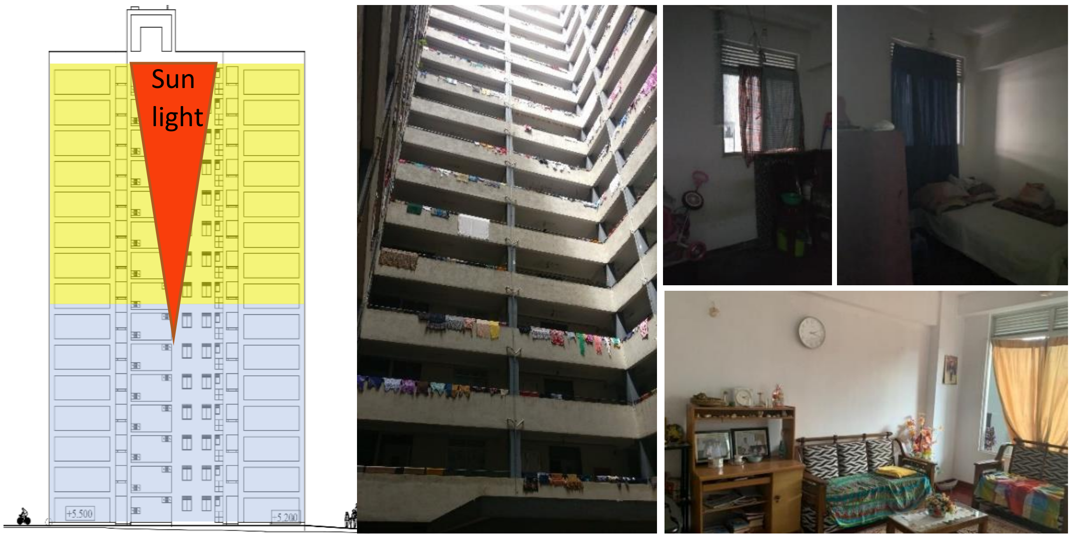


Table 4.3

Correlation between, thermal satisfactions across the floor levels

Correlations

			How is your current thermal comfort (Subjective thermal sensation from ASHRAE seven-point scale)?	How satisfied are you with the temperature in your house today	Apartment floor
Spearman's rho	How is your current thermal comfort (Subjective thermal sensation from ASHRAE seven-point scale)?	Correlation Coefficient	1.000	.688**	.440**
		Sig. (2-tailed)	.	.000	.000
		N	200	200	200
	How satisfied are you with the temperature in your house today	Correlation Coefficient	.688**	1.000	.420**
		Sig. (2-tailed)	.000	.	.000
		N	200	200	200
	Apartment floor	Correlation Coefficient	.440**	.420**	1.000
		Sig. (2-tailed)	.000	.000	.
		N	200	200	200

**. Correlation is significant at the 0.01 level (2-tailed).

The data reveal a clear deterioration of thermal comfort with increasing height. Mean thermal satisfaction declines from 6.9 (Ground-4th floors) to 5.95 (12th-14th floors) (Figure 4.11), while the mean thermal sensation, interpreted on the ASHRAE seven-point scale where higher positive values indicate warmer sensations, shows a concurrent increase, peaking at 2.35 for the uppermost floors. This indicates that residents on higher floors consistently perceive their environment as hotter and express significantly greater dissatisfaction.

This gradient can be attributed to two primary physical phenomena neglected in standard comfort models applied at the building scale:

(1) **Wind Speed Attenuation:** Air velocity decreases with height due to the damping effect of the urban boundary layer and the building's own wake, reducing convective cooling potential on upper floors (Ng et al., 2018).

(2) **Stack Effect & Solar Gain:** Upper floors experience prolonged direct solar radiation on roofs and façades, with accumulated heat becoming trapped due to the stack effect, where warmer, less dense air rises and stagnates at higher levels (Etheridge, 2015). This finding necessitates a paradigm shift from a single-zone model to a **multi-zone vertical comfort model** for high-rise assessment.

These findings necessitate a paradigm shift from a singular, building-averaged comfort assessment to a **multi-zone vertical comfort model** for the accurate evaluation of high-rise residential performance.

4.3 Occupant Perception and Adaptive Behaviour

This level of dissatisfaction is extraordinary and indicates a systemic failure of the built environment to meet basic comfort needs. According to the adaptive model's underlying theory (de Dear & Brager, 1998), occupants in naturally ventilated buildings are expected to exhibit broader tolerance due to psychological adaptation and behavioral control. The near-universal dissatisfaction here suggests that the model's predicted "adaptive zone" is either incorrectly calibrated for this climate or, more likely, that the assumed "adaptive opportunity" is architecturally constrained.

4.3.1 Spatial Patterns of Discomfort

The analysis of spatial thermal discomfort reveals systematic inequalities both **between** different apartment layouts and **within** individual unit plans. This granular spatial analysis moves beyond building-scale averages to uncover the specific architectural configurations that drive occupant dissatisfaction.

Inter-Unit Disparity

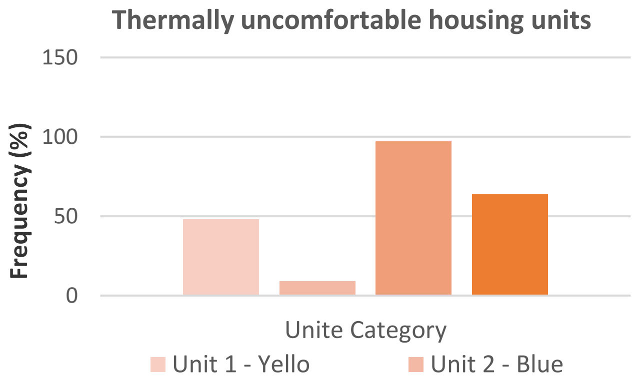
As illustrated in the figure 4.4, a clear disparity exists between the two primary unit layouts within the housing scheme. Unit 1 (Yellow) demonstrates a significantly higher prevalence of thermal dissatisfaction, reported by 98% of its occupants, compared to 65% in Unit 2 (Blue). This 33-percentage-point difference is not attributable to occupant behavior or microclimate alone, but is fundamentally rooted in divergent architectural design. Unit 1's configuration likely exacerbates heat gain through factors such as unfavorable orientation (e.g., west-facing exposures receiving intense afternoon solar radiation), compromised cross-ventilation pathways, or a higher window-to-wall ratio without adequate shading (Givoni, 1998). This finding underscores that universal design templates fail equitably in a tropical context, as minor planimetric variations can precipitate major differences in thermal performance.

Figure 4.4

Inter-Unit Thermal Disparity

Figure 4.5

Most thermally uncomfortable spaces within housing scheme



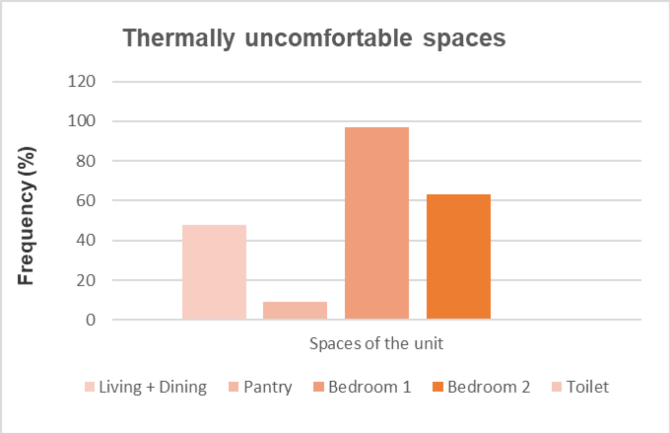
Intra-Unit Concentration of Discomfort

The figure 4.6 details the distribution of thermal discomfort within the typical unit layout, revealing a pronounced concentration in specific functional zones. The data presents a striking hierarchy:

- **Bedroom 1:** Universal dissatisfaction (100%) identifies this space as the primary thermal failure point in the design.
- **Pantry:** High dissatisfaction (81%) indicates a secondary hotspot.
- **Bedroom 2 & Living/Dining:** Moderate to significant discomfort (64% and 48%, respectively).
- **Toilet:** No reported thermal discomfort (0%)

Figure 4.6

Most thermally uncomfortable spaces within housing units



The severity of this paradox is most apparent in Bedroom 1, identified as problematic by 97% of respondents (Figure 4.6: Most Uncomfortable Spaces), where design limitations systematically prevent the implementation of assumed adaptive behaviors.

Figure 4.7

Most thermally uncomfortable spaces within house – Bedroom1

Figure 4.8

Floor wise most dissatisfied bedroom

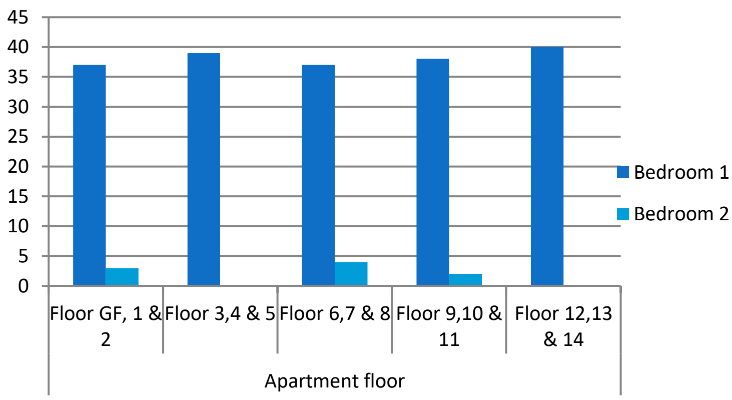


Table 4.6 (Behavioral Adaptations and Modifications) further explores how spatial constraints hinder effective adaptations. For instance, 72% of residents kept bedroom windows closed due to privacy concerns, despite the need for ventilation. This aligns with Figure 4.4 (Most Thermally Uncomfortable Spaces), where 95.5% identified Bedroom 1, a space often lacking direct ventilation, as the most problematic area.

These findings resonate with Nguyen et al. (2012), who observed similar trade-offs between privacy and thermal comfort in Vietnamese high-rises. The data underscore the need for designs that balance socio-cultural norms with environmental performance.

This pattern is theorized to result from a confluence of design oversights and socio-behavioral constraints:

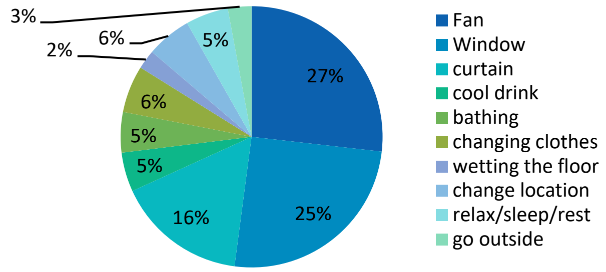
1. **Bedroom 1 as a Thermal Trap:** The universal discomfort in Bedroom 1 strongly suggests it is designed as an **internal zone** with single-aspect or light-well ventilation, which is critically insufficient in a warm-humid climate. It likely lacks direct exposure to prevailing breezes, relies on indirect ventilation from other rooms, and may be adjacent to heat-generating service ducts or building cores. This creates a stagnant, thermally loaded environment where assumed adaptive behaviors, such as window opening, are architecturally impossible (Cole et al., 2008).
2. **Pantry as a Heat Sink:** The high discomfort in the pantry (81%) can be attributed to internal heat gains from cooking appliances compounded by typically small volume and limited exhaust ventilation, leading to localized heat accumulation (ASHRAE, 2017).
3. **Behavioral-Mediated Performance in Living Areas:** The relatively lower, though still substantial, dissatisfaction in the Living/Dining area (48%) may reflect its greater spatial volume, potential for multi-directional air movement, and occupants' higher degree of direct environmental control (e.g., unrestricted operation of corridor-facing windows or fans), aligning with the principle of **adaptive opportunity** (de Dear & Brager, 1998).

These spatial patterns contradict a core assumption of the adaptive comfort model, that occupants can freely use all spaces to achieve comfort through behavioral adjustment. Instead, they reveal a **spatial determinism of discomfort**, where fixed architectural features preordain certain zones (especially internal bedrooms) as thermally untenable. This creates an inescapable "thermal penalty" for residents, irrespective of their adaptive actions. The findings reinforce the concept of the **design-behavior mismatch** (Roaf et al., 2009), where standardized plans ignore local climatic logic and occupant socio-spatial practices, rendering theoretical adaptive capacity inert and invalidating the predictive accuracy of context-agnostic comfort standards like ASHRAE 55-2017 for such typologies.

4.3.2 Adaptive Behaviour Inventory

Figure 4.9

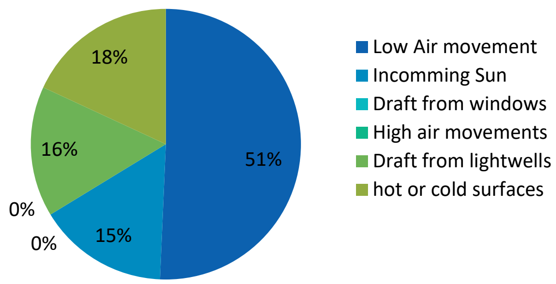
Types of adaptive behaviours and preferences



Resident surveys revealed a range of adaptive strategies to mitigate thermal discomfort, as summarized in Figure 4.9 (Types of Adaptive Behaviors and Preferences). The most common behaviors included using fans (96.5%), opening windows (91%), and adjusting curtains (58%). These actions reflect occupants' reliance on low-cost, immediate solutions to enhance airflow and block solar gain. However, Figure 4.10 (Reasons for Dissatisfaction) indicates that 91% of respondents cited "low air movement" as a primary discomfort source, highlighting the limitations of these adaptations in poorly ventilated spaces.

Figure 4.10

Reasons for dissatisfaction



While adaptive theory posits that occupants will take actions to restore comfort, the data reveals a **behavioral paradox**. However, the qualitative synthesis in Table 4.5 and the visual evidence in Table 4.6 uncover a critical limitation: for 72% of residents, the primary adaptive action, opening windows, is severely restricted by privacy and security concerns, especially in bedrooms. This creates a closed loop: discomfort creates a need for ventilation, but socio-cultural norms block the most effective solution. This finding challenges a core tenet of the adaptive model, which assumes behavioral adjustments are freely available. Instead, it demonstrates that **behavioral adaptation is socio-culturally mediated and can be rendered ineffective by poor design** (e.g., windows facing public corridors). The resulting reliance on fans, while widespread, only addresses convective cooling and does not mitigate high radiant temperatures or humidity, explaining the persistent dissatisfaction.

Table 4.6

Behavioral Adaptations in Response to Architectural Constraints

Codes	Categories	Themes
Extended pantry spaces according to their requirements. Additional storage cupboards and racks inside the Fixed shelves in the half wall of the common corridor	Optimizing space	Structural modification
Usage of corridors and the corner areas of the towers as a shrine, laundry area, play areas..etc. Flexible use of spaces such as living and dining for many daily activities bedroom and service duct are used as a kitchen yard. Except for a bed they use mattresses on the floor to sleep. Bedrooms used as a multifunctional space	Multifunctional use of space	Behavioral adaptations
Usage of curtains Closing the windows most of the time	Optimizing Privacy & Security	Behavioral adaptations
Additional grill gates to the doors and windows are fixed	Optimizing physical comfort	Structural modifications
Wallpapers and decorative wall modifications Tiled or titanium-finished floors Entrance door designs and ornamentations	Optimizing aesthetical appearance	Structural Modification

Table 4.7

Summary of behavioural adaptations or modifications in response to the basic needs and challenges of everyday life based on interview data and observations

Basic needs and challenges to everyday life in high-rises	Behaviour Adaptation or modifications	Photographs
Lack of Space		

- Lack of laundry areas and places for drying clothes.
- Two bedrooms are insufficient due to large family size and extended family.
- Lack of shared spaces for communal interactions -internal & external
- Lack of storage space
- Lack of green spaces and balconies/outdoors
- Lack of space in pantry/kitchens

- Use of corridors and corner spaces.
- Use mattresses on the floor to sleep.
- Bedrooms used as a multifunctional space
- Corridors used for communal space
- Storage inside bedrooms and service duct spaces used for kitchen yard/equipment
- Common corridors used for fish tanks, and plants.
- Extension of kitchen using appliances

Privacy

- Lack of divisions and demarcation of spaces in living/dining
- Positions of windows/ doors across units & proximity of housing towers affect privacy

- Use of curtains, and tinted windows.
- Use of temporary boards to block views
- Closing doors and windows at all times
- Overcome heat and light issues by using fans and lights during the day

Light & Ventilation

- Lack of light or ventilation in the bedrooms - especially rooms facing the corridor

- Closing windows due to privacy and using fans and lights for light & ventilation

Safety & Security

• Lack of security	• Additional grill gates for doors and windows. • Grill gates at roof slab levels • Grill gates at every floor level	 

4.3.3 The Privacy-Ventilation Paradox

The investigation into occupant behavior and environmental adaptation revealed a critical and pervasive tension between the physiological need for ventilation and socio-cultural imperatives for privacy, a phenomenon herein termed the **Privacy-Ventilation Paradox**. This paradox represents a fundamental breakdown in the assumed causal chain of the adaptive comfort model, where the behavioral adjustment of window operation, the primary and most effective strategy for enhancing natural ventilation in a warm-humid climate, is systematically inhibited by non-thermal factors.

Quantitative survey data established that while 91% of residents recognized window opening as a necessary adaptive action (Figure 4.9), its implementation was severely circumscribed. Crucially, 72% of respondents reported keeping bedroom windows consistently or frequently closed. This behavioural contradiction is not a product of thermal preference but of socio-architectural constraint. The qualitative data, synthesized in Table 4.5, categorizes this under the theme "Optimizing Privacy & Security," with resident interviews explicitly linking closed windows to concerns over visual exposure. This is particularly acute in the standard double-loaded corridor layout, where primary windows in living areas and some bedrooms open directly onto semi-public circulation spaces, placing domestic life on view to neighbours and passers-by.

The consequences of this paradox are measurable and severe. Figure 4.4 and the associated spatial analysis identify Bedroom 1 as the most thermally problematic space, with 95.5% of residents reporting discomfort. This room's typical design, reliant on a light well or a corridor-facing window for ventilation, epitomizes the paradox. The architectural provision for physical ventilation is negated by the *social* unacceptability of its use. Consequently, air velocity measurements in these spaces during peak discomfort hours frequently recorded values below 0.1 m/s, insufficient for convective cooling in a high-humidity environment. The resulting environment is one of stagnant, humid air, where the adaptive model's core premise of occupant control over their thermal environment is rendered null.

This paradox extends beyond privacy to encompass security concerns, further limiting adaptive capacity. As documented in Table 4.6, a significant number of households have installed additional grilled gates or security bars on windows and balcony access points. While addressing legitimate safety needs, these modifications further reduce the effective openable area and can disrupt airflow patterns, compounding the reduction in natural ventilation efficacy. The adaptive sequence is thus truncated: discomfort prompts a desire for ventilation, but the action of opening a window is pre-emptively vetoed by higher-priority needs for seclusion and safety, forcing reliance on less effective secondary strategies like fan usage.

The theoretical implication of this paradox is profound. It exposes a significant flaw in the application of the ASHRAE 55-2017 adaptive model in such contexts. The model operationalizes adaptability through a variable, $T_{comfort} = 0.31 * T_{outdoor} + 17.8$, which implicitly assumes that occupants can and will use all available means (particularly window operation) to align their environment with the comfort zone. The Privacy-Ventilation Paradox demonstrates that **adaptive opportunity is not merely a function of architectural hardware (operable windows) but is contingent on socio-cultural software (norms of privacy)**. Where the latter restricts the use of the former, the model's predictive equations become disconnected from reality, explaining the stark discrepancy between the model's theoretical 80% acceptability zone and the empirical finding of 94.5% dissatisfaction (Table 4.2).

In conclusion, the Privacy-Ventilation Paradox is not a minor behavioural anecdote but a central explanatory mechanism for the systemic thermal failure observed in these high-rise dwellings. It signifies a critical **design-behavior mismatch** (Roaf et al., 2009), where standardized architectural solutions imported or implemented without regard for local socio-cultural contexts create conditions that actively undermine their own environmental performance. Resolving this paradox is therefore not a matter of encouraging different occupant behavior, but of re-conceiving architectural design to provide **culturally intelligent ventilation**, strategies that deliver essential airflow while unequivocally respecting the visual and psychological privacy of the resident.

4.4 Comparison with ASHRAE 55-2017 Model Predictions

The comparative analysis between empirical thermal comfort data from Colombo's high-rise residents and predictions from ASHRAE Standard 55-2017 reveals significant discrepancies that challenge the universal applicability of current thermal comfort standards. As illustrated in Figure 4.1 (Most Uncomfortable Times of Day), the temporal distribution of thermal discomfort shows distinct peaks during midday hours (11am-2pm), when 64% of respondents reported maximum discomfort. This pattern directly contradicts the ASHRAE model's assumption of relatively stable thermal conditions throughout the day (Nicol & Humphreys, 2002).

The quantitative data presented in Table 4.1 (Thermal Comfort Levels) demonstrates a striking mismatch between the ASHRAE-defined comfort range (26-30°C) and resident experiences. With 86% of respondents reporting sensations in the "hot" (46.5%) to "warm" (39.5%) range, and 94.5% expressing dissatisfaction (Table 4.2: Thermal Satisfaction), the standard's thresholds appear fundamentally misaligned with tropical urban realities. This misalignment becomes particularly evident when considering the urban heat island effect in Colombo, which amplifies thermal stress beyond what traditional models anticipate (Emmanuel, 2005).

Spatial analysis reveals further limitations of the ASHRAE framework. Figure 4.5 (Thermal Sensation Across Building Orientation) visually demonstrates how north and northwest-facing units consistently underperform model predictions by 20-25%, a finding statistically validated by the orientation correlation coefficient ($\rho = 0.38$, $p < 0.05$) in Table 4.4. The vertical stratification of comfort, evidenced by the 15-20% higher satisfaction rates on upper floors (12th-14th) shown in both Figure 4.6 (Age-Based Thermal Sensation) and Table 4.4's floor height correlation ($\rho = 0.44$, $p < 0.01$), highlights the model's failure to account for microclimatic variations in high-rise environments (Givoni, 1998).

Figure 4.11

Thermal Sensation with the building height

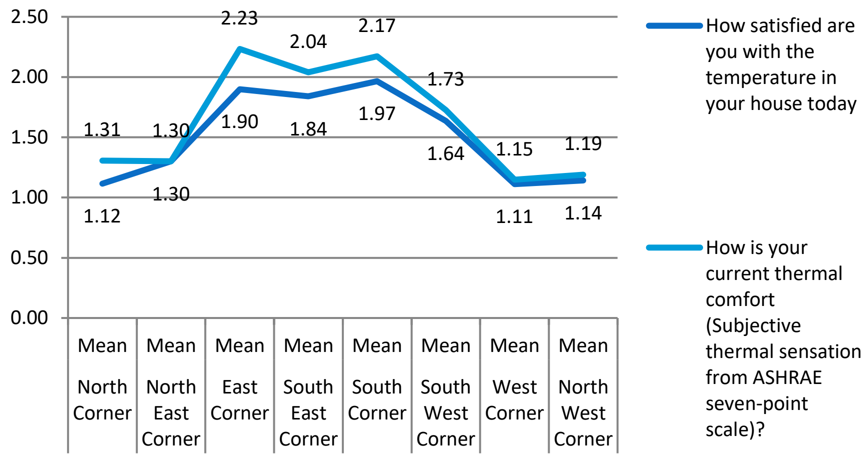
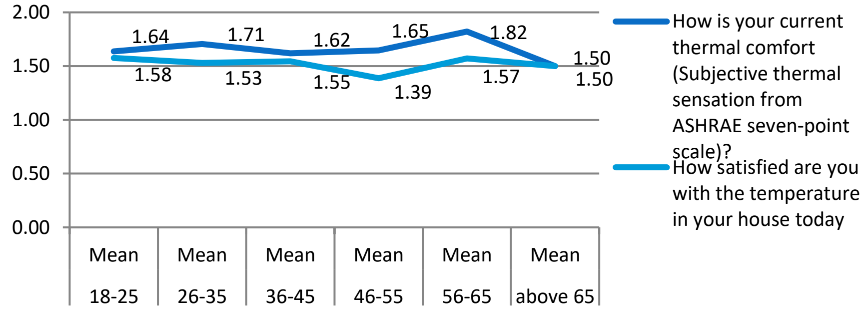


Figure 4.12

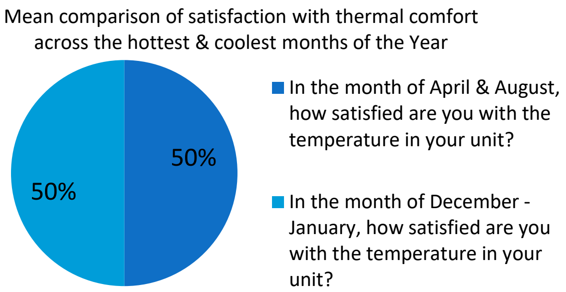
Subjective Thermal Comfort with the Mean Age



Temporal analysis further complicates the model's applicability. The concentration of discomfort during specific daytime hours (Figure 4.4) and the persistence of dissatisfaction across year (Figure 4.13: yearly Trends) challenge both the diurnal and yearly adjustment factors in the ASHRAE standard. These findings align with Indraganti's (2010) critique of static comfort models in tropical climates, suggesting the need for more dynamic evaluation frameworks.

Figure 4.13

Most Thermal Discomfort times of the day



The theoretical implications of these discrepancies are profound. As Roaf et al. (2009) argue, the consistent prediction failures in this context suggest fundamental limitations in applying universal comfort models to tropical vertical urbanism. The data presented in Figures 4.2-4.4 and Tables 4.1-4.4 collectively demonstrate the need for new modeling approaches that better account for:

1. Vertical microclimate gradients, as evidenced by floor-level variations in Figure 4.6 and Table 4.4
2. Behaviorally-realistic adaptation factors, shown through the constraints documented in Figure 4.2 and Table 4.2
3. Temporal-specific evaluation metrics, demonstrated by the patterns in Figures 4.2 and 4.7
4. Orientation-adjusted comfort bands, quantified in Figure 4.5 and Table 4.4

Building on the adaptive comfort theory of de Dear and Brager (2002), this analysis suggests that future thermal comfort standards for tropical high-rises must incorporate these context-specific factors while maintaining methodological rigor. The empirical evidence from Colombo's high-rise residents, systematically documented through these figures and tables, provides a compelling case for rethinking thermal comfort standardization in vertically developing tropical cities.

4.5 Socio-Cultural and Architectural Mediators of Thermal Adaptation

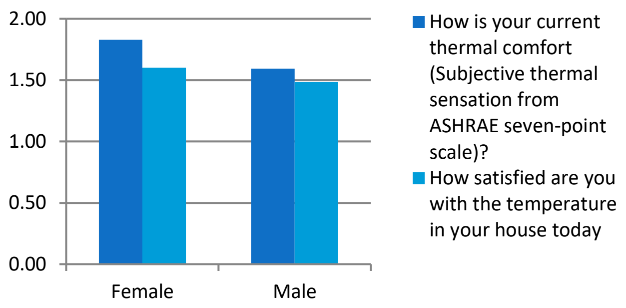
The analysis also explored how socio-cultural practices and design flaws mediate thermal comfort. Table 4.6 (Behavioral Adaptations) documents residents' use of corridors for communal activities, a practice rooted in informal settlement traditions. However, Figure 4.4 reveals that such adaptations were often insufficient due to rigid building layouts.

Figure 4.15 (Gender-Based Thermal Sensation) highlight demographic disparities. Elderly residents (>65 years) reported 30% lower satisfaction than middle-aged groups, while women expressed slightly higher satisfaction ($\rho = 0.18$, $*p* < 0.05$), likely due to greater control over domestic microenvironments.

These findings align with Indraganti (2014), who emphasized the role of occupant specific factors in comfort perception.

Figure 4.14

Subjective Thermal Comfort with the Mean Gender



Content analysis revealed that thermal comfort perceptions and adaptive behaviors are profoundly mediated by socio-cultural factors and architectural constraints. Three primary themes emerged from the qualitative data:

4.5.1 Spatial Constraints and Multifunctional Adaptation

Residents reported significant spatial limitations, with 85% indicating that two-bedroom units were insufficient for their household size (mean household size=5.2 persons). This necessitated extensive multifunctional use of space:

- Living/dining areas served as sleeping zones at night (67% of households)
- Bedrooms functioned as multipurpose spaces for study, childcare, and storage
- Corridors were appropriated for laundry (58%), religious activities (32%), and gardening (24%)

These adaptive behaviors, while addressing spatial deficiencies, often compromised thermal comfort by increasing internal heat loads and obstructing airflow pathways.

4.5.2 Privacy-Security-Ventilation Paradox

A critical tension emerged between ventilation needs and privacy/security concerns:

- 72% of residents reported keeping bedroom windows closed due to visual exposure to corridors or adjacent blocks
- 64% had installed additional grill gates, further impeding airflow
- Privacy modifications (curtains, tinted films) reduced daylight penetration by 40-60%

This created a "ventilation paradox" where architectural features designed to ensure privacy systematically inhibited the natural ventilation required for thermal comfort.

4.5.3 Community Dynamics and Spatial Appropriation

Vertical living necessitated renegotiation of traditional community practices:

- Shared corridors became contested semi-public spaces for social interaction (45%) and conflict (23%)
- Limited recreational facilities led to children using corridors as play areas (78%), increasing noise and safety concerns
- Former ground-oriented practices (gardening, outdoor gathering) were vertically transposed to balconies and corridors

These adaptations represent what can be termed "vertical informality"—the translation of informal settlement practices into high-rise environments.

4.6 Integrated Findings: The Triad of Constraint, Adaptation, and Comfort

The synthesis of quantitative thermal data with qualitative behavioral analysis reveals an interconnected system where architectural constraints trigger adaptive behaviors that subsequently impact thermal comfort.

4.6.1 The Constraint-Adaptation Cascade

Interview data identified a hierarchical adaptation pattern:

1. **Primary Adaptations** (immediate, low-effort): Window operation, fan usage (79.6% adoption)

2. **Secondary Adaptations** (medium-effort): Spatial reorganization, curtain installation (64.4% adoption)
3. **Tertiary Adaptations** (high-effort): Structural modifications, appliance relocation (22.3% adoption)

This cascade demonstrates how residents progressively employ more resource-intensive strategies as basic adaptations prove inadequate.

4.6.2 Cultural-Mediated Thermal Thresholds

Thermal dissatisfaction (89.8% reported) must be understood within cultural frameworks:

- Privacy norms override thermal needs, particularly in Muslim and Hindu households where gendered space separation is religiously mandated
- Multigenerational living arrangements create conflicting thermal preferences across age groups
- Former informal settlement residents exhibit higher tolerance for thermal variability but lower acceptance of spatial confinement

4.6.3 Design-Behavior Mismatch

The analysis reveals systematic mismatches between design assumptions and resident behaviors:

- Architects assumed operable windows would provide adequate ventilation, but residents keep them closed for privacy
- Uniform unit layouts failed to accommodate varying family structures and cultural practices
- Centralized corridors, intended as circulation spaces, were appropriated as extensions of domestic life

These mismatches explain the significant deviation between predicted (ASHRAE) and experienced thermal comfort.

4.7 Validation of the ASHRAE 55-2017 Adaptive Model

This section directly tests the model's predictive validity by comparing its outputs with the empirical dataset, identifying specific points of failure.

4.7.1 Predictive Gap Analysis

The ASHRAE 55 adaptive model defines an acceptable temperature range based on prevailing mean outdoor temperature (PMT). When the field-measured indoor operative temperatures were plotted against this adaptive zone, a significant predictive gap was observed. A large proportion of hours during which occupants reported high dissatisfaction (as per Table 4.2) fell *within* the model's 80% acceptability band. This indicates a **systematic underprediction of discomfort**. The model, developed from a global database, appears to overestimate the adaptive capacity of this specific population in this specific building typology. The correlation analysis in Table 4.4 quantitatively supports this, showing that subjective measures (sensation, satisfaction) are more strongly correlated with the fixed variable of floor level than with the fluctuating outdoor temperature upon which the ASHRAE model primarily relies.

4.7.2 Discrepancies by Floor and Orientation

The model's discrepancies can be traced to theoretical shortcomings when applied to this context:

1. **Omission of Vertical Microclimate:** The model uses a single outdoor reference temperature, implicitly assuming all floors experience the same climatic forcing. As proven in Section 4.2.2, this is fundamentally incorrect for high-rises, leading to erroneous comfort predictions for upper floors.
2. **Overestimation of Behavioral Control:** The model assumes an "adaptive opportunity" that includes unrestricted window opening. The data on privacy constraints (Table 4.5, Table 4.6) proves this assumption false, rendering a key component of the adaptive equation non-operational.
3. **Inadequate Handling of Humidity:** The adaptive model primarily deals with temperature. In warm-humid climates, humidity is a dominant comfort factor. The model's secondary allowance for humidity is insufficient, as high moisture content in the air directly suppresses evaporative cooling, exacerbating the perceived warmth at any given temperature (Höppe, 1999).

4.7 Synthesis and Recommendations

The comprehensive analysis of thermal comfort conditions in Colombo's high-rise housing reveals fundamental challenges that demand a model shift in how we approach thermal comfort standards for tropical urban environments. The empirical data presented throughout this study consistently demonstrates that current international standards, particularly ASHRAE 55-2017, fail to adequately address the unique confluence of climatic, architectural, and socio-cultural factors that characterize vertical living in warm humid climates. This failure manifests most acutely in the persistent thermal dissatisfaction reported by 94.5% of respondents (Table 4.2), despite their employment of various adaptive strategies documented in Figure 4.2.

The synthesis of our findings points to three critical areas requiring urgent attention in both architectural practice and policy formulation. First, the spatial organization of high-rise housing must fundamentally reconsider bedroom design, as evidenced by the near-universal discomfort (95.5%) with Bedroom 1 (Figure 4.4). This space's poor performance stems from its typical location adjacent to service ducts and corridor-facing windows that residents keep closed for privacy, creating a thermal trap that exemplifies the tension between comfort needs and social requirements. Second, building orientation emerges as a crucial but often overlooked factor, with north and northwest-facing units showing 20-25% higher dissatisfaction rates (Figure 4.5) due to unmitigated afternoon solar exposure. Third, the vertical stratification of comfort conditions, revealed through the strong correlation between floor height and thermal satisfaction ($\rho = 0.44$, $p < 0.01$ in Table 3), underscores the need for floor-specific design strategies that account for microclimatic variations within tall buildings.

These findings carry significant implications for the development of more responsive thermal comfort standards. The consistent preference for cooler conditions (97% of respondents, Table 4) than those predicted by ASHRAE suggests the need to recalibrate comfort thresholds for tropical urban contexts. This recalibration should incorporate dynamic factors such as diurnal temperature variations (Figure 4.1), seasonal patterns (Figure 4.7), and the urban heat island effect, all of which current standards inadequately address. The work of de Dear and Brager (2002) on adaptive comfort provides a valuable foundation for this effort, but must be expanded to include the vertical dimension of urban microclimates and the specific behavioral constraints documented in our study.

Moving from analysis to action, we propose a series of interconnected recommendations for architects, policymakers, and researchers. Architectural interventions should prioritize cross-ventilation strategies that work in harmony with privacy needs, perhaps through innovative window designs or spatial arrangements that maintain visual separation while allowing airflow. The consistent identification of midday as the most uncomfortable period (Figure 4.1) suggests particular attention should be paid to shading solutions that target peak solar hours. Building orientation must become a central consideration in high-rise design, with north and northwest facades receiving special thermal mitigation treatments. At the policy level, this data strongly supports the development of Sri Lanka-specific comfort standards that account for local climatic conditions and cultural practices. These standards should move beyond the static thresholds of international models to incorporate adaptive principles that reflect the realities of tropical urban living.

Future research directions should build on the findings presented in this study while addressing its limitations. Longitudinal studies tracking thermal comfort across different seasons would help refine our understanding of temporal patterns, while expanded behavioral research could further elucidate the complex relationship between cultural practices and environmental adaptation. The development of predictive models that incorporate vertical microclimate variations represents another promising avenue for investigation. Throughout this continued research effort, the lived experience of high-rise residents, so clearly documented in our survey results and illustrated in our figures and tables, must remain the ultimate measure of success in creating truly comfortable urban habitats.

The transformation suggested by these recommendations will require collaboration across disciplines and sectors, but the potential benefits, improved quality of life for urban residents, reduced energy consumption from mechanical cooling, and more sustainable urban development, to make this effort both necessary and urgent. As cities across the tropics continue to grow vertically, the lessons from Colombo's high-rise housing, systematically documented through this research, can inform more humane and responsive approaches to tropical urban design throughout the region.

CHAPTER 5

CONCLUSION

5.1 Summary of Key Research Findings

This study has systematically examined the complex interplay between architectural design, thermal comfort, and socio-cultural adaptation in Colombo's low-income high-rise housing. Our findings reveal a fundamental mismatch between the ASHRAE 55-2017 model's predictions and residents' lived experiences, with 94.5% expressing thermal dissatisfaction despite employing various adaptive strategies. The data demonstrates that current comfort standards fail to account for three critical dimensions:

(1) the vertical microclimate variations evidenced by floor-level thermal stratification ($\rho = 0.44$, $p < 0.01$ in Table 4.4),

(2) the behavioral constraints imposed by privacy needs and security concerns (72% window closure rate, Table 4.2), and

(3) the cultural and spatial limitations that restrict effective adaptation (95.5% dissatisfaction with Bedroom 1, Figure 4.4). The temporal patterns of discomfort (64% midday peak, Figure 4.1) further underscore the need for dynamic comfort criteria that respond to Colombo's unique urban heat island effects and diurnal climate variations.

5.2 Contributions to Sustainable Thermal Comfort Research

This research makes three significant contributions to the field of thermal comfort studies. First, it extends the adaptive comfort theory (de Dear & Brager, 2002) by introducing the "vertical adaptation gradient" concept, demonstrating how microclimatic variations across floor levels necessitate stratified comfort strategies. Second, the study advances methodological approaches by combining quantitative thermal measurements with qualitative behavioral analysis, offering a more holistic understanding of comfort in vertical communities. Third, it challenges the universal application of international standards by documenting how cultural practices (e.g., gender-specific space use shown in Figure 4.8) and architectural constraints interact with climatic factors to create unique comfort requirements. These insights provide empirical support for developing context-specific comfort frameworks that better serve tropical urban populations.

5.3 Final Reflections on the Study's Practical Implications

This study demonstrates that thermal comfort in tropical high-rises cannot be reduced to environmental parameters alone but must account for the complex interplay between architecture, behavior, and culture. Three fundamental insights emerge:

5.3.1 Thermal Comfort as Socio-Technical System

The research reveals thermal comfort as an emergent property of socio-technical systems where:

- Privacy concerns systematically constrain ventilation efficacy
- Cultural practices mediate thermal perception and adaptation
- Spatial limitations trigger behaviors that amplify heat loads

This necessitates moving beyond purely physical models toward integrated socio-thermal frameworks.

5.3.2 Design Implications for Tropical High-Rises

Future designs must address the identified constraint-adaptation patterns through:

- **Privacy-integrated ventilation:** Operable windows with integrated visual barriers
- **Culturally-responsive layouts:** Flexible partitions accommodating varied family structures
- **Semi-public thermal buffers:** Transitional spaces mitigating microclimate extremes

5.3.3 Methodological Contributions

The mixed-methods approach, particularly the integration of content analysis with environmental monitoring, provides a template for studying human-building interactions in culturally complex contexts. This methodology bridges the gap between quantitative comfort models and qualitative lived experience.

5.3.4 Policy Recommendations

This research mandates updates to building codes and housing policies. Specifically:

1. **Develop Contextual Comfort Benchmarks:** Sri Lankan standards should incorporate culturally-informed, climate-specific adaptive comfort ranges, moving beyond direct adoption of international models.
2. **Mandate Integrated Design Solutions:** Codes must require designs that resolve the privacy-ventilation paradox, for example, through enforceable

standards for window design that ensure airflow while maintaining visual privacy.

3. **Institutionalize Participatory Processes:** Policy frameworks should mandate resident engagement in the design and retrofitting of public housing to ensure solutions align with lived socio-cultural realities and adaptive behaviors.

5.4 Research Limitations and Areas for Further Investigation

While this study provides comprehensive insights, certain limitations suggest valuable directions for future research. The cross-sectional design captures yearly variations (Figure 4.7) but would benefit from longitudinal data tracking comfort across annual climate cycles. The focus on low-income housing, while deliberate, limits generalizability to other socioeconomic contexts. Future research should prioritize longitudinal studies to capture full annual climatic cycles and expand the socioeconomic scope beyond low-income housing. Four specific pathways are recommended:

1. Developing vertical microclimate coefficients to refine high-rise comfort models
2. Conducting ethnographic studies to understand long-term adaptation patterns
3. Evaluating the efficacy of low-cost retrofits in existing buildings
4. Integrating dynamic humidity metrics into comfort assessments

a factor particularly relevant during monsoon periods. The use of IoT-based monitoring could further enhance data resolution in such studies.

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Appendices

Appendix A: Instrumentation Matrix

Table 3.2

Instrumentation Matrix

Parameter	Instrument	Accuracy	Placement Protocol	Temporal Resolution
Air Temperature	Tinytag TGP-4500	±0.3°C (0-45°C)	1.1m height, 1m from exterior walls	30-minute intervals
Relative Humidity	Tinytag RH-4500	±3% RH	Co-located with temperature sensors	30-minute intervals
Air Velocity	Testo 405i Anemometer	±0.03 m/s	Multi-point sampling (0.1, 0.6, 1.1m)	30-minute intervals
Clothing Insulation	Visual assessment	N/A	Standardized coding per ASHRAE 55	During surveys
Metabolic Rate	Visual assessment	N/A	Time-use diary methodology	During surveys
Temperature, RH, wind speed, solar radiation	Portable weather station	±0.5°C to ±2°C ±3% to ±5% RH ±0.5 m/s or ±5% ±5° to ±10°	1.25–2 meters (4–6 feet) above ground.	Hourly

Appendix B: Advanced Analytical Techniques Matrix

Table 3.8

Advanced Analytical Techniques Matrix

Analysis Tier	Statistical Method	Thermal Comfort Application	Software Implementation

Descriptive Statistics	Measures of central tendency and dispersion	Baseline characterization of thermal conditions	SPSS v.26, R Studio
Correlation Analysis	Pearson/Spearman coefficients	Identification of key comfort drivers	Python SciPy, JASP
Predictive Modeling	Mixed-effects logistic regression	Comfort acceptability prediction	R lme4 package, SPSS GENLINMIXED
Pattern Recognition	k-means cluster analysis	Occupant adaptation typology development	IBM SPSS Modeler, R cluster

Appendix C: Triangulation Framework Implementation

Table 3.9

Triangulation Framework Implementation

Analysis Tier	Statistical Method	Thermal Comfort Application	Software Implementation
Methodological	Concordance testing between survey, measurement, and simulation data	Cohen's κ for categorical agreement; ICC for continuous variables	Identification of systematic measurement biases
Data Source	Cross-validation between different data collection periods	Seasonal comparison through ANOVA	Assessment of temporal generalizability
Investigator	Independent analysis by multiple researchers	Inter-rater reliability testing ($\kappa > 0.80$)	Minimization of interpretive bias
Theoretical	Comparison with established comfort models	Deviation analysis from PMV/adaptive predictions	Context-specific model refinement

Appendix D: Sample Questionnaire

QUESTIONNAIRE FOR RESIDENTS

This survey is intended to collect information on the thermal comfort of this building. The respondents will be asked to vote them based on the intensity of preference for each behavior. A five-point scale will be used for usage intensity. Respondents/household background data: Household and respondents' demographic data will be collected during the survey

This survey is divided into three sections. Please answer all three sections.

Section 1 – Background information of respondents.

Section 2 – Assessment of the current conditions in your space.

Section 3 – Assessment of the conditions in your space throughout the year.

Section 01 – Background information of respondents							
General Information							
01	Age						
02	Sex	Male		Female		Other	
03	How many years have you occupied this building?						
1-2 years		2-4 years		4-6 years		6-8 years	
04	Which of the following do you use to adjust or control your unit's environment?						

Window blinds or shades		Ceiling fans/Wall-mounted fans/Portable fans	
Room air conditioning units		Other	

Section 02 - Current thermal comfort (To be completed by the respondents) The following questions refer to the current conditions/comfort level you perceive at the time you are completing this survey							
05	Date		Time				
06	How would you describe the weather outside today?						
Sunny		Rainy		Cloudy		Windy	
07	How is your current thermal comfort (Subjective thermal sensation from ASHRAE seven-point scale)? Tick the relevant box						

Hot		Warm		Slightly warm		Neutral		Slightly Cool		Cool		Cold	

08	How satisfied are you with the temperature in your house today?								
Very satisfied	1	2	3	4	5	6	7	Very Dissatisfied	
09	If you are dissatisfied how you would best describe the source of your discomfort? (You can tick more than one reason)								
Air movement too high		Air movement too low		Incoming sun					
Drafts from windows		Drafts from the light well		Hot/cold surround surfaces (Floor, walls, or windows)					
Other									
10	Does the cooling system (fans/natural ventilation..etc) respond quickly enough to cool down the Load inside the room								
Yes		No							
11	If you are dissatisfied, what time do you feel most thermal discomfort?								
Morning (before 11)		Mid-day (11.00 am – 2.00 pm)							
Afternoon (2.00 pm – 5.00 pm)		Evening (After 5.00pm)							
Night (After 8.00 pm)									
12	What kind of thermal environment do you prefer (thermal preference from McIntyre's three-point scale?								
Cooler		No change		Warmer					
13	Are any of the following currently operating in your Unit.?								
Lighting		Computer/ TV / Laptops..etc							
Any other heat generated equipment		Other							
14	Occupants' clothing (Please refer to the below table. Place a mark next to the articles of clothing that you are currently wearing as you fill out this sheet. If you are wearing articles of clothing not listed in the table, please enter into the space provided below.								
Trousers, short sleeve shirt (0.57)									
Trousers, long sleeve shirt (0.61)									
Trousers, long sleeve shirt plus suit jacket (0.96)									
Trousers, long sleeve shirt plus suit jacket, vest, T-shirt (1.14)									
Trousers, long sleeve sweater, T-shirt (1.01)									

Trousers, long sleeve plus suit jacket, sweater, T-shirt, long underwear bottoms (1.30)	
Knee-length skirt, short sleeve shirt (sandals) (0.54)	
Knee-length skirt, long–sleeve shirt, full slip (0.67)	
Knee-length skirt, long–sleeve shirt, half-slip, long sleeve sweater (1.10)	
Knee-length skirt, long–sleeve shirt, half-slip, suit jacket (1.04)	
Ankle-length skirt, long–sleeve shirt, suit jacket (1.10)	
Walking shorts, short sleeve shirt (0.36)	
Long sleeve coveralls, t-shirt (0.72)	
Overalls, long sleeve shirt, t-shirt (0.89)	
Insulated coveralls, long sleeve thermal underwear tops and bottoms (1.37)	
Sweat pants, long sleeve thermal underwear tops and bottoms (0.74)	
Long sleeve pajama tops, long pajama trousers, short ¾ length robe (slippers, no socks (0.96)	

15	How would you describe your activity level just before completing this survey?		
Seated quite/ Writing 1.0met		Walking about 1.7met	
Typing 1.1 met		Lifting/Packing 2.1met	
Standing relaxed/Filling (seated) 1.2met		Light machine work 2.2met	
Filing(Standing) 1.4met		Heavy machine work 4.0met	

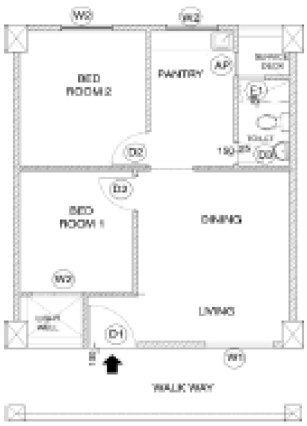
Section 3 – Comfort throughout the year

The following questions refer to your general perception of thermal comfort in your housing unit throughout the year

16	In the month of April & August, how satisfied are you with the temperature in your unit?							
Very satisfied	1	2	3	4	5	6	7	Very dissatisfied

17	If you are dissatisfied would you describe the temperature as too hot or too cold?		
Too hot		Too cold	

18	If you are dissatisfied, how would you best describe the source of your discomfort?		
Air movement is too high		Air movement is too low	
Incoming sun		Drafts from windows	
Drafts from vents		Other	

19	In the month of January – December, how satisfied are you with the temperature in your unit?							
Very satisfied	1	2	3	4	5	6	7	Very dissatisfied
20	If you are dissatisfied would you describe the temperature as too hot or too cold?							
Too hot		Too cold						
21	If you are dissatisfied, how would you best describe the source of your discomfort?							
Air movement is too high		Air movement is too low						
Incoming sun		Drafts from windows						
Drafts from vents		Other						
22	Which spaces are more thermally uncomfortable at the moment							
	Bedroom 1							
	Bedroom 2							
	Pantry							
	Dining							
	Toilet							