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Energy and Comfort Performance of Fan-Assisted Mixed-Mode Cooling: A Tropical Case Study

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When it all started ...

"Atmospheric conditions in the tropics have serious effects, both physical and mental, upon the inhabitants. In an article in the Electrical Review of November 8, Prof. C. A. Middleton Smith of the University of Hong Kong states that it is difficult for those who live in temperate regions to realise the depression produced on human energy by living for months in a climate with a night and day temperature of about 90° F (32°C) and a relative humidity of more than 90 per cent. With the help of electrical power and the new methods of producing cold mechanically, it is now possible to manufacture climatic conditions that are almost perfect. By the use of a small electrically driven machine in his private room in the University, Prof. Smith can make the climate in it as pleasant as on a summer day in England. Six hours after the machine has been at work, it has extracted a gallon and a half of water from the air in the room. The effect of the two contrasting atmospheric conditions within and outside the room upon bodily comfort is most marked, and he has found by experience that he can double his lecture hours and yet be less fatigued at the end of the day. He says that no educated person in the tropics who can afford an electrically driven refrigerator would now risk having a 'disease-carrying' icebox. He has, for the last sixteen years, advocated air-conditioning in the tropics. One of the most extensive applications of the system in China today is that of the new million-pound building of the Hong Kong and Shanghai Bank. There are six air conditioning plants for the whole building. Electric motors are used for driving ammonia compressors. Three pumps are required for the condenser water circulation, and there are six inlet fans which drive 229,000 cubic feet of air a minute. The total rating of the electric motors used is 800 horse-power."

Air-Conditioning in the Tropics. Nature 136, 905 (1935)

Abstract

Rethinking comfort and cooling usage in indoor spaces bring an opportunity to address the projected rise in cooling demand and support the energy transition. Assessing energy use and comfort of alternative cooling solutions in buildings is crucial for the Architecture, Engineering, and Construction industry.

Mixed-mode cooling strategies bridge the gap between often treated as opposed Air Conditioned (AC) buildings and Naturally Ventilated (NV) buildings. They are gaining interest in the built environment for both hot climates and heatwave management. They have been shown to deliver satisfaction levels equal to or higher than those of conventional mechanically cooled systems at a lower energy cost. Fan-assisted Mixed-mode cooling strategies combine the air movement from ceiling fans with both NV and AC operations. They aim to provide comfortable indoor conditions while reducing reliance on mechanically cooled systems alone, thereby lowering cooling energy use. Indeed, air movement from fans can delay the start of air conditioning and allow a more flexible thermostat setpoint. Despite this potential, the quantification of the effective performance of Fan-assisted mixed-mode cooling strategies remains sparse and under-recognized. Furthermore, they lack a robust evaluation and end-to-end design toolchain, which limits their adoption in the built environment.

This dissertation addresses these gaps by (i) evaluating the performance of various cooling strategies of an in-use mixed-mode building in a tropical climate. It introduces (ii) a method to select a thermal comfort index suitable for mixed-mode applications with significant air movement and (iii) a co-simulation framework able of reproducing the complete sequence of various mixed-mode cooling operations.

The two-year experimental study adds to a better understanding of the role of ceiling fans coupled in both NV and AC cooling operations. It shows that mixed-mode fan-assisted strategies provide acceptable comfort for more than 90% of occupants at very low energy cost. Operation with ceiling fans maintains satisfactory conditions while greatly reducing the need for air conditioning, with consumption up to four times lower than that of a comparable conventional building. Test periods without fans have shown that acceptable conditions drop sharply and air conditioning use increases significantly, with no noticeable improvement in perceived comfort. Overall, the results confirm the key role of air movement in maintaining comfortable indoor conditions at very low energy use.

The proposed comfort model selection process combines an extensive review of thermal comfort theories and models with qualitative and quantitative screening and sensitivity analyses based on hot-season field campaigns, including environmental monitoring, energy measurements, and occupant feedback. Selection is based on the comfort index's ability to represent adaptive mechanisms, predict occupants' thermal sensation under hot, humid conditions, and respond appropriately to controllable cooling parameters.

Building on these conclusions, a flexible, easy-to-implement simulation framework is designed to investigate alternative cooling control strategies and their impact on both comfort and energy use. The proposed framework enables the simulation of any uncontrolled or comfort-based control scenario. Results prove that comfort-based mixed-mode control can target comfortable conditions while delaying or reducing the intensity of air-conditioning operation, thereby achieving lower cooling energy consumption.

Beyond the performance study that illustrates the relevance of MM operation, this work proposes an integrated methodology that combines literature-based qualitative model selection, quantitative validation by field observations, and simulation-based analysis to support the design and evaluation of mixed-mode cooling strategies.

Keywords: Mixed-mode buildings; Ceiling fans; Thermal comfort; Tropical climate; Building energy modeling (BEM); Co-simulation

Résumé

Repenser le confort et l'utilisation du rafraîchissement dans les espaces bâtis offre l'opportunité de répondre à la hausse de la demande en climatisation et de soutenir la transition énergétique. L'évaluation de la consommation énergétique et du confort des solutions de rafraichissement alternatives est cruciale pour le secteur de l'architecture, de l'ingénierie et de la construction.

Les stratégies de rafraîchissement hybrides comblent le fossé entre les bâtiments climatisés (AC) et les bâtiments à ventilation naturelle (NV), souvent considérés comme opposés. Elles suscitent un intérêt croissant dans le secteur du bâtiment, tant pour les climats chauds que pour la gestion des vagues de chaleur. Il a été démontré qu'elles offrent des niveaux de satisfaction égaux, voire supérieurs, à ceux des systèmes de refroidissement mécanique conventionnels, tout en nécessitant un coût énergétique moindre. Les stratégies de refroidissement hybrides assistées par ventilateur combinent le mouvement d'air des ventilateurs de plafond avec la ventilation naturelle et la climatisation. Elles visent à assurer des conditions intérieures confortables tout en réduisant la dépendance aux seuls systèmes de refroidissement par compression mécanique, ce qui diminue la consommation d'énergie liée au refroidissement. En effet, le flux d'air des ventilateurs peut retarder le démarrage de la climatisation et offrir une flexibilité accrue dans le réglage de la consigne. Malgré ce potentiel, la quantification des performances effectives des stratégies de refroidissement hybrides assistées par ventilateur reste rare et sous-estimée. De plus, l'absence d'une chaîne d'outils robuste d'évaluation et de conception de bout en bout limite leur adoption dans le secteur du bâtiment.

Cette thèse contribue à combler ces lacunes en (i) évaluant la performance de différentes stratégies de refroidissement d'un bâtiment mixte dans un climat tropical. Elle présente (ii) une méthode de sélection d'un indice de confort thermique adapté aux applications mixtes en présence d'une importante circulation d'air et (iii) propose un cadre de co-simulation capable de reproduire la séquence complète de différentes opérations de rafraîchissement en mode mixte.

L'étude expérimentale menée sur deux ans contribue à une meilleure compréhension du rôle des ventilateurs de plafond lorsqu'ils sont couplés aux systèmes de refroidissement par ventilation naturelle et par climatisation. Elle montre que les stratégies de refroidissement en mode mixte assistées par ventilateurs offrent un confort des occupants acceptable à plus

de 90%, ceci à un coût énergétique très faible. Le fonctionnement avec des ventilateurs de plafond maintient des conditions satisfaisantes tout en réduisant considérablement les besoins en climatisation, avec une consommation jusqu'à quatre fois inférieure à celle d'un bâtiment conventionnel comparable. Les périodes de test sans ventilateurs ont montré une chute brutale des conditions acceptables et une augmentation significative de l'utilisation de la climatisation, sans amélioration notable du confort perçu. Globalement, les résultats confirment le rôle essentiel de la circulation de l'air dans le maintien de conditions intérieures confortables, tout en minimisant la consommation d'énergie.

Le processus de sélection du modèle de confort proposé combine une analyse approfondie de la théorie du confort thermique, la confrontation entre prédiction et mesure, et une analyse de sensibilité, toutes deux fondées sur des campagnes de terrain menées en saison chaude. Ces campagnes incluent la mesure physique environnementale, les consommations énergétiques et les retours des occupants. La sélection repose sur la capacité de l'indice de confort à représenter les mécanismes d'adaptation et à prédire la sensation thermique des occupants dans des conditions chaudes et humides, tout en restant compatible avec une logique de pilotage.

À partir de ces conclusions, un cadre de simulation flexible et facile à mettre en œuvre a été conçu pour étudier différentes stratégies de pilotage du rafraîchissement et leur impact sur le confort et la consommation d'énergie. Ce cadre permet de simuler tout scénario de pilotage, qu'il soit non contrôlé ou basé sur le confort. Les résultats démontrent qu'une régulation mixte basée sur le confort permet d'atteindre des conditions confortables tout en retardant ou en réduisant l'intensité du fonctionnement de la climatisation, ce qui permet de réduire la consommation d'énergie liée au rafraîchissement.

Au-delà de l'étude de la performance du rafraîchissement mixte, qui illustre la pertinence de son fonctionnement, ce travail propose une méthodologie intégrée combinant la sélection qualitative de modèles issus de la littérature, la validation quantitative par des observations de terrain et l'analyse par simulation afin de soutenir la conception et l'évaluation de stratégies de rafraîchissement en mode mixte.

Mots-clés: Bâtiments à mode mixte; Ventilateurs de plafond; Confort thermique; Climat tropical; Modélisation énergétique du bâtiment; Co-simulation

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Acronyms

AC Air-Conditioning. (*p. 1, 5, 27, 28, 101, 139, 141, 142, 144, 147, 154, 183, 189*)
ADEME French Agency for Ecological Transition. (*p. 3*)
AEC Architecture, Engineering and Construction. (*p. 19, 23, 40, 139, 214*)
AM Adaptive Model. (*p. xix, 24, 28, 38, 60, 62, 63, 71, 82, 142–145, 147, 152*)
ANOVA Analysis of Variance. (*p. 170*)
ASEAN Association of Southeast Asian Nations. (*p. 4*)
ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers. (*p. 19, 61, 62, 140*)
AT Apparent Temperature. (*p. 40*)

BBCC Building Bioclimatic Comfort Chart. (*p. xviii, 11, 12, 41, 43*)
BEM Building Energy Models. (*p. xxv, 23, 83, 102, 140, 141, 181, 186, 188, 191, 193–195*)
BES Building Energy Simulation. (*p. 142, 182, 185*)

CE Cooling Effect. (*p. 7*)
CF Ceiling Fan. (*p. 6, 51, 101, 141, 183*)
CFIAC Ceiling Fan Integrated Air Conditioning. (*p. 22*)

DISC Thermal Discomfort. (*p. 57*)
DMV Dynamic Mean Vote. (*p. 69*)

ECI Equatorial Comfort Index. (*p. 41*)
EER Energy Efficiency Ratio. (*p. 5, 191*)
EIR Energy Input Ratio. (*p. 189*)
EMS Energy Managment Syste. (*p. 192*)
ET Effective Temperature. (*p. 41*)
EU European Union. (*p. 2*)

FAST Fourier Amplitude Sensitivity Test. (*p. 170*)
FMI Functional Mock-Up Interface. (*p. 193*)
FMU Functional Mock-Up. (*p. 191, 193*)

GHG Greenhouse Gaz. (*p. 1, 3, 18*)
GSA Global Sensitivity Analysis. (*p. 170*)

HI Heat Index. (*p. 40*)
HVAC Heating Ventilation and Air-Conditioning. (*p. 7, 8, 14, 19, 140, 189*)

IEQ Indoor Environmental Quality. (*p. 19*)
IPCC Intergovernmental Panel on Climate Change. (*p. 2, 4*)

KGC Köppen Geiger Climate Classification. (*p. xviii, xxiv, 8–11, 100*)
KTC Köppen Trewartha Climate Classification. (*p. xxiv, 8–11*)

MEP Mechanical, Electrical, Plumbing. (*p. 23, 141*)
MM Mixed-Mode. (*p. 1, 6, 40, 140, 141, 144, 145, 147, 153, 214*)

NV Natural Ventilation. (*p. 6, 27, 28, 51, 139, 141, 142, 144, 146, 147, 152, 154*)
NZEB Net Zero Energy Building. (*p. 15*)

PCD Personal Comfort Device. (*p. 7, 8, 27, 140, 148*)
PHS Predicted Heat Strain. (*p. 41*)
PMV Predicted Mean Vote. (*p. 24, 38*)

RBD Random Balanced Design. (*p. 170*)

SA Sensitivity Analysis. (*p. 168*)
SDGs Sustainable Development Goals. (*p. 5*)
SET Standard Effective Temperature. (*p. 38, 55, 56*)
SMV Static Mean Vote. (*p. 69*)

TCC Trewartha Climate Classification. (*p. 8*)
THM Thermal Heat-balance Models. (*p. 24, 28, 38, 40, 45, 52, 83, 147*)
Top Operative Temperature. (*p. 41*)
TSI Tropical Sumner Index. (*p. 41*)
TSV Thermal Sensation Vote. (*p. 38, 154*)

UTCI Universal Thermal Comfort Index. (*p. 41*)

WBGT Wet Bulb Globe Temperature. (*p. 40*)
WCI Wind Chill Index. (*p. 41*)

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1

Context, background and definitions

This chapter provides the context for this thesis research work, offering the reader essential background information and definitions.

In the first section, the overall challenge of making people feel comfortable in new or retrofitted buildings is exposed, as well as the inherent energy use and Greenhouse Gaz (GHG) emissions it implies. It emphasises the shift in mind to operate toward more sustainable cooling solutions. Assuming Air-Conditioning (AC) performance enhancement will not be enough to meet global cooling energy demands, it introduces low-energy-consuming alternatives that can offer viable options for designing comfortable spaces in hot and humid conditions, for both daily operation and heatwave management.

A second section focuses on tropical environments and Mixed-Mode (MM) cooling strategies. To better understand the need for cooling in this context, it defines tropical conditions and climate subcategories, situating them within the broader exploration of hot climates. Their characteristics are compared, with a focus on the potential applicability of mixed-mode cooling operations.

Lastly, this chapter addresses the knowledge gap in this thesis work, formulates research questions, and describes the methodology used to contribute to the modelling and simulation of mixed-mode operations.

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1.1 Stakes of maintaining people comfortable in a global warming context

1.1.1 Building industry's opportunity to tackle energy transition

The latest Intergovernmental Panel on Climate Change (IPCC) report [1] makes an alarming observation concerning greenhouse gas emissions produced by anthropogenic activity. Global warming of 1.5°C to 3°C, which is already being felt globally, will have consequences in many areas of our economy, such as access to food, water and energy. Geopolitical movements, particularly recent conflicts in Eastern Europe and the Middle East, intensify these trends and affect Europe and the World. The European directives focused on the resilience of our territories to move towards food security and critical supply autonomy, such as materials and energy, which are the path towards an ecological and digital transition. The European Green Deal set these guidelines to achieve carbon neutrality and reduce environmental degradation by 2050. The Paris Agreement urges us to act to limit global warming to below 2°C above pre-industrial levels, while also striving to restrict it to 1.5°C further [2]. This climate, economic and energy crisis requires a faster-than-expected energy transition. Our territories must be prepared to move without oil resources towards energy autonomy, helping to ensure their sovereignty and stemming the growing precariousness in the face of this resource.

Our operating and consumption habits, including those in the building sector, must be questioned. Rethinking the building industry and building usage is an essential opportunity for our societies to reduce carbon emissions. Buildings generate an average of 37% of global energy-related CO_2 emissions. In cities like London, Tokyo, Paris, and New York, the share can reach 70%. The most significant emissions come from operational carbon — primarily heating and cooling[3]. 40% of the total energy consumed in cities corresponds to commercial and residential buildings. Since 2007, 50% of the world's population has been urban. On the European scale, the European Union (EU) 2022 Strategic Foresight Report [4] for the twinning of the energy and digital transition reports a doubling of the areas to be built by 2060 to cope with this European urban demographic trend. Added to this would be the demand to retrofit existing buildings with a new constraint to manage summer comfort and

heat waves. The French Agency for Ecological Transition (ADEME) published its prospective scenarios in 2021 [5]. As an illustration, the 2020 energy use for cooling in the building sector is 5 TWh for the residential sector and nearly 11 TWh for the commercial sector in mainland France, in temperate climates. Their outermost territories, located mainly in the tropical belt, represent 9% of the total French cooling demand for only 5.3% of the overall national surface area to be air-conditioned. Furthermore, it is stated that the impact of the loss of refrigerant fluids, which are known to emit high levels of CO_2, and their end-of-life treatment would represent approximately 3.5 million tonnes of greenhouse gas emissions, bringing the annual bill to 4.4 million tonnes of CO_2. The 2024 International Energy Agency report [6] shows an unprecedented global electricity demand increase. It increased more in 2024 than in the last decade (+2.2% compared to the 1.3% average 2013-2023), representing 1100 TWh, equivalent to twice the annual Japanese demand or 3 times USA demand for cooling. Among the causes, the report spots the growing demand for cooling in countries like India, China and the United States, where extreme temperatures were recorded. This increase is responsible for 80% of Greenhouse Gaz emissions growth. The building operations demand accounts for 60% of the total growth in 2024.

Air conditioning has become a consumer good [7], sometimes having a status symbol of the modern western family in the residential sector and giving the impression of efficiency and progressiveness in the business sector, as illustrated by Agbemabiese et al. [7]. The socio-professional situation also influences access to air conditioning, not only in developing countries but also in Europe. As an illustration, *CODA Stratégie* surveys for France [5] show that 37% of executives and senior intellectual professions are equipped, compared to 19% to 24% for socio-professional categories with more modest incomes, or 27% for retirees. Nearly a third of households without one, with income permitting, are considering purchasing an air conditioning system to manage heatwave episodes and provide summer comfort. It becomes evident that cooling demand is about to increase significantly in the following decades. The spread of air conditioning also rapidly teaches our body to hate the heat and makes us addicted to coolth [8], [9]. Nevertheless, Prins [8] stated, taking the example of America, that the cultural and technological roots behind this addiction *"also contains the means to move on to cleverer, more environment-friendly "post-coolth" technologies."*

1.1.2 The tropics facing cooling demand increase

Countries from the tropical belt will face an even more rapid growth in energy demand for cooling. In 2019, Rodriguez et al. [10] noted that by 2030, the world's urban population is expected to increase from 50% to 60% and then rise to 75% by 2050. At the same time horizon, 50% of the population will live in the tropical belt, where people will face summer comfort issues all year round. We observe the most significant and rapid development of cities in this region, especially in rapidly developing countries. This leads to a cyclical increase in the income of its population, and naturally, with higher comfort expectations, i.e., a "right to cold" [10]. The need for cooling is gradually increasing with the growing urbanisation and westernisation of comfort levels. In the 1990s, the AC market penetration rate in residential

buildings in Bangkok, Thailand, was 40% , while it was 77% in the US at that time. It is now saturated in Thai cities, which illustrates the trend acceleration that is about to follow its neighbours in the tropical belt. This is confirmed by IPCC report [1]. It mentions that compressor-based Air Conditioning, as the sole means of maintaining comfortable conditions, is dramatically increasing in adoption in low- and middle-income countries where incomes rise and temperatures increase [11]. This includes territories in Southeast Asia (Thailand, Vietnam, Indonesia, The Philippines) as well as Brazil, Pakistan, Bangladesh and Nigeria. The AC penetration rate is expected to increase from 3.6 billion to 9.5 billion units. Biardeau et al. [11] note that these countries have more total cooling day exposure than the US, which already consumes 400 TWh of electricity to cool spaces. In India, by 2030, the energy demand for cooling will increase by 220% to 300% of the current level according to the scenario of penetration of the air conditioning market in buildings [12]. Developing countries are responsible for 80% of the electricity demand increase in 2024, even as China's growth stagnates [6].

At the tropical scale, Haddad et al. [13] were able to estimate a 78% increase in cooling consumption on the climate scenarios of 2060. In addition, countries seeing their energy production increase sharply, particularly those in Association of Southeast Asian Nations (ASEAN), cultivate a symbolic image of affluence and prestige associated with freshly air-conditioned interior spaces [14]. The evocative titled report, "Freezing Tropics", cites Singapore as an example with comment from government research agency A*STAR: *"Air-conditioning has evolved into an entitlement that people feel they cannot live without. Alternative initiatives are seen as reducing the comfort level of people, even if cooling capacities remain the same. For instance, some cars use diffusion AC systems that are energy efficient, and can cool the interior fast, but passengers complain about the lack of cold wind."* Less energy-intensive solutions are underrepresented in five of the six countries surveyed, as shown by the results shown in figure 1.1 [14]. Vietnam and the Philippines appear to be more involved in a policy shift away from air conditioning, reporting a wider adoption of alternative solutions such as fans, internal and external sunshades. However, the opportunity for a more effective design approach to reduce the use of air conditioning in public buildings remains significant. Beyond the energy consumption inherent in cooling spaces, the multiplication of air conditioners generates heat releases in outdoor spaces, thus creating new, warmer urban microclimates, encouraging greater use of air conditioners for indoor comfort. This situation seems inextricable in hot and humid climate cities without a paradigm shift.

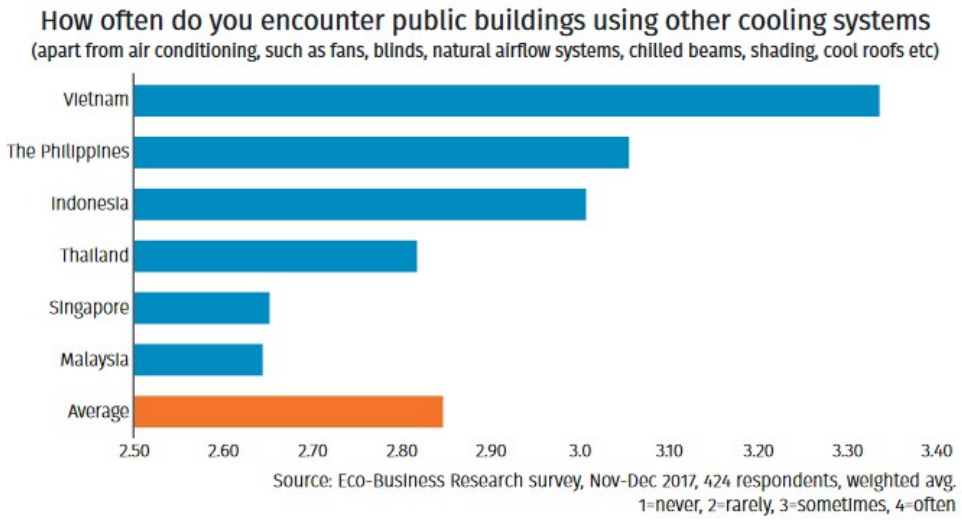

Figure 1.1: *Eco-Business Research survey on alternatives to air conditioning for 6 countries in the tropical belt whose energy consumption is increasing sharply. Survey funded by the KIGALI Cooling Efficiency Program* [14]

1.1.3 Toward mixed-mode operation to maintain cooling energy demand

Air-Conditioning (AC) plays a significant role in energy consumption, whether in western markets, where it helps manage heat waves, or in tropical regions, where it is a means to maintain comfortable conditions year-round. Technology, building design, and operation serve as the primary means to control cooling energy demand, acting at different levels.

Technological innovation can improve environmental assessment, such as Air-Conditioning (AC) energy class and Energy Efficiency Ratio (EER), but remains an insufficient lever. Technology alone will not make it possible to achieve ambitious objectives despite a prediction of 85% more performance across the entire fleet (air conditioners > A++ class and EER > 6.4). This example is illustrated for France (mainland France and its outermost territories) by modelling the different scenarios of the ADEME 2050 forecasts [5]. The report mentions that the main obstacle is manufacturers' inability to provide a breakthrough solution more effective than the INVERTER systems of the last two decades. In all the prospective scenarios, quadrupling the air-conditioned surfaces with A+++ type technologies would double the demand for electricity in the residential sector; a similar trend is expected in the commercial building sector. In the tropical belt, India and South Africa recognise that more efficient systems could help to contain the increase in their emissions, but would not be sufficient to achieve the United Nations Sustainable Development Goals (SDGs) [1].

Air-conditioning-centred building design and its operation must be deeply reevaluated in the tropics. On one hand, the primary question is whether we should adopt current western standards, which involve relying solely on a mechanical compression system to maintain a narrow range of ambient conditions between 23 and 26°, as determined by tests in a climatic chamber and driven by market forces, by the end of the 20th century. [8], [15]. Furthermore, with the emergence of the smart grid paradigm, the design and operation of building systems

should move away from traditional fixed-setpoint AC-driven design practices [16]. On the other hand, we must consider whether one should entirely eschew mechanical compression cooling by relying solely on natural ventilation, even if it compromises the comfort of occupants on certain days throughout the year.

Agbemabises et al. [7] are interested in these issues for two cases of tropical climate, namely Thailand in Southeast Asia and Ghana in tropical Africa. They highlight that adopting Western standards for thermal comfort is certainly unnecessarily resource-consuming but may even be inappropriate for the socio-cultural context. The dependence on air conditioning in these territories is due to the misuse of Western standards for thermal comfort or their inadequacy for the population and the more severe climate of these regions [10]. Populations in tropical climates can remain in a comfortable situation without air conditioning or with a higher setpoint temperature than the Western standard recommends, as demonstrated by researchers specialised in building comfort in naturally ventilated buildings like Nicol, De Dear, and Brager [17]–[19].

Natural Ventilation (NV) is one lever to reduce this energy consumption at the cost of potential uncontrolled discomfort drift during the hottest peak season. Designers in tropical climates can adopt more sustainable cooling techniques while guaranteeing the greatest possible comfort. Readopting and adapting the concepts of vernacular bioclimatic tropical architecture to modern buildings, making extensive use of the principles of natural ventilation and Ceiling Fan (CF) is a viable option to cool indoor space [20]. Increased air speed on the user leads to a situation of comfort even at high temperature and/or humidity [21]. This is achieved at a very low cost, given that a ceiling fan uses 20 [11] to 30 [22] times less electricity than a typical air conditioner and can cut energy use [23]. Nevertheless, fully naturally ventilated buildings can sometimes reach their limits, as they may be insufficient to tackle extreme heat and humidity conditions. Other factors impacting overall comfort, satisfaction, and wellness in buildings, such as acoustic nuisances, dusty environments, or incompatibility with fire exhaust systems, may be obstacles to naturally ventilated spaces [24], [25]. In this context, designers typically opt for the 100% mechanically cooled option, and users can only rely on compressor-based Air Conditioning (AC) to maintain their comfort, albeit at the cost of high energy consumption year-round.

Mixed-Mode (MM) cooling is an alternative to the global reliance on mechanical compression air conditioning as the only means to target comfort, when NV is insufficient year-round. This operation type can be easily applied to new constructions. It is also an excellent alternative to refurbished ones, where the building envelope does not allow a performant natural cross ventilation in the tropics. Mixed-Mode cooling operation offers the flexibility to target both comfort and lower energy use in tropical climates. MM operation for cooling tropical buildings is at the border between naturally ventilated buildings (NV) and fully air-conditioned buildings (AC). Its operation is simple: natural ventilation and ceiling fans are favoured most of the year. When indoor conditions deteriorate, AC is used in conjunction with ceiling fans, while users can adapt their clothing. The exclusive use of AC

units is banned. This cascade cooling operation aims to lower energy use while maximising occupants' comfort by using ceiling fans to first delay the start of AC units and secondly raise the setpoints.

Ceiling fan and air movement in general has been subject to field survey research over the past four decades, highlighting the advantages of these devices in thermal comfort enhancement in hot and humid conditions, while minimising energy use by three means [26]–[41]:

(1) **Ceiling fans can delay the start of AC** when used in conjunction with NV. This is possible because air movement increases convection transfer on occupants' skin, enhancing evapotranspiration heat loss. It thus leads to comfortable conditions at higher temperatures or relative humidity than with still air. The Cooling Effect (CE) of ceiling fans permits compensating for 2.8-3.3 °C temperature change, increasing the comfortable conditions over 24-26°C/70% RH range of a standard comfort zone [42], namely extending the upper limit of the summer comfort zone up to 29.4°C [26].

(2) **Ceiling fan usage has recently been proven to raise temperature setpoints of AC units** in traditional air-conditioned buildings in the tropics. Thus, it yields to reduced energy use. In laboratory experiments in the Tropical climate of Thailand, Atthajariyakul et al. [43] showed that the temperature setpoint of Air-conditioning can be increased up to 28 when a desk fan providing local air velocity in the [0.5-2m/s] range is available. Chen et al. [44] proposed a system that replaces supply ducts and diffusers with air nozzles that supply fresh air directly to the fan blade, favouring good air mixing. While advocating warmer-than-conventional AC operating space temperatures (28°) when the fan is on, they also mention that temperature distribution is more homogenous, avoiding cool spots caused by dumping.

(3) **Coupling the ceiling fans with air conditioning can lead to a reduction in energy use** [23], [45]. Gokarakonda et al. [46] investigated MM cooling solutions in residential bedrooms in India. Their research aims to analyse the impact of AC and fan usage behaviour on energy use conservation. Liu et al. [45] mention that jumping from 23°C to 26°C will reduce AC consumption by 17% while the increase in fan consumption will be only 0.7% of the total bill. Kent et al. [47] conducted a field survey of comfort and energy use among over 35 occupants of a Net Zero Energy Building (NZEB) in Singapore for 11 weeks. They could measure the direct influence of desk and ceiling fan use by raising the thermostat setpoint by 2.5°C to 26.5°C without affecting the occupant's thermal satisfaction or dissatisfaction with air movement. This study highlights an energy use reduction potential of 32% and a CF energy share of 3.5% of the total HVAC system. It also illustrates that the combined use of ceiling fans with AC could lead to under-sizing the chillers, pumps, and cooling towers due to higher nominal setpoints. Consequently, this can reduce the overall investment and operating costs. Malik et al. [22] simulated the energy demand and associated greenhouse (GH) emissions reduction in the case of the Fan-First scenario. They highlighted that the comfort threshold could be extended by using a ceiling fan in addition to AC. The use of Personal Comfort Device (PCD) could also deal with non-uniformity of thermal comfort perception for a group of occupants [9]. Also, this solution could lead to up to a 76% reduction in energy use and

GH emissions. Miller et al. [48] conducted a 29-month survey in a building retrofitted with 99 automated ceiling fans and showed savings on AC compressor between 36% and 41% while providing comfort across a wider range of temperature than when AC was used solely. Rugani et al. [49] simulated several cases of Personal Comfort Device (PCD) proving their efficiency in both cold and hot conditions to maintain equal comfort to occupants and reduce HVAC electricity demand with up to 53% overall energy reduction for cases in arid climates.

The simultaneous use of ceiling fan with natural ventilation and also with air-conditioning appears as a viable alternative to tackle hot conditions while maintaining the energy demand associated with cooling. This Mixed-mode strategy could be applied to new construction and to retrofit buildings. It seems particularly adapted to hot and humid climate characteristics and sounds promising to other types of climate sharing tough, uncomfortable hot seasons.

1.2 Mixed-mode application in hot and tropical climates : Background and definitions

1.2.1 Climate classification and tropical climates specificities

The German scientist Wladimir Köppen (1946-1940) is the main instigator of the most widely used climate classification on an international scale, first published in 1900 [50] and mapped in Figure 1.2. Initially intended for agronomy and botany, its purpose was to classify vegetation groups by climatic zone. Geiger has preserved the original philosophy in numerous updates (1954, 1957, 1960), which brought up the work of Köppen in recent publications. It uses a colour code and a density level to represent the climatic zones on a world map. The five zones, differentiated by letters, represent the vegetation groups of (A) the equatorial zone, (B) the arid zone, (C) the mild temperate zone, (D) the snowy zone, and (E) the polar zone. Each zone has a second letter to qualify the precipitation levels: W: desert, S: steppe, f: very humid (fully humid), s: summer dry, w: winter dry, m: monsoonal. Finally, the last letter characterises the temperature levels (h: hot and arid, k: cold and arid, a: hot summer, b: warm summer, c: cool summer, d: continental (extremely continental), F: polar frost, T: polar tundra). This classification is called the Köppen Geiger Climate Classification (KGC) system. In 1966, Trewartha proposed a modified Köppen classification to overcome specific gaps, mainly in mid-latitude climates. This system is known as the Köppen Trewartha Climate Classification (KTC) or Trewartha Climate Classification (TCC). Seven groups are also represented by letters. (A: Tropical climates, B: Dry (arid and semi-arid) climates, C: Subtropical climates, D: Temperate and continental climates, E: Boreal climates, F: Polar climates, H: Highland climates. Lower case letter describes, just as in the KGC system, the temperature and precipitation levels, however, these letters are specific to each major climate group (A: r, w, s, B: S, W, C: s, w, f, D: o, c, F: t, i)[51]. Table 1.1 shows the correspondences between the two classifications regarding surface area ratio on the globe.

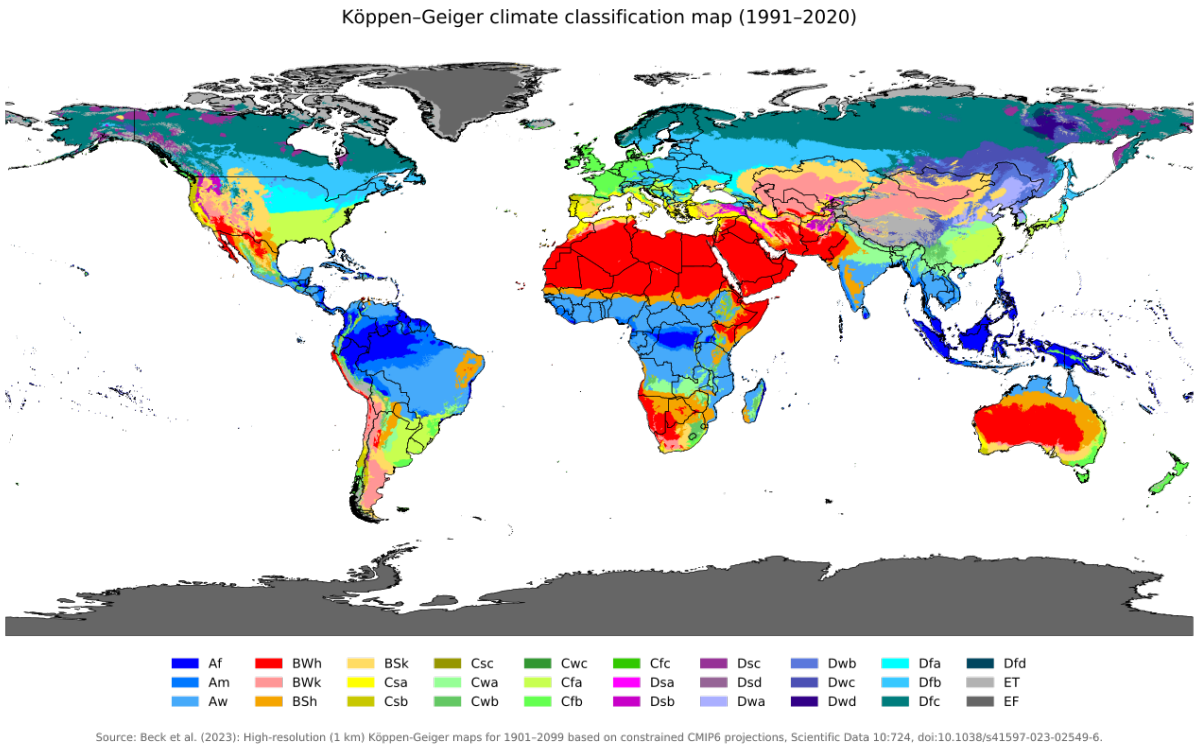

Figure 1.2: *Geographic distribution of the Köppen-Geiger (KGC) climates groups at a resolution of 1km* [52]

Table 1.1: *Percentage of continental area covered by climate type according to the two Köppen-Geiger (KGC in rows) and Köppen-Trewartha (KTC in columns) classifications. Table reproduced from* [51]

	Ar	Aw	BW	BS	Cs	Cw	Cf	Do	Dc	E	Ft	Fi	Sum
Af	5.10												5.10
Aw	0.38	11.17		2.09									13.63
Am	1.92	1.74											3.66
BW		0.01	16.76	1.08	0.50		0.01			0.11			18.47
BS		0.01	2.52	6.36	0.27		0.23	0.22	0.39	0.02	0.13		10.15
Cs					0.40		0.46	0.76	0.40	0.05			2.07
Cw				1.46		0.77	2.71	0.38	0.26	0.02			5.59
Cf				0.57			4.72	1.74	1.48	0.17			8.69
Ds								0.48	0.14				0.62
Dw		0.03	1.06					1.14	2.16				4.39
Df				0.42						7.51	12.43		20.36
ET											6.10		6.10
EF												1.16	1.16
Sum	7.40	12.93	19.31	13.04	1.17	0.77	8.12	3.11	11.65	14.99	6.34	1.16	

The inter-tropical belt, shown in Figure 1.3 is governed by the equatorial climate zone of group A of KTC and KGC. Temperatures are warm all year round with no marked seasons. Day-night temperature differences remain small during the warmest months. The climate of group A has the same mean characteristic in both classification systems, namely a monthly minimum temperature of 18°C. It is subdivided into four typologies according to the type of precipitation only. KTC system, which is most common in the botany field, adds value in mid-latitudes, but the tropical zone is almost identical to that in KGC. The latter is considered throughout this manuscript.

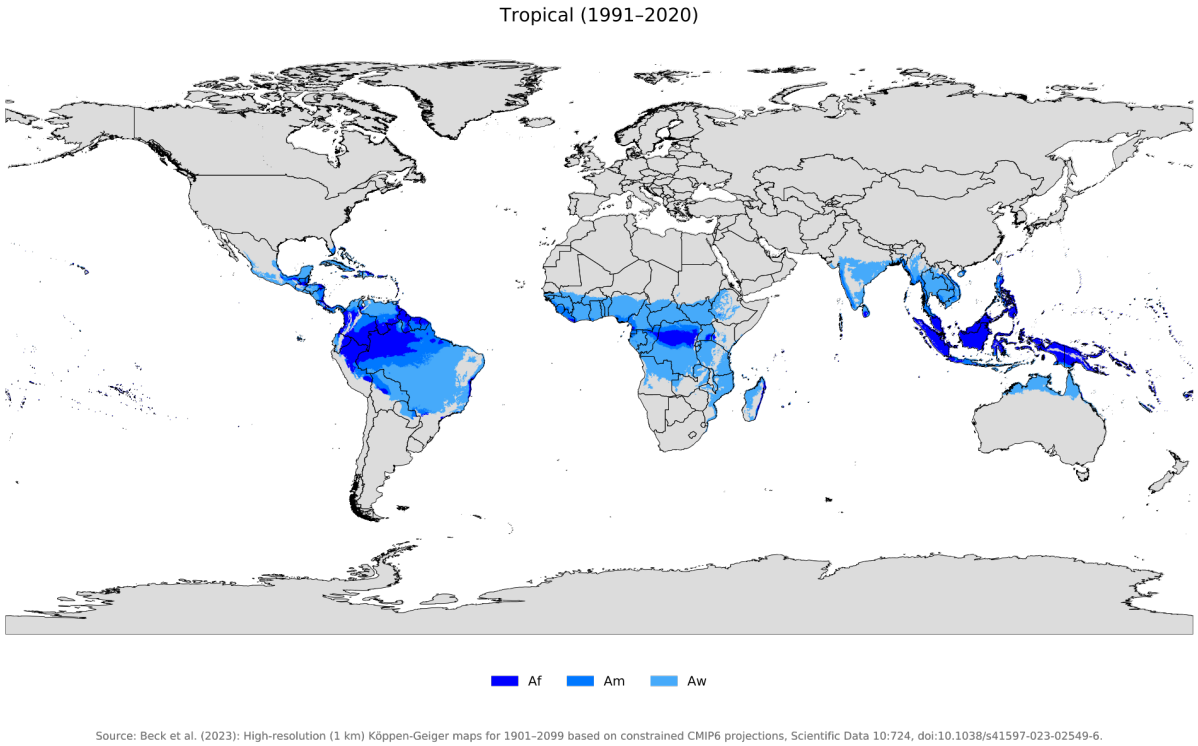

Figure 1.3: *Geographic distribution of the different tropical climates of group A (KGC) at a resolution of 1km* [52]

Beck et al.[52] propose maps projected at a 1 km resolution, allowing for a fine-scale analysis of climates. Rubel et al. [53] updated the global climate map using the KGC system based on temperature and precipitation measurements from 1951 to 2000. They provide projections for 2001-2025, 2025-2050, 2051-2075, and 2076-2100, utilising different digital maps according to four CO_2 emission scenarios (A1F1, A2, B1, and B2), accessible online. These projections indicate a shift in climatic zones, particularly for tropical climates of type Af and Am, which are expected to expand in surface area by 2.2% to 3.4%. This expansion aligns with the observed widening of the tropical belt over recent decades. The studies listed in Seidel's work [54] agree on a widening of several degrees of latitude due to precipitation and wind trends associated with the poleward shift of the Gulf Stream current.

KGC	Climate	Precipitation	KTC	Climate	Precipitation threshold 55mm (P)	Alternative name
Af	Tropical rainforest	$P > 60$mm	Ar	Tropical humid or wet	< 2 dry months, $>$ 10 wet months, $P > 55$mm	Wet equatorial = Tropical rainforest without cyclone
Aw	Tropical humid (Tropical wet)	$P_m < 60$mm over several months, Dry winter, No forests, Insufficient precipitation	Aw	Tropical humid (Tropical wet)	> 2 dry months, Dry winter, $P > 55$mm	
As	Tropical dry	$P_m < 60$mm, Dry summer, No Forests, Insufficient precipitation	As	Tropical dry		
Am	Tropical monsoon	P_m dry < 60mm, Forests possible, dry months compensated by precipitation	Am	Tropical monsoon		Coastal climate dominated by wind

Table 1.2: *Equivalence of climate subdivisions of group A according to the Köppen Trewartha Climate Classification (KTC) and Köppen Geiger Climate Classification (KGC) systems*

1.2.2 Tropical climate among other hot climates: broadening MM applications

While this thesis work is based on a tropical case study and focuses on this type of climate-specificity, the Mixed-mode cooling solutions could be beneficial to other climates experiencing hot conditions. Among them, the climates from groups B (Arid) and C (temperate) may be good candidates. Figure 1.4 shows twelve subplots of cities in different climates using the Building Bioclimatic Comfort Chart (BBCC) zones proposed by Givoni [55] and described later in section 2.2.2. Each BBCC plot displays the data from an hourly weather file on a psychrometric chart, with temperature on the x-axis and specific humidity on the y-axis. Curved lines represent relative humidity lines from 0 % at the bottom to 100% at the top. Each point of the weather file is plotted based on its temperature and humidity. The overlayed zones represented here are the "Still air" zone and the Natural Ventilation (NV) zone. Comfort is achievable with an adequate building design, regardless of whether air movement is present, provided the point is in the Still air zone. For points in the NV zone, comfort is achieved through air movement and natural ventilation design. Outside of those, one would need another strategy to maintain comfortable conditions.

The first two rows show six tropical climates. The first row is dedicated to the representative climates of the French overseas territories, the second to worldwide examples. The French overseas climates depicted here conform to the general description of a tropical environment as defined in table 1.2. Nevertheless, we can notice several differences between Am (blue), Aw (orange), and Af (green), respectively, for St-Pierre (Reunion Island), Dzaoudzi (Mayotte), and Cayenne (Guyana). St-Pierre's climate is the coldest, with a well-defined cold season, as recorded temperatures can be as low as 15 °C. Relative humidity is above 65 %. Dzaoudzi

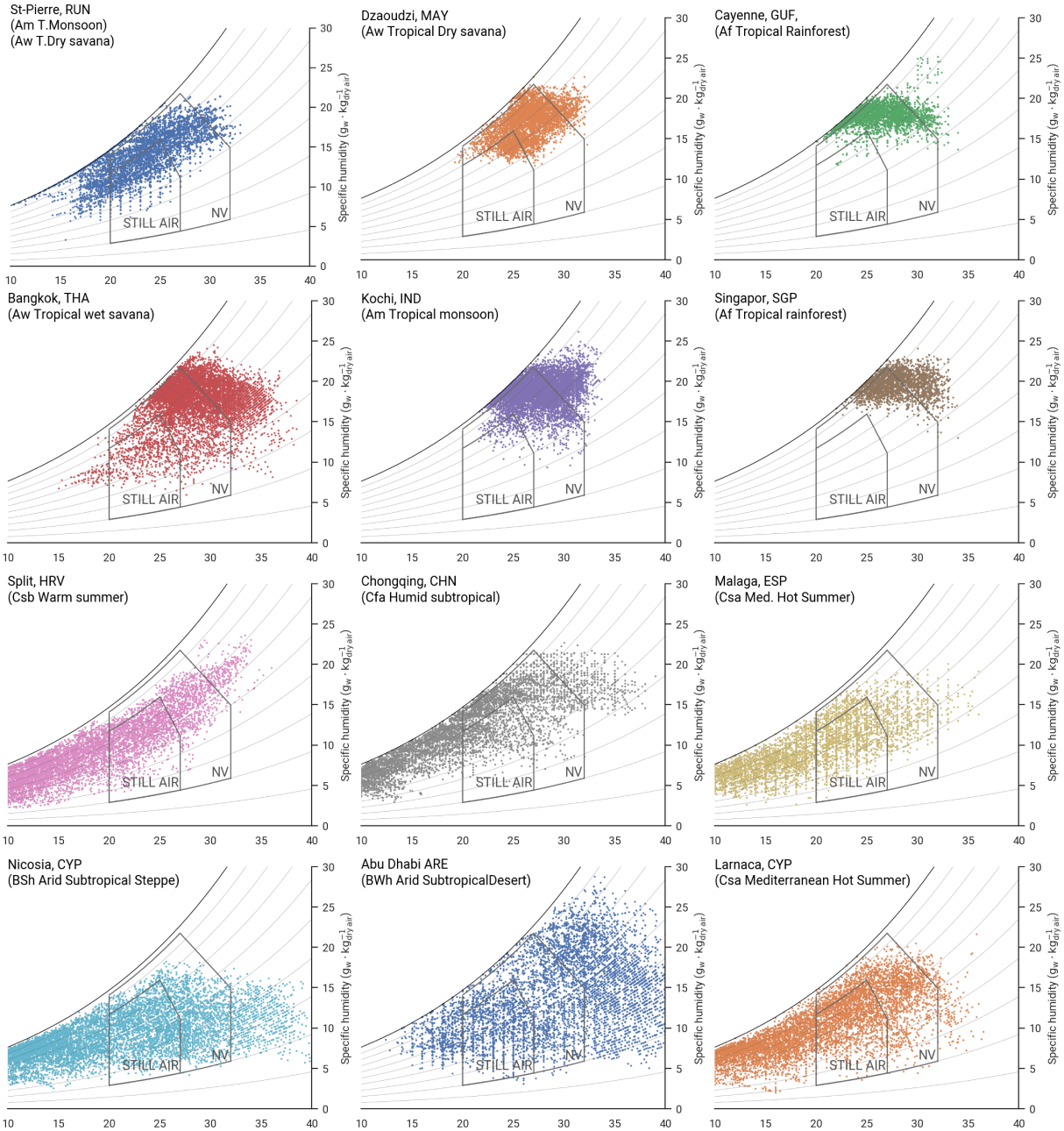

Figure 1.4: *Hot climates characteristics comparison over the Building Building Bioclimatic Comfort Chart (BBCC)*

and Cayenne demonstrate that no cold season consistently brings every point above 20°C. For the three plots, points outside the Still Air zone would require significant effort in the design of the building to avoid Air conditioning (e.g., natural cross ventilation). Additionally, if the outside wind is insufficient, those points would require, at best, a ceiling fan, and at worst, air conditioning. Outside the NV zone, they basically would be air-conditioned. This basic example quickly shows which part of the year needs to be conditioned.
The second row shows examples of the same climate type as for the French overseas territories, but in other countries and with much extreme conditions. The number of points outside NV zones is much more critical for Bangkok (red), Kochi (purple), and Singapore (brown), for example. It is worth mentioning that such large cities may have minimal wind potential in a densely urbanised area, reducing the effectiveness of natural ventilation as a comfort measure. This again doubles the number of hours that require to be air-conditioned. Furthermore, Kochi and Singapore have relative humidity above 70 % and temperature above 23°C yearly.

Rows 3 and 4 show examples from Arid and temperate climates that can present similarities to the tropical climates during part of the year, particularly in extreme hot and humid conditions. As for a European example, Split in Croatia (pink) faces a very hot (up to 34°C) and humid (70-90%) summer during which Mixed-mode cooling could be beneficial. Other areas, such as Málaga in Spain (yellow) or Nicosia in Cyprus (light blue), might be less impacted by extreme humidity, but remain, respectively, hot (up to 35°C) to very hot (up to 40°C). Larnaca in Cyprus could face the same cooling demand as Saint-Pierre, Reunion Island. Outside Europe, the examples of Chongqing in China (grey) and Abu Dhabi (blue) demonstrate that even in a B-group dry climate, such as those found in the Middle East, temperature can still lead to very humid conditions during the summer period, with even more extreme conditions than those found in the tropics. Indeed, Abu Dhabi climate shows a huge amount of points outside the NV zones and over 70% RH with temperatures ranging from 26°C to 35°C.

Those examples of tropical climates show the diversity of conditions even in a unique subgroup of the Köppen classification. Also, quickly analysing other cities' weather files reveals hot and humid tropical conditions patterns in other countries, whether they are classified as temperate or even desert climates, such as Cfa and BWh ones.

1.2.3 Mixed-mode cooling among other cooling strategies

The current context of global warming has led to a significant increase in the use of air conditioning and, consequently, an increase in energy consumption in tropical climates. Carlucci et al. [56] have listed the three cooling modes described in the most common international standards :

Compressor-based Air-conditioning (AC operation)

The use of compressor-based mechanical cooling is a response to periods of heat. It is recognised in international standards as the air-conditioned mode (AC: Air Conditioned building). It is considered an active cooling system, as it consumes considerable energy to function. The operating principle uses the laws of thermodynamics to transfer heat from the inside to the outside. The refrigeration machine generally consists of a four-step cyclic process: (1) compression of a refrigerant, where the refrigerant is pressurized to increase its temperature and energy; (2) condensation, where the hot, high-pressure refrigerant gas is cooled and condensed into a liquid; (3) expansion, where the high-pressure liquid refrigerant is allowed to expand, reducing its temperature and energy; (4) evaporation, where the low-pressure liquid refrigerant absorbs heat from the indoor air and evaporates into a gas. For each complete cycle, the system compressor consumes electrical energy for the mechanical compression of the refrigerant and to operate the fan, which enhances heat exchange with the outside at the condensing unit. Through this process, the indoor air can be both cooled and dehumidified under certain conditions. Almost all AC building systems are sized based on comfortable temperatures in still air conditions (< 0.15 m/s). Any air movement would be considered a draft and provoke a feeling of coolth [44].

Cooling via AC is very energy-intensive and deviations can be observed, namely:

- users find themselves in a passive situation with regard to the management of their comfort if the air conditioning is centrally controlled,
- a process of addiction to cold conditions can develop,
- users tend to be more demanding with regard to ambient conditions (higher expectation, lower comfort temperature setpoint, extension of the air conditioning period, which can extend throughout the entire year),
- starting from the principle that air conditioning alone solves the problem of comfort, designers can be less stringent on the performance of the envelope when no standard or ambitious energy-use targets are in place.

These deviations negatively impact both the sizing of the whole Heating Ventilation and Air-Conditioning (HVAC) systems and their consumption.

Natural ventilation (NV operation or NV + Ceiling Fan operation)

On the contrary, a second approach involves adapting vernacular bioclimatic principles [24], [57]–[60]. This approach utilises wind-driven cross ventilation through large openings to facilitate natural cooling of spaces. The objective serves two purposes: (a) to remove internal heat gains rather than just for hygienic air renewal, (b) to create an airflow around the occupant to promote convection, which aids evapotranspiration and therefore cooling. Ceiling fans are often added as complementary, low-energy-intensive cooling equipment to create an air speed for the occupant, making the perceived temperature feel cooler than the ambient temperature. The effect of air movement on body cooling, whether from NV, CF or

both, is well-documented and is dependent on relative humidity, with a maximum air speed threshold of 1.5 m/s for a relative humidity level greater than 80% (Figure 1.5).

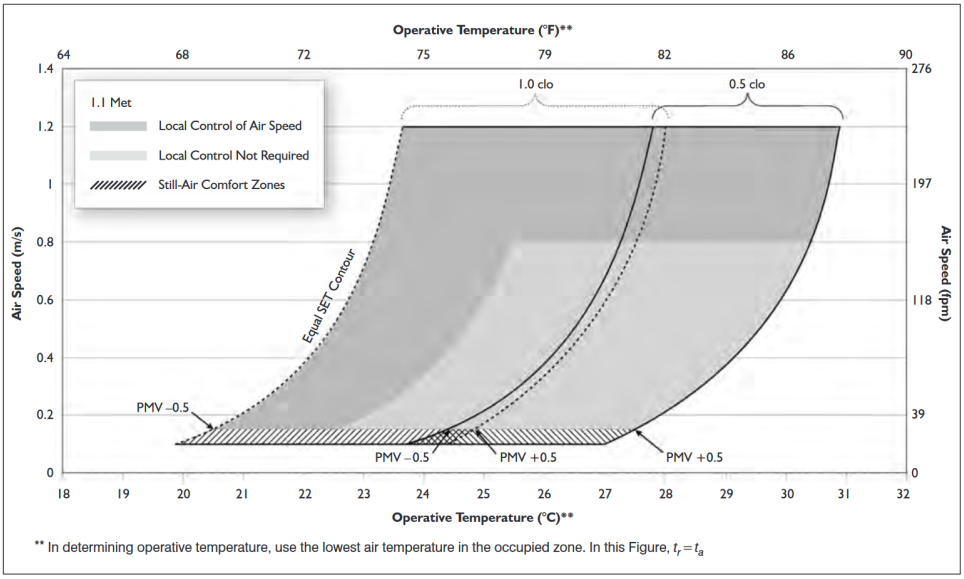

Figure 1.5: *Warm climate comfortable zones thanks to air movement* [61]

In the last decades of the twentieth century, Fanger found that a comfortable subject has a skin temperature independent from air velocity, implying that any combination of temperature/air velocity will yield the same comfortable conditions [27]. Rohles [26] mentions that an air speed of 1 m/s allows extending the comfortable upper limit temperature from 26.1°C to 29.7°C. Givoni makes a similar observation where 1 m/s allows one to go beyond 30°C; he proposes a zone for, as stated, *"hot developing countries"*, ranging up to 32°C with an air speed of 1 to 2 m/s [55], [62]. Ho et al.[28] show that an air speed of 0.5 to 1 m/s allows for extending the temperature range from 2.8 to 3.3°C.

In international standards, this type of operation is referred to as a naturally ventilated building (NV). It is considered passive cooling, as it consumes very little energy to function, primarily due to the use of ceiling fans. Natural ventilation, combined with ceiling fans, has proven effective in tropical climates, as demonstrated by several case studies, particularly in Reunion Island. Lenoir et al.[63]–[65] were able to study the first Net Zero Energy Building (NZEB) NZEB in a tropical climate, ENERPOS, handed over in 2009. They conducted a series of comfort surveys to evaluate the performance of this design type, which combines natural cross ventilation with ceiling fans.

The building envelope is designed to allow for comfortable cross-ventilation with large openings on opposite facades. The classroom depth is reduced to 6 meters to avoid pressure losses, and central horizontal circulation is eliminated for the same reason, in favour of external walkways (Figure 1.6). Ceiling fans enhance the natural ventilation system, ensuring that the air speed over the occupants remains at a minimum of 1m/s, which helps maintain a perceived temperature several degrees cooler. The surveys are based on the ISO 10551- 1995 standard and cover approximately 500 students. The results indicate that users are more comfortable at

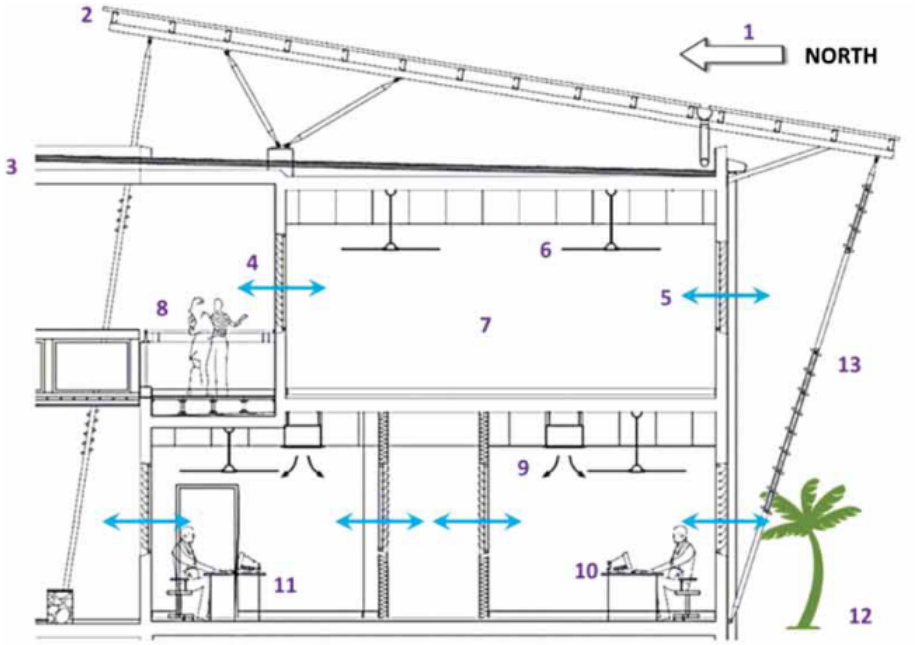

Figure 1.6: *Cross-section of the principle of natural cross ventilation of the Enerpos building in St-Pierre* [64]

temperatures below 30°C and air speeds of roughly 1 m/s. Thus, even on the hottest days of the year, users remain comfortable in offices and classrooms. Payet et al.[66] make a similar observation on the first bioclimatic amphitheatre in a tropical climate located in the city of St Denis de La Reunion, delivered in 2014. This is a 550-seat amphitheatre with no mechanical or compression cooling system for occupant comfort. Given the significant width this type of construction imposes, cross-ventilation alone on two opposing facades proves limiting due to excessive pressure losses. The innovation in the passive cooling system's design involves creating an upward airflow through a roof draft effect. The creation of an open 'U'-shaped cover generates a depression effect that drives the prevailing winds at the roof ridge, as illustrated in Figure 1.7. This design allows air to circulate from the building's façades, under the stands and seats, to create a minimum air speed of 1 m/s over the occupants. The results of six months of field surveys in 2015 reveal that only 14% of the surveyed occupants feel "slightly warm" during the austral summer months (December to March), the hottest period of the year. 78% of the occupants report being on the so-called "neutral" comfort scale, where they feel "neither hot nor cold". The observation was made while no ceiling fans were installed, illustrating the efficiency of the wind-driven NV building envelope design.

Designs based solely on natural ventilation have proven effective, but they may face challenges in extreme outdoor air temperatures and humidity or where wind is insufficient, even with complementary ceiling fans. This is particularly true during severe heat waves or in the case of a new or renovated building in a dense urban environment, where the heat island phenomenon is pronounced. Allard et al. [24] also mention other operational constraints that can lead to the failure of a design exclusively based on the passive principle of

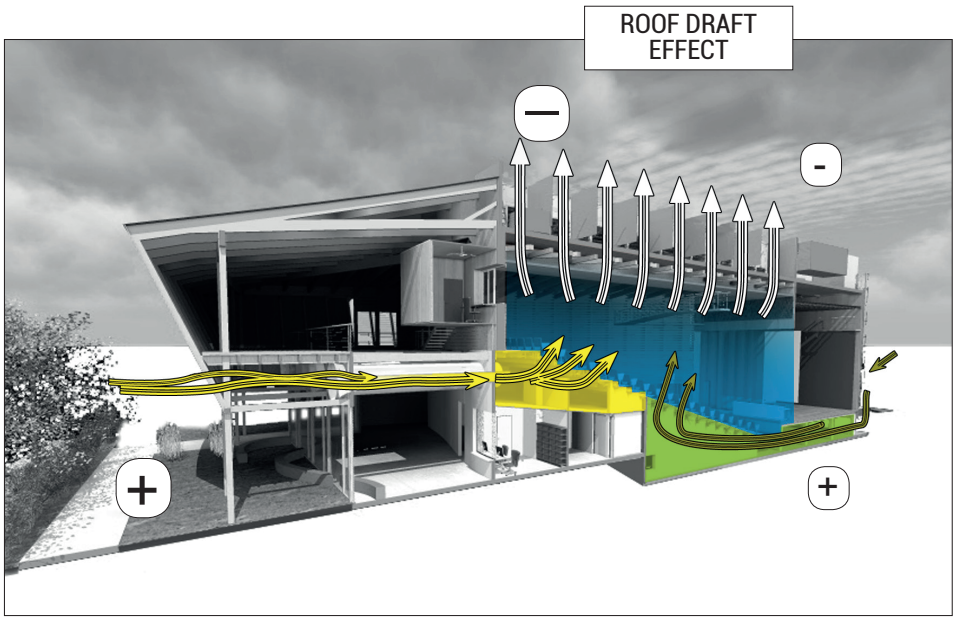

Figure 1.7: *Natural ventilation concept of the Moufia bioclimatic amphitheater (image credit CAUE of Reunion Island)*

natural ventilation. These include noise disturbance, safety constraints, compliance with fire regulations, indoor air quality (IAQ) and pollution. In those cases, natural ventilation alone, even coupled with a ceiling fan, could prove insufficient to ensure the comfort of occupants throughout the year or in all occupied spaces of the same building.

Mixed-mode and Mixed-mode cooling operation (MM operation)

In a tropical climate, the mixed-mode cooling solution on which this thesis is based combines the benefits of AC and NV modes. The ceiling fan becomes a key element in the transition between a naturally ventilated (NV) mode and an air-conditioned (AC) mode.

Unlike the air-conditioned building (AC), which seeks to maintain ideal ambient conditions under all circumstances, the mixed-mode cooling solution (MM) primarily utilises natural ventilation, thanks to large openings in the façade and ceiling fans, similar to those found in naturally ventilated (NV) buildings. However, it also activates a mechanical system when comfort conditions cannot be achieved passively, alone or with fans. **The mechanical system is systematically used in conjunction with ceiling fans**.

As mentioned, the use of a fan with an air velocity of 0.5-2.0 ms^{-1} helps lower perceived temperature. When occupants are given the option to activate the air conditioning, the ceiling fan can either delay the start of the air conditioners or raise the setpoint temperature, while maintaining an optimal level of comfort at lower energy consumption.

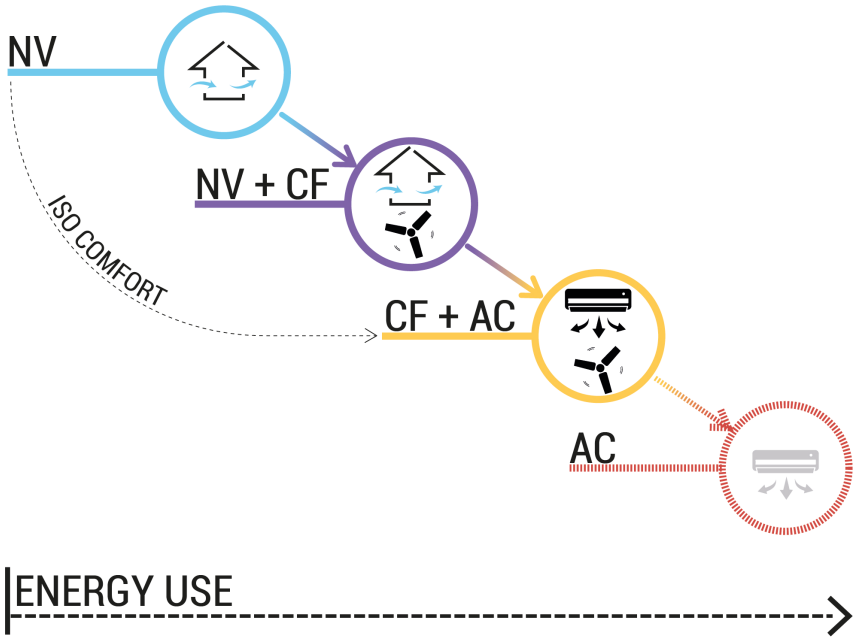

Figure 1.8: *Mixed-mode cascade cooling strategy sequences*

It is possible to consider a cascade sequence of the different cooling solutions, with progressive or simultaneous use, as shown in Figure 1.8 and enumerated hereafter:

- **NV alone**: Exclusive use of natural ventilation through large openings to achieve thermal comfort.
- **NV + Fans**: Adding a ceiling fan or another device to increase air speed when NV alone is not enough. Allowing for the delay in the use of air conditioning. Ceiling fans require minimal energy to operate.
- **Fans + AC**: Combined use of the ceiling fan with air conditioning, allowing a higher setpoint temperature with the same thermal comfort performance, consuming less than exclusive use of AC
- **AC alone**: When air movement is not suited to the space's function, thermal comfort can only be achieved through air conditioning. In typical usage scenarios, this approach should largely be avoided.

This operation type has several advantages:

- A well-designed MM cooled building - with properly designed envelope morphology, composition, openings and shading devices - can cut off mechanical cooling use throughout much of the year, leading to a reduction in energy use and GHG emissions, [22], [47], [67], [68]

- A reduced use of AC in time and nominal power might also lead to a reduction in chiller sizing, yielding to less investment costs, particularly in conjunction with ceiling fan [47]
- Enhance health and productivity, reducing Indoor Environmental Quality IEQ-related issues [67]

In international standards, this type of mixed-mode cooling operation is still not yet clearly defined, yielding a misunderstanding in the Architecture, Engineering and Construction (AEC) industry on how to model, simulate and design such coupled cooling systems and operation. Standards lack flexibility for innovative or unconventional approaches to designing HVAC systems. [9], [67], [69], [70]. No consensual protocols exists for control strategies [69].

To amend the ASHRAE 55 standard in the early 2000s, Brager et al. [9] launched a Mixed-mode research program in the US. It highlighted the advantages of this type of design compared to traditional air-conditioned and naturally ventilated buildings. More than 150 buildings have been detailed in the United States by the Berkley Lab, and 12 buildings have been the subject of satisfaction surveys, conducted on approximately 1,200 participants. They were compared to 358 other conventional AC buildings on around ten satisfaction points, including thermal comfort. MM buildings only have a total of 25% dissatisfaction, while the AC buildings in the database reveal that 41% of employees express dissatisfaction with thermal comfort (Figure 1.9). Beyond that, the study reveals that air-conditioned buildings, in 89% of cases, do not meet the comfort requirements of ASHRAE 55 80% acceptability. The investigators tried to define mixed-mode operations as follows:*"Mixed-mode" refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from vents or operable windows (either manually or automatically controlled), and mechanical systems that may provide ventilation, interior air distribution and/or some form of cooling"*[9], [69]. These solutions can be classified into several sub-operations that are described in the literature by the same author. Classifications are based on whether natural ventilation and mechanical cooling are in operation at the same time and/or in the same spaces or not. The taxonomy was initially defined by Max Fordman and then revised by Bordass et al. [9], [71] and are reproduced from [9]:

1. **Contingency**: Building is designed either as an air-conditioned building with provisions to convert to natural ventilation or as an NV building with space allocated for future installation of HVAC equipment. Can be used when the designer anticipates significant changes in the future building use. Contingency mixed-mode (MM) designs are very rare.
2. **Zoned**: Different zones within the building have different conditioning strategies. Many buildings, both old and new, can be classified as zoned MM schemes. Typical examples: Naturally ventilated office building with operable windows and a ducted heating/ventilation system, and supplemental mechanical cooling provided only to conference rooms.

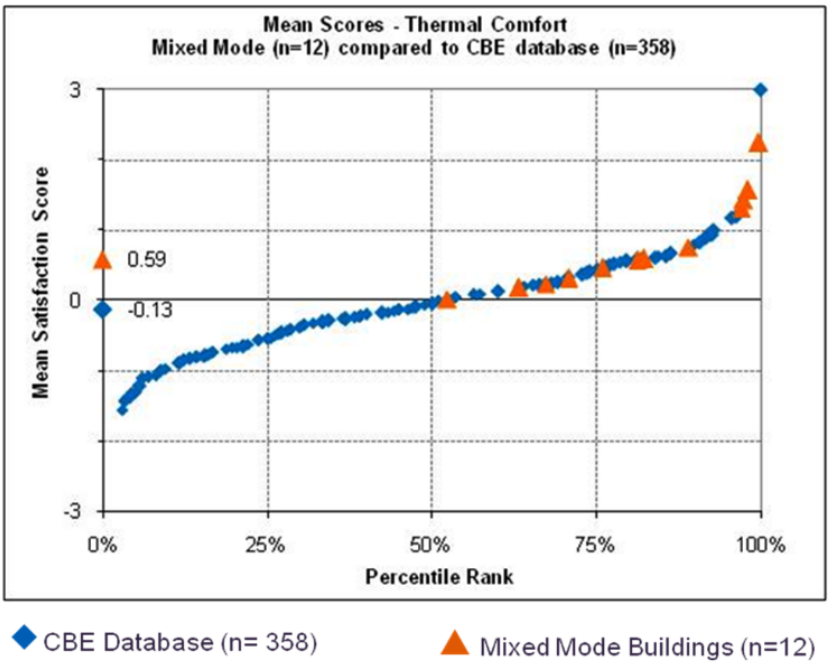

Figure 1.9: *Thermal comfort satisfaction in AC and MM building based on CBE surveys* [68]

3. **Complementary**: Building is designed with AC and NV capability in the same spaces. This category is further subdivided into Alternate, Changeover, and Concurrent MM strategies, as described below.
   (a) **Alternate**: Building includes provisions and equipment for both AC and NV but operates indefinitely in one mode or the other. Like hereabove mentionned *Contingency* taxonomy, this strategy is very uncommon and only applicable in situations where significant changes in the building use are anticipated.
   (b) **Changeover**: Building "change-over" between NV and AC on a seasonal or even daily basis. The building automation system may determine the mode of operating (AC or NV) based on outdoor temperature, an occupancy sensor, a window (open or closed) sensor, or based on operator commands. Typical examples: Individual offices with operable windows and personal air conditioning units that shut down for a given office anytime a sensor indicates that a window has been opened; or a building envelope where automatic louvers open to provide natural ventilation when the HVAC system is in economizer mode, and then close when the system is in cooling or heating mode.
   (c) **Concurrent**: AC system and NV provisions operate in the same space and at the same time. The HVAC system may serve as supplemental or "background" ventilation and cooling while occupants are free to open windows based on individual preference. Typical example: Open-plan office space with standard VAV air-conditioning systems and operable windows. Perimeter VAV zones go to minimum air when the sensor indicates that a window has been opened.

Brager et al. in 2006 simplified this approach by summarising three categories:

- **Concurrent**: This approach uses both natural ventilation and mechanical cooling simultaneously in the same areas of the building.
- **Changeover**: In this method, natural ventilation and mechanical cooling operate differently based on the season or time of day.
- **Zoned**: This strategy involves dividing spaces into zones according to the preferred mode of operation, utilising either natural ventilation or air conditioning.

Europe is also facing various diverse climate types and such different building operation modes, hence a differentiated approach is proposed by Kalz et al. in 2010 [72] based on the principle that the former European Standard ex-EN15251 (now updated to EN16798) does not sufficiently differentiate the cooling design strategies into the three categories AC, NV, and MM. This creates ambiguity about mixed-mode (MM) buildings in particular. Thus, a proposal in five categories is provided by Kalz et al.[72] :

- **Buildings without cooling**
- **Low-energy buildings with passive cooling**
- **Low-energy buildings with air-based mechanical cooling**
- **Low-energy buildings with water-based mechanical cooling**:
- **Buildings with mixed-mode cooling - combination of air-conditioning and air or water-based mechanical cooling**
- **Buildings with air-conditioning**

To define mixed-mode cooling operation effectively, several key aspects should be considered.

First, in the sense of Brager's [69] definition, the American standard considers this operation to be a primary use of air conditioning in periods and/or spaces where natural ventilation is possible. The European standard assumes that the MM building utilises a mechanical cooling system with low energy consumption (e.g., an earth tube system). Ceiling fans are not included in the definition of low-energy passive cooling. Furthermore, the EN 16798 standard [42] mentions MM buildings as operating with AC in summer but with no heating in winter, e.g., operating in natural ventilation mode.

Also, it is crucial to distinguish between *Air-conditioning* and cooling concepts. Air conditioning is a system designed to maintain ambient conditions within a very narrow range of temperature and relative humidity. The cooling concept refers to a system (or coupled systems) that lowers ambient conditions to make it feel colder, without adhering to strict predefined conditions.

Although often implied in each of these categories, the intervention of a ceiling fan as a complement to a passive or active cooling system is never explicitly mentioned in the standard. ASHRAE 55: 2020 [73] mentions in the case of naturally ventilated (NV) buildings the notion of "Elevated air speed", initially integrated since the ASHRAE 55:2009 version in the chapter "building design and operation" under the name "Elevated indoor air movement". It specifies the possibility of "using a mechanical system for air distribution" in its general definition.

The most recent standard for ceiling fans is ASHRAE 2020: 216 [44], which relates to the characterisation of equipment of this type to apply the results to calculate the comfort index. However, the normative or standard documents never mention the notion of coupling an air conditioner with a ceiling fan or other means of providing air movement for occupants.

To our knowledge, few authors have proposed a precise name and definition for the combination of air conditioning and air movement for comfort. Chen et al. first proposed a Ceiling Fan Integrated Air Conditioning (CFIAC) solution in 2020 [44], but it does not imply any cascade cooling strategy with NV. The whole cascade cooling operation studied in this thesis work and described in Figure 1.8 takes over the characteristics of **mixed mode building**, with Brager's **changeover operation** main category and **fan-assisted air-conditioning** operation described by Malik et al. in their study, highlighting the comfort-energy gain potential of Fan-first scenario [22]. An alternative naming in the literature proposed by the Center for Built Environment (CBE) team in the *"Fan for cooling guidebook"* is *"Ceiling fans integrated AC system"*.

In the following chapters and sections, these terms will be used interchangeably to describe the cooling cascade shown in Figure 1.8.

1.3 Problem statement and methodology

1.3.1 Knowledge gap and problem statement

Ceiling fans are gaining popularity as an efficient way to reduce the extensive use of mechanical cooling in buildings, but they remain under-recognised as a means to change the use of AC when used simultaneously. The emerging research on these topics is promising. It confirms the benefits of air movement on thermal comfort and satisfaction in naturally ventilated buildings. Moreover, it demonstrates that it can have a similar effect when used in conjunction with an air conditioning system. It highlights and quantifies the potential energy reduction and equipment undersizing, delaying the start of AC and upping the temperature setpoint in new or existing buildings in tropical climates. Furthermore, joint utilisation of ceiling fans and air conditioning can enhance buildings' demand response capability and thermal storage capacity [45], [74].

Designing and operating a building with very low energy consumption related to cooling (NV building) is relatively straightforward, but at the cost of uncontrolled comfort throughout the year in a harsh environment. Proposing a structure that ensures perfect comfort (AC building) is also feasible at the cost of potential energy drift. However, achieving both objectives simultaneously — balancing energy consumption and comfort — remains a more complex challenge. How can the performance of this cascade cooling approach be evaluated to both design the most optimal system and ensure that energy consumption supports equal comfort for occupants? Considering the variety of scenarios involving natural ventilation, ceiling fans, and coupled ceiling fans with air conditioning, this approach is relatively understudied and less prevalent in the practices of Architects and Engineers, particularly in tropical environments. Very little guidance and performance data are available on operating

ceiling fans with air conditioning unless adapting the AC use with predefined setpoints [48], [75].

Despite recent interest and promising results in combining ceiling fans with air conditioning in mixed mode operation [22], [46], [47], and, the recently published guidebook "Fans for cooling people" [75], **research remains sparse in directives on how to model, simulate and optimise such complex scenarios to assess comfort, energy performance, with the final objective to size the whole cooling system and maximise comfort-energy gains**. Building Energy Models (BEM) tools often overlook the potential to model a full range of adaptive opportunities, such as the use of ceiling fans or flexible clothing. This aspect remains unexplored, primarily in building energy modelling practices, due to the lack of appropriate tools, which are understood here as methods, models, and frameworks adapted to mixed-mode (MM) operation.

The tools capable of assessing the interest of these solutions primarily rely on building simulations and suffer from a lack of a comprehensive range of operating modes and relevant indicators that can help choose the best strategy for mixed-mode operation. Building Energy Models (BEM) are commonly used by the Architecture, Engineering and Construction (AEC) industry to size AC systems appropriately. With coupled AC-Ceiling Fan systems, Mechanical, Electrical, Plumbing (MEP) engineers will have to simulate the control - whether automated or manual – of AC thermostats and a wide range of air velocities in the BEM. One could then accurately estimate the coupled system's energy use and comfort performance to size it accordingly. In addition, the intrinsic performance of systems is either only partially represented (in the case of ceiling fans) or is very complex to implement (in the case of air conditioning systems) by the models present in building simulation tools. It very often leads to a poor assessment of electricity consumption and oversizing of installations (system production and distribution). Finally, given the diversity of operating modes applicable to buildings, the definition of indicators capable of taking into account both the aspects of energy performance and comfort (temperature, hygrometry, air speed, etc.) remains to be found to propose solutions guaranteeing maximum comfort at the lowest cost [75], [76].

Conducting numerous simulation scenarios to determine the optimal combination of cooling systems and operations is crucial for delivering the highest thermal comfort to building users at the lowest investment and operating costs. This involves identifying the optimisation process's objective function and suggesting a simulation framework that is not computationally demanding.

It is easy to understand that the way thermal comfort is modelled will significantly impact the simulation of coupled cooling system operations in buildings. Borgeson et al.[77] highlighted in 2011 that the choice of comfort criteria significantly impacts the overall comfort assessment of mixed-mode buildings and that future research is needed to better support comfort modelling in such cooling operations. The issue has not been addressed so far, as recently mentioned by Parkinson et al. [78]: *There is no agreement in either the research or professional communities about how best to define thermal comfort operating conditions for mixed-mode buildings*. Therefore, selecting the appropriate model for this purpose is a crucial step that requires further investigation. Various models are available to predict user comfort

in buildings. However, it can be challenging to select one of them outside of a normative framework for the MM cooling solution [79]. Standards and literature contrast naturally ventilated buildings (field measurement-based empirical approach modelling, known as the Adaptive Model (AM) approach) with air-conditioned buildings (analytical approach modelling, known as Thermal Heat-balance Models (THM)). In NV buildings, occupants are considered fully adaptable, i.e., they maintain their comfort by operating openings, solar shading devices, and ceiling fans. In AC buildings, they are supposed to be passive users. This dichotomy is reflected in standards, with the comfort models dedicated to NV and AC buildings, respectively, the adaptive model (AM) and THM Fanger's Predicted Mean Vote (PMV). Research in this field has been very active over the past two decades. Efforts have been made to bridge the gap between the Thermal Heat balance approach and the adaptive theory. While promising, these require further investigation to match the needs of the MM cooling operation.

The problem this thesis addresses can be stated as follows: **Designers lack robust modelling tools to predict the performance of mixed-mode cooling in tropical climates, which limits its adoption.**

1.3.2 Objectives of the thesis work and research questions

Having identified the need for tools which enable the simulation and size coupled cooling systems of the Mixed mode operations, we are now able to state the two objectives of the present work:

The primary aim of this research project was to explore to what extent the MM cascade cooling operation, including ceiling fans, is a viable alternative to the exclusive use of AC from a thermal comfort and energy perspective in a tropical climate. The secondary aim was to propose an optimisation-ready comfort-based simulation framework to model and simulate scenarios involving mixed-mode operation.

In this thesis, the focus was made on an occupied case study to understand and quantify the comfort and energy performance of a tropical office building in summer mixed-mode operation when occupants have full access to building elements to maintain their comfort (window manoeuvrability, solar shading, full clothing flexibility, AC setpoint and fan control).

The key research (RQ) and technical (TQ) questions for this research were as follows:

- RQ 1: What is the benefit of a ceiling fan in the case of tropical summer mixed-mode operation, and, to what extent can we push comfort limits in a fully adaptive office building operation?
- RQ 2: What would be the most adapted comfort model(s) to simulate Mixed-mode operation (Fan-First / fan-assisted AC) control in Building Energy Model for the case of MM building during a tropical summer?

- RQ 3: Is the comfort model relevant enough to control mixed-mode adaptive opportunities (use of ceiling fan, clothing flexibility) in front of controlling AC setpoint temperature in tropical conditions? (How would the comfort model respond to a change in air velocity and clothing in front of the AC setpoint temperature shift?)
- RQ 4: Does the comfort-based MM control have a significant impact on comfort assessment and energy performance of the cooling system?
- TQ 1: How to quickly model and simulate scenarios in BEM to assess mixed-mode operation performance from the perspective of sizing/operation optimisation?

1.3.3 Methodology and manuscript outline

To answer those questions, we propose the following methodology:

- Conduct a comprehensive literature review on comfort modelling in the built environment, emphasising mixed-mode operation in tropical climates and building energy modelling to identify the most relevant existing models.
- Setup a field survey in an occupied office over two consecutive tropical summers to assess comfort and energy use, assisting in the selection of comfort models.
- Propose a comfort model selection methodology based on (1) literature review qualitative screening, (2) a quantitative screening based on experimental comfort survey, and (3) the sensitivity of the comfort model to challenge its applicability in mixed-mode application in the tropics
- Propose a simulation framework to assess the performance improvement of MM comfort-based control over predefined scenarios.

The methodology and the contribution of each chapter are summarized in Table 1.3.

Table 1.3: *Manuscript structure, outline of links between content and research/technical questions*

Chapters	**Title**	**Content**	**Contribute to :**
2	Modelling comfort in tropical Mixed-mode cooled buildings	Literature review regarding Thermal Heat balance Models, Adaptive Models, recent research on comfort modelling	RQ 2, RQ 3
3	Experimental aspect	Comfort and cooling system energy and usage analysis	RQ 1, RQ 2
4	Comfort model selection for Mixed-mode control modelling	Selection criteria definition, literature review analysis and model preselection, measure-prediction comparison, sensitivity analysis	RQ 2, RQ 3
5	Mixed-mode Control simulation framework proposition	Case study co-simulation example	RQ 4 and TQ 1

1.3.4 List of publications associated with this thesis

Journal publication

[80] **Maxime Boulinguez**, Aurélie Foucquier, Jean Castaing-Lasvignottes. Sensitivity analysis of Gagge's Standard Effective Temperature for fan-first cooling control strategy in tropical mixed-mode buildings. *Building and Environment, 2025, 272, pp.112667.* ⟨10.1016/j.buildenv.2025.112667⟩. ⟨hal-04958917⟩

Conference publications (national and international)

[81] Maareva Payet, **Maxime Boulinguez**, Valentin Fargeas, COOLIBRI project. Lowering cooling energy use by coupling ceiling fans to air conditioners: an adaptive user perspective, in Journal of Physics: Conference Series, CISBAT Conference Lausanne, In press, publication Nov. 2025.

[82] **Maxime Boulinguez**, Aurélie Foucquier, Olivier Marc, Jean Castaing-Lasvignottes. Cartographie des modèles de confort : application aux bâtiments en rafraîchissement mixte en climat tropical. *IBPSA Conference France 2022 (International Building Performance Simulation Association), May 2024, Chalons-en-Champagne, France.* pp.1-8. ⟨cea-03988262⟩

[83] **Maxime Boulinguez**, Jean Castaing-Lasvignottes, Olivier Marc Marc. Development of a simplified model for evaluating refrigeration capacity and power consumption of air conditioning units based on heat exchanger entropic temperature definition. *26th IIR International Congress of Refrigeration (ICR 2023), IIF-IIR, AFF, Aug 2023, Paris Congress Center | Paris, France* ⟨10.18462/iir.icr.2023.0781⟩. ⟨hal-04669375⟩

[84] **Maxime Boulinguez**, Jean Castaing-Lasvignottes, Aurélie Foucquier. Pilotage des systèmes en rafraichissement mixte centré sur le confort: une étude de sensibilité du modèle de Gagge pour une application en climat tropical. *IBPSA Conference France 2024 (International Building Performance Simulation Association), IBPSA, May 2024, La Rochelle - Ile d'Oléron, France.* ⟨hal-04669415⟩

[85] Arnaud JAY, Aurélie Foucquier, **Maxime Boulinguez**, Gwenaelle Haese, Simon Thebault, et al.. Towards an alternative cooling: Optimisation of the successive use of the cooling systems from passive to active -Development of design and control strategies of the hybrid cooling. *43rd AIVC conference "Ventilation, IEQ and health in sustainable buildings - 11th TightVent conference and the 9th venticool conference, AIVC, Aug 2022, Aalborg (DK), Denmark.* ⟨hal-04669395⟩

[86] Gwenaelle Haese, **Maxime Boulinguez**, Pierre Bernaud, Anthony Couzinet. An innovative approach to better understand hot discomfort, based on the measurement of global human responses, including physiological and sensory indicators : application to end users

of mixed mode cooled buildings under tropical climate conditions. *43rd AIVC conference "Ventilation, IEQ and health in sustainable buildings - 11th TightVent conference and the 9th venticool conference, AIVC, Oct 2023, Aalborg (DK), Denmark.* ⟨hal-04669391⟩

Other research

[87] Maäréva Payet, **Maxime Boulinguez**, Mathieu David, Philippe Lauret, François Garde. Windows and ceiling fan occupant behaviour model coupling methodology with building energy models, a tropical case study. *43rd AIVC conference "Ventilation, IEQ and health in sustainable buildings - 11th TightVent conference and the 9th venticool conference, AIVC, Oct 2023, Aalborg (DK), Denmark.* ⟨hal-04669401⟩

1.3.5 Research scope and limitations

Research in the built environment, particularly on thermal comfort of occupants in office space, is not confined to thermal engineering but extends to broader areas of expertise, such as human-centred disciplines, e.g. physiology, psychology, sociology, or specific physics expertise, e.g. fluid dynamics or refrigeration modelling. Given the complexity of the subject of this thesis, its scope was intentionally narrowed in the following ways:

Cooling people is possible with a wide range of equipment, from different types of HVAC air-based cooling systems, earth tube systems, radiant cooling, evaporative cooling, ceiling fans, desk fans and all kinds of Personal Comfort Device (PCD) of the latter subcategories that can be applied to Mixed-mode cooling strategies. The present work is limited to Ceiling Fan-assisted cooling in the presence of Natural Ventilation (NV) and Split system air-to-air Air-Conditioning (AC)

The studied building was a small retrofitted office based in the south of Reunion Island, representative of the local economic landscape dominated by small to medium-sized companies with facilities of a few hundreds of square meters.

The studied population consisted of a team of architects and related professionals with a high level of awareness about bioclimatic design, energy efficiency and sustainability in general. While this may have introduced a bias in the performance assessment of the Mixed-mode solution, it also set ambitious and achievable objectives for comfort and energy performance.

The scope of this study was limited to the evaluation and comparison of thermal comfort surveys with off-the-shelf modelling and prediction techniques. State-of-the-art statistical analysis of the data to produce a new model was considered out of the scope of this work.

2

Modelling comfort in Mixed-mode cooled buildings

This chapter introduces all key notions of thermal comfort and provides an overview of how it can be modelled in the built environment. It reviews the literature with a focus on cooling operations and mixed-mode applications in hot conditions to determine whether off-the-shelf solutions have already been identified as suitable for our topic.

In the first section, general aspects of thermal comfort are exposed, such as thermoregulation, influencing factors, and methods of assessment. A second section gives a general picture of traditional methods for modelling comfort in the built environment, such as Thermal Heat-balance Models (THM) and Adaptive Model (AM). It also addresses the dichotomy between Natural Ventilation (NV) and Air-Conditioning (AC) in the built environment, both from a literature and a standard perspective. The final section explores the past two decades of active research in the comfort modelling field, highlighting attempts to address the limitations of traditional methods.

This chapter supports the understanding of how the comfort field survey of chapter 3: *"Experimental aspect"* was set up and serves as a knowledge base for chapter 4: *"Comfort model selection for Mixed-mode control modelling"*.

Several topics are outside the scope of this thesis, focusing on off-the-shelf indoor thermal comfort models. Hence, the heat stress index, comfort model applicable to outdoor, and machine learning techniques are not developed in this work.

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2.1 Background on Thermal comfort

2.1.1 Human Thermal comfort

Hensen [88], [89] defines Thermal Comfort as *"a state in which there are no driving impulses to correct the environment by the behaviour"*. ASHARE 55 Standard [90] describes it as *"a condition of mind that expresses satisfaction with the thermal environment"* in which one finds oneself. It is only assessed subjectively. All humans are not equal when it comes to thermal comfort. The variability of each individual, from a physiological and psychological point of view, impacts its ability to adapt to prolonged exposure. Hence, thermal comfort could be widely influenced by organisational, social, and cultural factors and individual inter-differences in mood [88], age or gender, food diet, and clothing habits [91]. Even chrono-related aspects such as acclimatisation periods [91], season, time of day and circadian circle influence thermal perception [92].

Thermal comfort is a state of mind, implying a cognitive process rather than a state of condition solely based on environmental variables. [88]. Thermal comfort (or discomfort), satisfaction and acceptability are subjective judgments, while thermal sensation may be considered as an objective condition[88], [89]. The subject's thermal opinions will statistically differ in identical controlled conditions, even if the population is homogeneous [88]. Hence, sensation and comfort are the two dimensions of thermal perception [16]. Deviation from a comfortable condition provokes thermoregulation processes of the human body. They are defined as "*an attempt to avoid what humans call thermal discomfort or displeasure and to obtain thermal pleasure*" [16]. It is assumed that thermal sensation is felt as neutral when thermoregulation processes of the human body are at their minimal level for maintaining a reasonably constant acceptable core temperature for a given ambient condition and metabolic activity [94]. ISO7730:2005 [95] and EN 16798:2009 [42] do not define thermal comfort but state that *"human thermal sensations are mainly related to the thermal balance of the body as a whole"*.

From a physiological point of view, the human body is the seat of autonomous thermoregulation processes. It bathes in the ambience and interacts with it by means of the skin, which is the largest organ of the human body [96]. The skin surface is affected by environmental parameters such as air temperature, vapor pressure, and air velocity. Thousands of

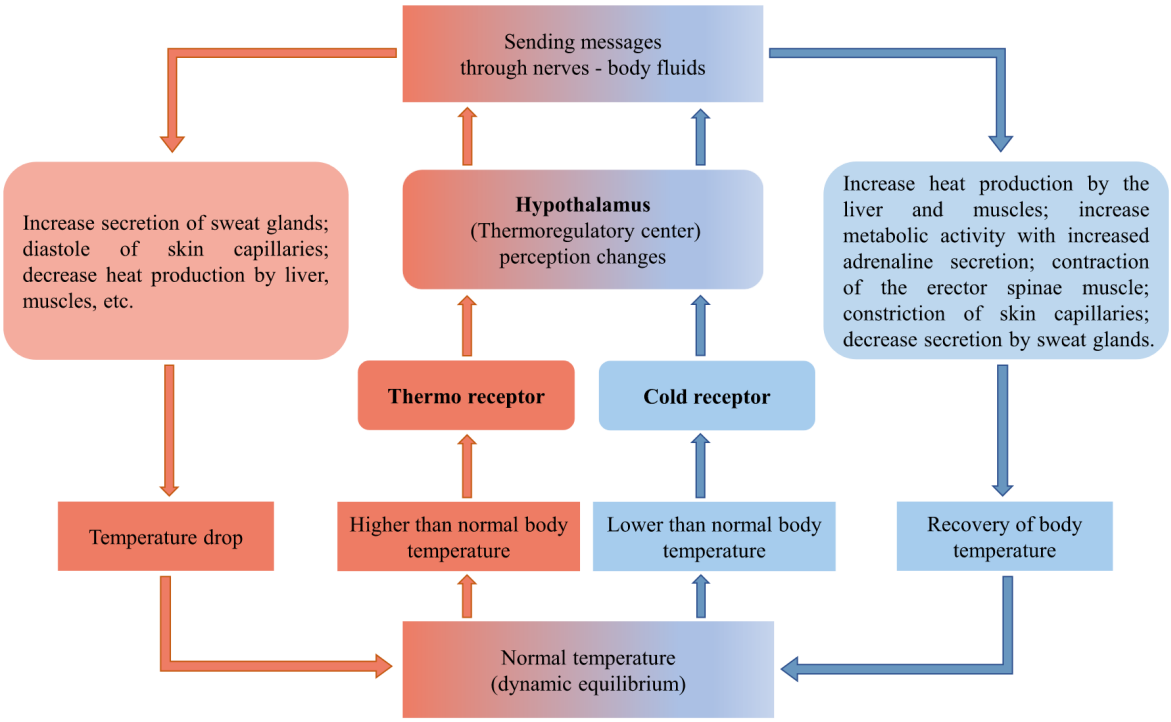

Figure 2.1: *Human thermoregulation processes reproduced from Zhao et al.* [93]

thermoreceptors and cold receptors cover it. The difference between the core temperature of the human body and the temperature of the environment is the driving force behind the heat transfers that take place between the body and the environment. As shown in the figure 2.1, regulatory signals are triggered when the core temperature deviates from its neutral/normal temperature (around 36.7°C). Organs, tissues, muscles and blood flow vary to regulate heat production or dissipation [93]. Just to note, vasomotor and evaporative regulation mechanisms are subject to acclimatization. As mentioned by [15], blood flow volume increases up to 20% in hot climates and sweat secretion rate increases after several weeks of exposure. Those physiological adaptations are governed by the hypothalamus gland.

Beyond physiology, it is worth noting that Humans are adaptable and can acclimatize to a wide range of conditions if they are used to doing so. Strictly conditioning spaces providing a non-changing uniform environment can reduce this adaptability [15]. From an architectural design point of view, architects should provide through the building a favourable thermal environment. *"Overall, a precondition of human well-being in terms of both productivity and health, appears to be the achievement of a harmonious balance between minimization of physiological responses (that is, the state that we subjectively interpret as thermal "comfort"), and maximization of acclimatization."*[15]

2.1.2 Factor of thermal comfort

The variables influencing the thermal balance of the human body and thermal comfort perception can be described in two categories :

- Environmental variables are air temperature, mean radiant temperature, relative humidity and air velocity around the subject;
- Main personal variables, also mentioned as individual parameters, are metabolism (related to the level of physical activity) and insulation (related to the level of clothing). Other contextual factors, often individual, such as acclimatisation, health and body shape, weight and subcutaneous fat, age, gender, food and drinks, stress levels, and building type, would contribute to perceived comfort.

Personal variables

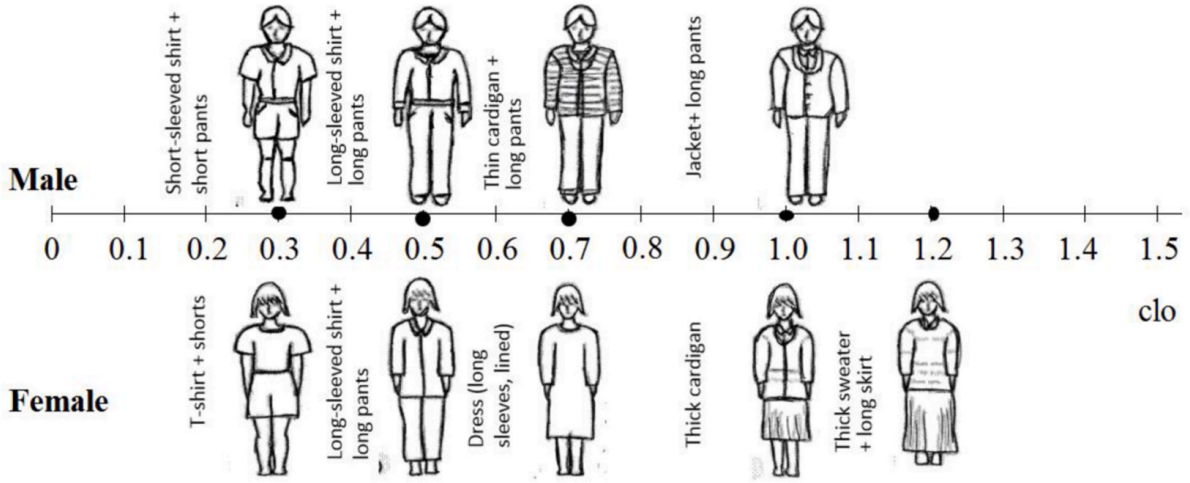

Figure 2.2: *Clothing value ranges for men and women reproduced from* [97]

Thermal insulation (I_{cl}) **or Clothing** (CLO), expressed in clo, is also defined in the standards ISO7730 and ASHRAE 55:2023 as the insulation of an ensemble of garments according to Eq.2.1. Typical values for summer clothing ranges from 0.25 to 0.6 clo while it can reach 1.2 clo for indoor winter heavyweight clothing ensemble. Figure 2.2 shows typical ensembles of clothing for indoor conditions

$$I_{cl} = 0,161 + 0,835 \sum I_{clu} \textit{where } I_{clu} \textit{ are unitary pieces of garment} \tag{2.1}$$

It is mentioned that this resultant insulation can fluctuate depending on the metabolism and/or airspeed (relative and walking) around the subject, namely due to convection. It is rarely taken into consideration in the inputs of comfort models as mentioned by d'Ambriosio Alphano et al. [98]. Note that the two standards propose different calculation methods for the resulting insulation to be applied as input to the models. 'Dynamic clothing insulation' (CLO_{DYN}) stands for ASHRAE (Eq. 2.2), and "Total resultant clothing insulation" ($I_{T,r}$ (Eq. 2.3, 2.4 and 2.5) for ISO 7730 [99], as described in ISO 9920 [100].

ASHRAE method :

$$CLO_{\mathrm{DYN}} = I_{\mathrm{cl}} \times (0.6 + 0.4/M), \quad \textit{for } M \textit{ (Metabolism)} > 1.2 \tag{2.2}$$

ISO 9920/7730/EN16798-2 method :

For a normally dressed person for an intrisic ensemble insulation $0.6 < I_{cl} < 1.4$ clo (or a total insulation of $1.2 < I_T < 2$ clo including air layer boundary insulation):

$$\begin{aligned} I_{\mathrm{T,r}} = I_{\mathrm{T}} \cdot \exp\Big(& -0.281 \cdot (v_{\mathrm{ar}} - 0.15) + 0.44 \cdot (v_{\mathrm{ar}} - 0.15)^2 \\ & - 0.492 \cdot v_{\mathrm{w}} + 0.176 \cdot v_{\mathrm{w}}^2 \Big) \end{aligned} \tag{2.3}$$

For a nude person ($I_{cl} = 0$ clo), the air layer insulation is considered as follows:

$$\begin{aligned} I_{\mathrm{T,r}} = I_{\mathrm{air,\,static}} \cdot \exp\Big(& -0.533 \cdot (v_{\mathrm{ar}} - 0.15) + 0.069 \cdot (v_{\mathrm{ar}} - 0.15)^2 \\ & - 0.462 \cdot v_{\mathrm{w}} + 0.201 \cdot v_{\mathrm{w}}^2 \Big) \end{aligned} \tag{2.4}$$

For a lightly dressed person ($0 < I_{Cl} < 0.6$ clo), a linear relation is to be used between Eq.2.3 and Eq.2.4 :

$$I_{\mathrm{T,r}} = \frac{\left((0.6 - I_{\mathrm{cl}})\, I_{\mathrm{T,r,\,nude}} + I_{\mathrm{cl}} \times I_{\mathrm{T,r,\,dressed}}\right)}{0.6} \tag{2.5}$$

Where I_a is air insulation, V_ar air velocity relative to the subject calculated based on Eq.2.7and V_w walking speed as in Eq. 2.6.

An update of the coefficients of the equations of the European standard is also available in the work of Nielsen et al. [101] but not integrated into the ISO 7730 [99] and 9920 standards[100]. Current values of clothing combinations adapted to the tropical climate, such as *shorts and a short-sleeved shirt or t-shirt* and *lightweight pants and a short-sleeved shirt or t-shirt*, are respectively between 0.4 and 0.6. Both standards advise to stitch to 1.0 clo for the winter period and 0.5 clo for the summer period while it has been shown users can have a much wider flexibility from 0.23 clo in summer and 1.23 in winter [102], [103]. In addition to garment ensembles, when the subject is sitting, 0.01-0.15 clo is added to the total sum of the pieces if the design of the chair provides extra insulation on the seat and back. The latest ASHRAE 55:2023 [104] provides a table listing chair types and the recommended added clo value for the total insulation. It is reproduced in table 2.1.

Thermal insulation is one of the input parameters for analytical comfort models. This parameter is often assumed to be constant or entered according to a seasonal schedule in Building Energy Models. Several indices exist that enable a more refined approach and thus reduce the bias introduced by individual variables entering the models. For example,

Table 2.1: *ASHRAE 55:2023 recommended added insulation for chairs* [104]

Chair type	Added insulation (clo)
Net chair[a]	-
Metal chair	-
Wooden side-arm chair[b]	-
Wooden stool	+0.01 clo
Standard office chair	+0.10 clo
Executive chair	+0.15 clo

a. A chair constructed from thin, widely spaced cords that provide no thermal insulation b. Informative Note: This chair was used in most of the basic studies of thermal comfort that were used to establish the PMV-PPD index.

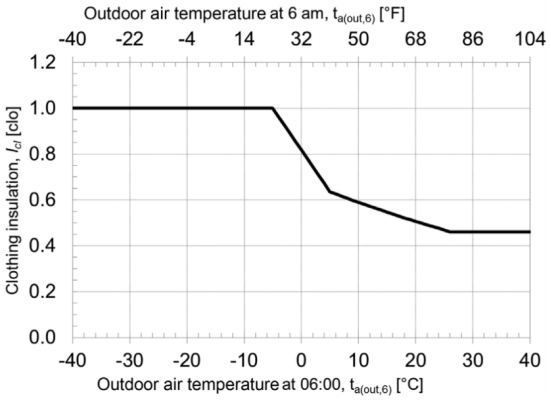

Figure 2.3: *Dynamic clothing prediction model from* [105] *and reproduced from* [104]

Schiavon's model depends on the outdoor and indoor temperatures at 6 a.m [104], [105]. Figure 2.3 shows that thermal insulation is limited to a minimal threshold of 0.46 clo if outside air temperature at 6:00 am is over 20°C, which is often the case in tropical climate summer season. Ngarambe [106] model depends on the mode of transportation used to get to the office. This allows for an average clo value. Parsons [107] also proposes an Equivalent Clothing Index (ECI) that adjusts the CLO value based on the individual's clothing adaptation opportunities. This solution has the advantage of being dynamic throughout the day.

Metabolism (M **or** MET) is a direct result of the subject's activity in its environment. It is the energy produced by the body which, depending on the conditions, must be conserved (cold conditions) or dissipated (hot conditions). It is expressed in met. 1 met corresponds to 58.2 W per square meter of outer skin surface. European and American standards provide tables of activity and corresponding metabolisms. Regarding the order of magnitude, for standard activity, the metabolism is around 1-1.2 met: a person sitting at rest will have a metabolism close to 1 met (i.e. 58.2 W/m²), in office activity around 1.1 met, standing 1.2 met.

Environmental variables

The main environmental variables are as follows and are given by ASHRAE 55 [104]:

Dry Bulb temperature (T_{db} **in** ($°C$)) is defined as the average air dry bulb temperature surrounding the subject. It is measured using a dry-bulb thermometer at three heights (foot 0.1 m, height 0.6 m, head 1.1 m).

Mean radiant temperature (T_r **in** ($°C$) is relative to the subject's position (view factor) in relation to the surfaces of vertical and horizontal walls whose materials emit or absorb heat (depending on the emissivity of the material). It may be higher than the dry air temperature if the subject is facing a hot window in direct sunlight or on underfloor heating, and less important if the subject is near a cold wall.

Relative humidity (rh **in %**) corresponds to the ratio of specific humidity or water vapor pressure to weight in dry air at a given temperature and pressure. This variable can influence a subject's ability to evacuate heat through perspiration. In hot and humid climates, relative humidity reduces the natural capacity for evapotranspiration.

Air velocity (V_a **in** $m.s^{-1}$) corresponds to the average velocity in the subject's immediate environment. It can be induced by a natural air current or a mechanical device. It is measured in laboratory experiments at three heights (foot 0.1 m, height 0.6 m, head 1.1 m) and is directionless. Note again that "measured" V_a cannot be used directly as an input variable in comfort models. It is appropriate to use a relative velocity V_{rel} (Eq. 2.6) that takes into account body velocity (V_w) (Eq. 2.6 caused by body movement via metabolic activity (M) and/or walking.

$$v_{\mathrm{w}} = 0.3(M - 1) \tag{2.6}$$

$$v_{\mathrm{rel}} = \sqrt{v_a^2 + v_w^2} \tag{2.7}$$

It is essential to note that the uncertainty associated with these input variables (values averaged according to a measurement protocol, and the lack of knowledge regarding the definitions of the variables) introduces bias to the uncertainty of the model used, particularly well illustrated in the case of the PMV model in [98]. Additionally, certain inconsistencies in the standards regarding the transcription of specific formulas and computer calculation programs are noted in Parsons's work [107], which also provides guidance for on site measurement of these variables according to ISO 7726 [108].

2.1.3 Assessing thermal comfort

Before developing computational approaches to comfort modelling, it seems interesting to empirically evaluate the sensations or thermal perception of individuals. Voting scales have been developed for this purpose since the early 20th century. Their principles are still the basis for comfort assessment today. However, there is a great variety in the degree of finesse, continuity and type of vote (or combination of votes) collected. These are 2 to 7-point scales that can be found in the literature as shown in Table 2.2. The votes collected are classified according to the following categories [63], [104], [109]–[111]:

Thermal sensation : This describes the occupant's perception of the ambience when voting. Vote corresponding to the physiological aspect of comfort. Thermal sensation votes are typically from -3 to 3 : -3 : Very Cold,-2 : Cold, -1:Slightly Cold, 0 : Neutral, 1 : Slightly Warm, 2 : Warm, 3 : Hot . While the terminology is "Thermal", it refers to a sensation that can be influenced by variables other than temperature only.

Thermal preference : This describes the occupant's preference with respect to the thermal conditions of the space to which it is exposed. An occupant may feel 'comfortable' but have a preference for a cooler or warmer thermal environment. Thermal preference votes are typically a 3-point scale: Warmer, No change, and Cooler.

Thermal comfort : This provides additional judgment information to the thermal sensation vote. It describes the occupant's state of mind in its thermal environment. The thermal comfort scale usually ranges from 1 (Very uncomfortable) to 6 (Very comfortable).

Acceptability: This measures how acceptable the occupant finds the thermal conditions of the space. An occupant might feel slightly warm but still be in an acceptable condition. Thermal acceptability can be a 2-point (Acceptable, Unacceptable) or a 4-point scale (Acceptable, Just acceptable, Just unacceptable, Unacceptable).

Satisfaction: This describes whether or not the occupant is satisfied with the current ambient conditions. Thermal acceptability can be a 2-point (Satisfied, Dissatisfied) or a 4-point scale (Satisfied, Just Satisfied, Just Dissatisfied, Dissatisfied).

Air Movement acceptability and preference : To our knowledge, the most commonly used assessment method for air movement does not take into account the sensation of air movement. It is measured on two independent scales, enabling voters to indicate their level of air movement acceptability (Unacceptable, Acceptable) and their preference (Less, No change, More).

Humphreys et al. [112] as well as [113], reports the heterogeneity of the application of a single scale in comfort surveys. It should be noted, however, that the most widely used scale

Year		1923	1936	1937	1937	1967	1968	1968	1969	1978		2007	2007
Author		Houghten and Yaglou	Bedford	Bedford	Winslow, Herrington, and Gagge	Gagge	ASHRAE / ISO 7730 / ISO 10551	ASHRAE / ISO 7730	ASHRAE / ISO 7730	McIntyre / ASHRAE	Nicol	ISO10551	ISO10551
Points		5 points	7 points	8 points	5 points	7 points	7 points	4 Points	5 Points	3 points	5 points	7 points	5 points
Type		Sensation et jugement	Sensation et Jugement	Sensation et Jugement	Jugement	Sensation	Sensation	Jugement	Acceptability	Preference	Preference	Sensation	Jugement
Scale	-3		Cold	Much too cool		Cold	Cold	Very uncomfortable					
	-2	Too cold (Not comfortable and preferred warmer)	Cool	Too cool	Very Unpleasant	Cool	Cool	Uncomfortable			Prefer much cooler	Cold	
	-1	Comfortably Cool (Comfortable but preferred slightly)	Comfortable Cool	Comfortably cool	Unpleasant	Slightly Cool	Slightly Cool	Slightly Comfortable		Prefer Cooler	Prefer a bit cooler	Slightly Cool	
	0	Very Comfortable (Comfortable and no change desired)	Comfortable	Comfortable	Indifferent	Comfortable	Neutral	Comfortable	unacceptable	No Change	No Change	Neutral	Comfortable
	1	Comfortably Warm (Comfortable but preferred slightly cooler)	Comfortable warm	Comfortably warm	Pleasant	Slightly Warm	Slightly Warm		acceptable	Prefer Warmer	Prefer a bit warmer	Slightly Warm	Slightly uncomfortable
	2	Too Warm (Not comfortable and preferred cooler)	Warm	Too warm	Very pleasant	Warm	Warm				Prefer much warmer	Warm	Uncomfortable
	3		Hot	Much too warm		Hot	Hot					Hot	Very uncomfortable
	4											Very Hot	Extremely uncomfortable

Table 2.2: *Thermal Sensation Scales from Various Studies*

is the Thermal Sensation Scale of ASHRAE [104]. It is a seven-point scale ranging from -3 to +3 and centred on neutrality (cold, cool, slightly cool, neutral, slightly warm, warm, hot), as listed by Schweiker et al. [110]. Both models of Fanger's PMV and Nicol's adaptive model are based on empirical data from subjective evaluations using this scale, conducted in controlled chambers and occupied buildings.

Several assumptions about the use of this scale can be questioned: its continuity, the equidistance of the markers, and its independence from context. Indeed, comfort surveys can be constructed either categorically, when there is no possibility of voting between two values (e.g., hot and very hot), or pseudo-continuously, when it is possible to vote between two values exactly as one wishes. It has been shown that marker equidistance significantly influenced the TSV vote, and that the distance between two markers is not perceived as constant. The observation is similar to the binarity of the non-centred acceptability scale, for which continuous alternatives exist. In their article, Schweiker et al. [110] list various scales related to thermal sensation, thermal comfort and thermal preference to illustrate the historical changes over the years. Two of the main findings are that most people do not perceive the sensation scale categories as equidistant and that the ranges of conditions considered "comfortable" vary. This has not yet been addressed in the literature and should be taken into consideration when analysing votes. In addition, McIntyre et al. [114] demonstrated that the linear relationship between the physical temperature in the room and the thermal sensation is not valid for the extreme categories (-3, -2, +2, +3). De Dear et al. [115] show that the votes are also influenced by the type of cooling installed in the building (AC or NV). The implicit and explicit assumptions of the use of comfort scales are therefore strongly called into question. Beyond this, the geographical and sociocultural context, climate, and season are parameters influencing voters' interpretation of the scale. It is explicitly noted that bias may arise in the notion of preferred comfort conditions. It is defined as the semantic artefact hypothesis. For example, a population from high latitudes may describe 'slightly warm' as a preferred comfort condition, while populations from tropical latitudes may describe 'slightly cold' as a preferred comfort condition. In another article, Schweiker et al. [116] cite two studies in Brazil to illustrate this hypothesis of long-term adaptation in tropical climates. On a larger scale, the author also cites the work of Cheung et al. [117] on the entire ASHRAE Global Comfort Database I [109], described later in this chapter, showing a more substantial influence of this semantic artefact hypothesis in hot climates than cold climates. A similar observation can be made regarding the notion of so-called neutrality temperature, which can be higher in hot climates than in cold climates. Finally, the neutrality of thermal sensation ('neutral' / 'neither cold nor warm') is, on the one hand, often difficult for voters to assess and, on the other hand, does not represent judgment or preference.

While current scales should not be entirely questioned, particular attention must be paid to tools for assessing comfort by voters in occupied sites (such as laboratory conditions or buildings in use) and the way these surveys are used to validate a model and build a new one. Neutral sensation, centred around zero, may not reveal perceived comfort. Combining

different independent voting scales (thermal sensation, acceptability, and preference) would reduce bias but is not systematically integrated into surveys. The authors provide several recommendations regarding details to be recorded in future comfort surveys, such as language and translations, the context of the study (climate, culture), and, of course, the multiplicity of scales used and their formalisation in the survey (paper, web/mobile application, scale, markers).

2.2 Traditional Thermal Comfort modelling approaches

2.2.1 Overview

Several modelling approaches exist in both the literature and standards. The main milestones of the comfort research are highlighted by Karyono et al. [118] in Figure 2.4. Early methods were primarily indices calculated based on physical measurements. They are described in 2.2.2. In parallel, the first approach is defined in the literature as analytical (also known as rational). It aims to produce a heat balance of the human body. It accounts for heat exchanges between the body and its environment and sometimes a certain number of thermoregulatory processes. It is called the Thermal Heat Balance Approach. Most of the time, the Thermal Heat-balance Models (THM) is coupled with a sensation model to predict a Thermal Sensation Vote (TSV). Most well-known models in the building industry are Fanger's Predicted Mean Vote (PMV) [119] and Gagge Two-node model and its Standard Effective Temperature (SET) index [120], [121]. The second approach is field survey-based, providing a statistical response to comfort modelling. Comfort surveys in occupied buildings help establish the ambient conditions that lead to comfortable votes (thermal neutrality) while accounting for adaptation effects. This approach resulted in the Adaptive Model (AM) [122]–[124]. It does not offer the possibility to predict a thermal sensation but rather a comfortable temperature range within which a certain percentage of the population will be in acceptable conditions. It aims to describe comfort with psychological, behavioural, and acclimatisation dimensions, while THM is only physiologically oriented. Both approaches have pros and cons, different validity domains, and varying degrees of accuracy under certain conditions. The key aspect of these two approaches is that THM models (like the PMV) are originally designed for conditioned buildings, whereas Adaptive Models are dedicated to NV buildings.

Standards and literature contrast naturally ventilated (NV) buildings (field measurement-based empirical approach modelling) with air-conditioned (AC) buildings (analytical approach modelling, known as Thermal Heat-balance Model or THM). In NV buildings, occupants are considered fully adaptable, i.e., they maintain their comfort by operating openings, solar shading devices, and ceiling fans and have a certain degree of self-adaptation. In AC buildings, they are supposed to be passive users. This dichotomy is reflected in standards with the comfort models dedicated to NV and AC buildings, respectively, the Adaptive Model (AM) and THM Fanger's PMV (Predicted Mean Vote) [42], [104]. From

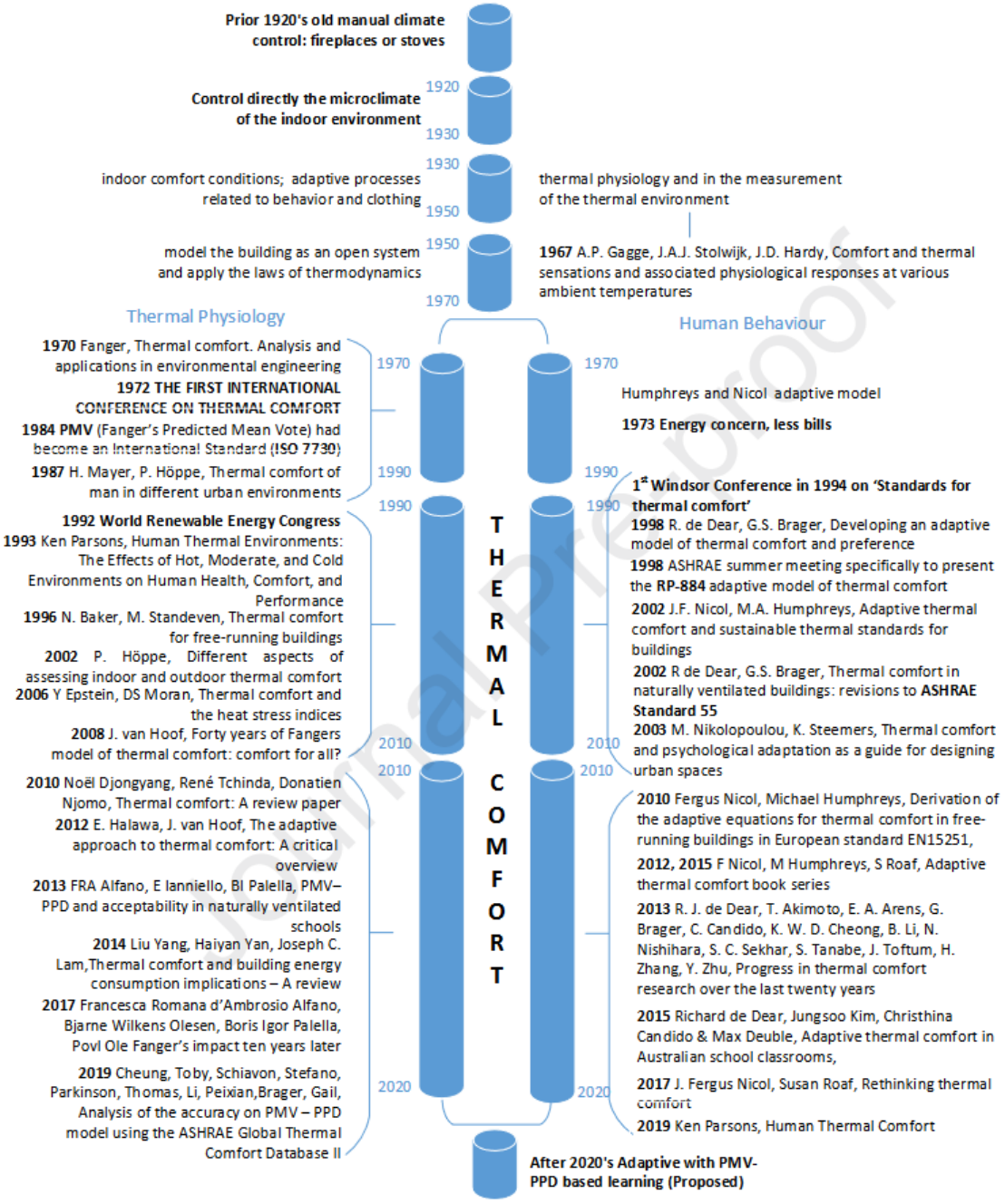

Figure 2.4: *History of key thermal comfort research* [118]

2010, the ASHRAE 55 standard includes another THM model, the Gagge two-node model [121], to calculate a cooling effect (CE) [104] further entered as input to the Fanger model (names adjusted PMV or PMV_{CE}). It aims to enhance air velocity's contribution over 1.0 m.s-1, the normative limit of the PMV. To find the best of both worlds, over the last two decades, scientific research has been very active in that field. It has provided new research to modify the traditional approaches or integrate the adaptive theory into Thermal Heat-balance Models models. **Because various models exist to predict users' comfort in buildings, it can be challenging to select one of them outside of a normative framework for the MM cooling solution [79], specifically the Fan-assisted one in tropical conditions. This chapter provides an extensive review of traditional methods and the most up-to-date research that apply to the built environment, emphasising their applicability to MM cooling strategy.**

2.2.2 Physical measurement-based indices

Environmental variable-based equivalent temperatures and stress indices

The **operative temperature** is a well-established index in the AEC industry. It is defined as a uniform temperature to account for the influence of radiation from the surrounding surfaces and convection inherent to air movements on the human body. It corresponds to the temperature of an isothermal imaginary black enclosure in which an occupant exchanges the same quantity of radiative and convective heat as in the real environment [99]. Generally, it is defined as the mean radiant and air temperature, the average weighted by convective and radiative heat transfer coefficients (Eq. 2.8, but for low air speeds (<0.2 $m.s^{-1}$), it corresponds to the arithmetic mean of the average air and radiant temperatures.

$$
\begin{aligned}
t_{op} &= \frac{t_r + \left(t_a \times \sqrt{10v}\right)}{1 + \sqrt{10v}} \\
&\textit{expressed in } ^{\circ}\mathrm{C} \textit{ with,} \\
&t_a : \text{air temperature in } ^{\circ}\mathrm{C}, \\
&t_r : \text{mean radiant temperature in } ^{\circ}\mathrm{C}, \\
&v : \text{air velocity in m·s}^{-1}
\end{aligned}
\tag{2.8}
$$

Apparent Temperature (AT) is a comprehensive concept that corresponds to the temperature felt by humans, taking into account the effects of air temperature, air movement (only the cooling effects in cold temperatures), and relative humidity, as does the operating temperature. Although rarely used in the characterization of indoor spaces, it is the basis for several heat stress indices such as the Humidex, which describes how hot and humid an environment is for an average person; the **Heat Index (HI)**, which measures the effect of humidity on hot temperatures (>27°C) by reducing evapotranspiration potential; and the **Wet Bulb Globe Temperature (WBGT)**, which adds the radiation component to the variables

of temperature, humidity, and air movement, particularly for taking into account outdoor solar radiation. Finally, the **Effective Temperature** (**ET**) is defined by Yaglou et al.[15] as a temperature given at a standard value of humidity and air speed for which one would have the same sensation as in the real environment. Other empirical indices, such as those of Webb and Sharma [125], are dedicated to the tropical climate (**Equatorial Comfort Index** (**ECI**) in 1959 and **Tropical Sumner Index** (**TSI**) in 1986) but were only tested in India [15], [126].

The **Predicted Heat Strain** (**PHS**) index is designed to assess the risk of exposure to a subject in a hot environment. It allows the calculation of core and skin temperatures. It was standardised in 1989 by ISO 7933 and has been regularly updated, notably in ISO 7933:2004. Particularly suited to very constrained environments, such as industrial, mining, and military settings, to ensure safe working conditions for workers, it has not been widely used in the construction sector under classic office activity conditions [127].

The **Wind Chill Index** (**WCI**) is used to determine the percentage of heat loss by radiation and convection on a subject similar to a cylinder filled with water at 33°C in cold conditions. It is valid for wind conditions below 80km/h and does not appear to represent the reality of exchanges with the flesh of the human body, nor to be used in the field of weak air movements, nor in hot and humid conditions [128]. The **Universal Thermal Comfort Index** (**UTCI**) is another well-known index that assesses body exchange and stress in relation to meteorological conditions. It is dedicated to assessing outdoor comfort.[129]

Overall, this enumeration is far from exhaustive, but unless classical Operative Temperature and Effective Temperature, those indices are more focused on thermal stress or outdoor comfort assessment. The indoor built environment preferably focuses on thermal sensation, thermal comfort or satisfaction.

Building Bioclimatic Comfort Charts BBCC

The representation of comfort zones on the psychrometric chart has been widely used since the work of Olgyay in 1963 [130], who was a pioneer in this field. Figures 2.5 and 2.6 illustrate the Bioclimatic Diagrams for Buildings by Olgyay and Givoni (Building Bioclimatic Comfort Chart (BBCC)), respectively. The latter is based initially on the psychrometric chart to identify bioclimatic strategies applicable to building design, given specific climatic conditions. The diagram features zones that correspond to these strategies.

Two zones are particularly relevant for tropical climates. Zone 1 of Givoni's BBCC as shown on figure 2.6 indicates comfortable conditions with calm winds (air velocity less than 0.25 m/s), while Zone 2 corresponds to comfortable conditions with air movement between 0.25 and 2 m/s, with temperatures ranging up to 32°C. The limits of both Zones 1 and 2 were established through surveys conducted in Europe, Israel, and the USA for the initial zones, and later updated based on data from hot and humid countries [55], [62], [131].

The other zones (3, 4, 5, and 6) stem from the authors' complementary work on evaporative cooling, thermal inertia, and mechanical ventilation. These zones serve as a design guide, enabling the identification of passive design strategies by illustrating climatic conditions layered over the zones. In this context, they are integrated into ASHRAE 55.

It is essential to note that the boundaries of these zones have never been mathematically defined and are referenced only in the authors' books and publications. As a result, variations in the definitions of still air and natural ventilation zones can appear after several decades, and their boundaries may differ at the discretion of the authors. [62], [131]–[134]

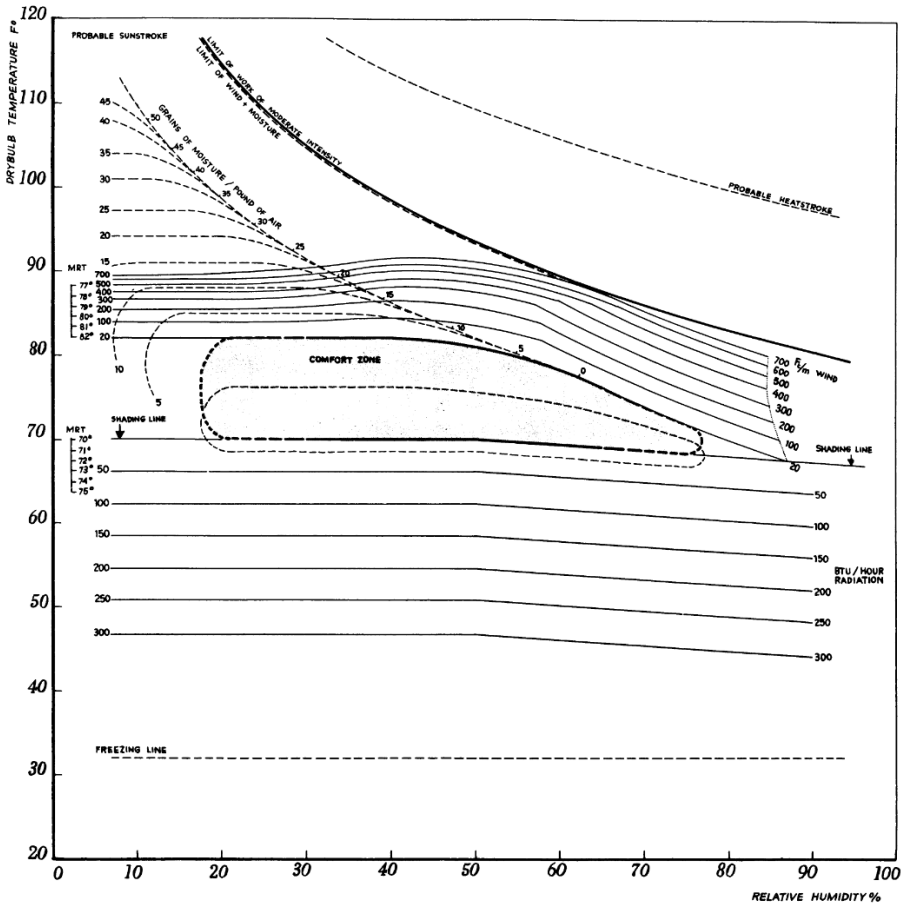

Figure 2.5: *Olgay original T-RH comfort bioclimatic chart from his book* [135] (*originally in Fahrenheit, for reference,* $70\,^{\circ}\mathrm{F} = 21\,^{\circ}\mathrm{C}$, $90\,^{\circ}\mathrm{F} = 32\,^{\circ}\mathrm{C}$)

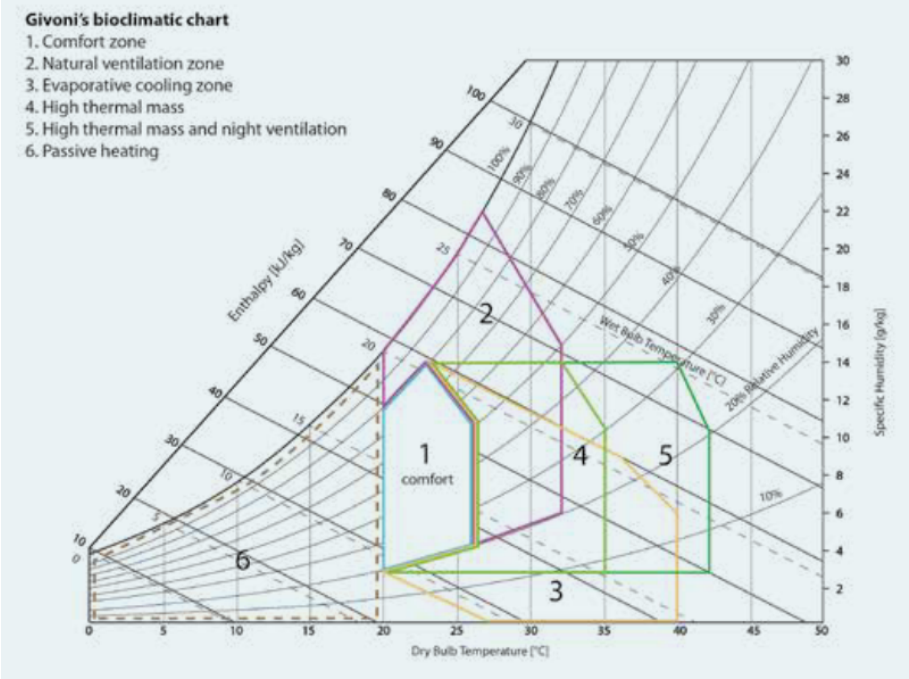

Figure 2.6: *Givoni's Building Bioclimatic Comfort Chart (BBCC) with design zones reproduced from* [130]

2.2.3 Thermal Heat-balance Models and indices

Thermoregulatory system and Heat balance

Establishing thermal balance between the environment and the human body is the most common approach in the literature for modeling the physiological aspects of thermal comfort. As mentioned, the environment significantly influences the human body's thermal balance, which tends to maintain, in regular rest and exercise, its internal core temperature at around 36.5-37 °C through various regulatory mechanisms. The human body is composed of a warmer central core (the interior of the body) and a peripheral envelope with a lower and more variable temperature. The heat produced inside the body core, principally by metabolism, i.e. oxidation of food [89], must be transferred to the outer envelope to ensure thermal homeostasis in the central core. This occurs to a small extent by conduction through the tissues, but blood circulation ensures most of this heat transfer. A person in a theoretical situation of comfort sees its heat balance cancelled out. The subject is hyperthermic if the balance is positive (more heat accumulated than dissipated). Conversely, if it is negative (more heat is dissipated than accumulated), then the subject is hypothermic. The heat balance of heat transfer by skin and respiration can be written as Eq.2.9 and detailed in Eq.2.10. Heat produced by the body is dissipated in the ambience in a sensible and a latent part. Heat exchange are conduction (C_d), convection (C_v), evaporation (E), respiration (C_{res} and E_{res}), and radiation (R) [136]. Most of the time, in building-dedicated heat balance models, conduction can be neglected [15]

$$\begin{gathered}\text{Heat storage in skin and the body} \\ = \\ \text{Heat production} \\ - \\ \text{Heat loss at skin layer and by respiration}\end{gathered} \tag{2.9}$$

$$\begin{aligned} S &= M - (W + Q_{sk} + Q_{res}) \\ S_{sk} + S_c &= M - (W + (C_v + R + C_d + E_{sk}) + (C_{res} + E_{res})) \end{aligned} \tag{2.10}$$

Where:

- $M =$ metabolism (basal + shivering), W/m^2,
- $W =$ mechanical work done by the body, W/m^2,
- $Q_{\text{res}} =$ heat loss by respiration, W/m^2,
- $Q_{\text{sk}} =$ heat flow through skin, W/m^2,
- $C_{\text{res}} =$ convective heat flow by respiration, W/m^2,
- $E_{\text{res}} =$ latent heat flow by respiration, W/m^2,
- $C_v =$ convective heat at skin surface, W/m^2,
- $R =$ radiative heat at skin surface, W/m^2,
- $C_d =$ conductive heat at skin surface, W/m^2,
- $E_{\text{sk}} =$ latent heat by evaporation at skin surface, W/m^2,
- $S_{\text{cr}} =$ heat storage in body core, W/m^2,
- $S_{\text{sk}} =$ heat storage in skin layer, W/m^2.

Skin surface exchange and respiration are the two ways to dissipate body sensible and latent heat. At the skin level, sensible heat exchange occurs through radiation, convection, and conduction, while latent heat is transferred through the evaporation of water mass from sweating through the skin and permeable clothing. At the lungs' level, heat exchanges are convection (sensible) and evaporation (latent). In general, heat transfer is a function of environmental variables, skin temperature (or clothing temperature), and wetness, and is expressed for 1 unit of body outer surface (approximately 1.8 m² for a standard subject). Their mathematical formulae combine analytical and empirical approaches and are algebraic, namely, they can be positive or negative.[137]

There are 3 types of comfort models developed on this principle: one-node models, two-node models and multi-node models. Each of these nodes can be applied to several segments representing each part of the human body in varying degrees of detail as illustrated in Fig. 2.8. One segment simplifies the human body to a cylinder. The thermoregulation system is simplified by empirical equations based on experimental measurements in order to respond to external stresses. Nevertheless, the exchange in the two-node model's can take

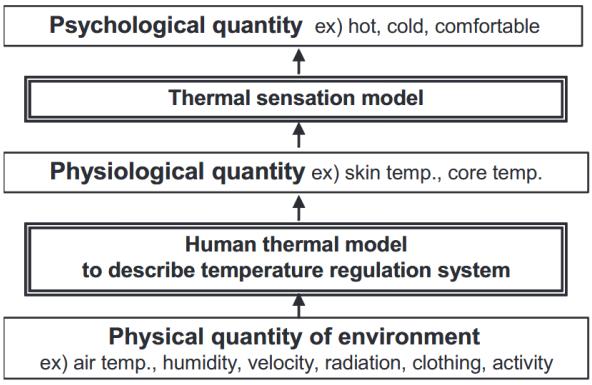

Figure 2.7: *Predication of heat-balance and sensation response of the human body in a given ambience, reproduced from* [138]

place between two concentric cylinders with a uniform temperature distribution. On the other hand, the level of complexity increases with the number of nodes (>2), with the possibility of discretising the temperature and exchanges between each tissue, detailing the envelope of the human body with as many nodes (core, muscle, fat, skin...) as possible. Numerous assessment indices, some of which apply to buildings, derive from these concepts. Indeed, it is essential to mention that the human thermal model provides a physiological quantity that serves as input to a sensation model, as illustrated by 2.7. Thermal sensation is a psychological quantity that expresses the occupant's feeling. In the following sections, we will describe several sensation models that are built from the same Thermal Heat-balance Models.

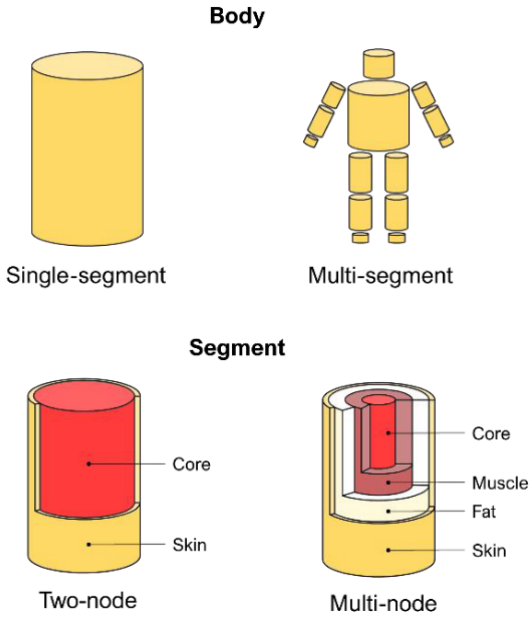

Figure 2.8: *Representation of model segments for two-node and multi-node models reproduced from* [139]

Although the multi-segment and multi-node approaches are the most comprehensive, the computational resources required by these models make them less prone to be used for building energy simulation, which aims to determine averaged outputs at the scale of a uniform thermal zone environment[140]. They are intended to calculate core and skin

temperatures for a human body represented by multiple segments in a non-symmetrical environment, like an automotive passenger compartment. Contemporary buildings, whose design has been guided by standards for the past decades, generally have a high level of insulation and conditioned space, allowing a homogeneous temperature distribution [140]. Thus, for models seeking to represent the physiological functioning of the human body in the building, norms and standards have until now retained a simplified approach in steady state in a homogeneous and symmetrical environment embodied by the Fanger one-node model [119] and its less usual but more defined two-node counterpart namely the Gagge two-node model [121], [141].

Fanger's 1 node sensation and satisfaction models

Widely represented for applications related to construction engineering, the Fanger model [119] is the basis of international standards (ISO7730, EN16798, CIBSE, ASHARE55) [98]. Initiated in the early 1970s to face early energy concerns, the approach of this single-node physiological model is based on the simplification of thermoregulation processes, whose exchange equations were determined from experimental measurements on approximately 1,400 subjects in a climatic chamber, thereby offering the possibility of homogeneous conditions and a steady state. The model evaluates its thermal sensation by solving a heat balance equation for a subject, integrating environmental and individual variables. In a situation of equilibrium, of theoretical comfort, the heat load $(L = M - W)$ is equal to the difference between the heat production of metabolic work (M) and external work (W). In other words, thermal neutrality is achieved when the heat dissipated equals the amount produced and not used for external work, e.g $L = 0$.

For analogy with the general heat balance equation 2.10, Fanger names H, the body's net heat production, which is actually the total heat production minus the external work of efficiency eta, namely $M.(1-\eta)$. The storage component is assumed to be zero at equilibrium. Hence, in conditions of long exposure in a moderate constant thermal environment [119], net heat production equals total heat dissipated by convection (C), radiation (R) and evaporatation (E) at equilibrium as in Eq.2.11. The original equations of Fanger [119] are presented in his book in obsolete metrics. They are reproduced in Auliciems and Sokolay, who describe the process of equation construction in [15]. The set of equations is entirely reproduced hereafter :

The initial equation expressing thermal balance is given by [15]:

$$H - E - C - R = 0 \tag{2.11}$$

Refining this equation and introducing the conduction of skin/clothing surface through the clothing (K) the double equation given by Fanger in his book [15], [119]:

$$H - E_{\text{diff}} - E_{\text{rsw}} - E_{\text{resp}} - L = K = R + C \tag{2.12}$$

where:

- H = the internal heat production of the human body $H = M(1-\eta)$ (kcal/h)
- E_{diff} = the heat loss by water vapour diffusion through the skin
- E_{rsw} = the heat loss by evaporation of sweat from the surface of the skin
- E_{resp} = the latent respiration loss
- L = dry respiration loss (kcal/h)
- K = heat transfer from skin to outer clothing surface (kcal/h)
- R = radiation loss from the outer surface of the clothed body (kcal/h)
- C = convection loss from the outer surface of the clothed body (kcal/h)

The heat loss by skin diffusion through the skin is not a thermoregulatory process but is the insensible perspiration. Proportional to the difference between vapor pressure of the ambience and the skin, it is calculated as follows(in Kcal/hr) and reproduced from [15]:

$$E_{\text{diff}} = \lambda.m.A_d.(p_s - p_a) \tag{2.13}$$

where:

- λ is the latent heat of evaporation of water (575 kcal/kg at 35°C)
- m is the skin permeance ($6.1e^{-4}\ kg/h\ m^2\ mmHg$)
- A_d is the body surface area with Dubois method, described in [94], [142]
- p_s is the saturation vapor pressure at skin temperature (mmHg)
- p_a is the vapor pressure of ambient air (mmHg)

Substituting numerical values and skin temperature relation and knowing from steam tables that p_s can be approximated by $1.92t_s - 25.3$ and knowing that the comfortable temperature is defined by $t_s = 35.7 - \frac{0.032 \cdot H}{A_d}$, diffusion can be expressed as follows [15]:

$$\begin{aligned} E_{\text{diff}} &= 0.35.A_d.[1.92.t_s - 25.3 - p_a] \\ E_{\text{diff}} &= 0.35.A_d.\left[43 - 0.061\left(\frac{M}{A_d}\right)(1-\eta) - p_a\right] \end{aligned} \tag{2.14}$$

Then, evaporative sweating loss is given by equation 2.15. Auliciem [15] mentions that for the comfort equation of the average situation, it should remain in very narrow limits. thus it only depends on the exchange surface and the internal heat production. Fanger [119] mentions that sweat secretion fully evaporates in moderate activities for people in a situation of thermal comfort. He also mentions that thermal comfort conditions occurs at a mean skin temperature between 33-34°C with no sweating. Equation 2.15 is derived from an experimental study on college-age persons for which Fanger lowered the comfortable room temperature when the activity got higher:

$$E_{\text{rsw}} = 0.42A_d[(H/A_d) - 50] \quad \text{, knowing that 50 kcal/h·m}^2 = 1 \text{ met} \tag{2.15}$$

The latent heat loss from respiration is:

$$E_{\text{resp}} = V(HR_{\text{ex}} - HR_{\text{in}}).\lambda \tag{2.16}$$

where :

- V = pulmonary ventilation rate, found as 0.006 M (kg/h)
- HR = humidity ratio of air as exhaled and inhaled
- λ = latent heat of evaporation of water (575 kcal/kg)

Dry respiration loss is calculated, after substituting humidity ratio and vapor pressures, as:

$$E_{resp} = 0.0023M(44 - p_a) \text{ in kcal/h} \tag{2.17}$$

Fanger simplified the dry heat loss by respiration by considering it to be low compared to other heat transfers. He proposes that expired air temperature can be approximated to 34°C [119], [143].

$$L = 0.0014M(34 - t_a) \text{ in kcal/h} \tag{2.18}$$

When all three E_x terms are subtracted from H, the remaining heat is transferred by conduction through the clothing (K), that is, by radiation and convection $(R + C)$ from the outer surface of clothing [15].

$$K = \frac{A_d \cdot (t_s - t_{cl})}{0.18 \cdot I_{cl}} \tag{2.19}$$

Where:

- I_{cl} = insulation of clothing in clo units
- t_s = skin temperature
- t_{cl} = clothing surface temperature

It is then possible to substitute with t_s expression $(t_s = 35.7 - \frac{0.032 \cdot H}{A_d})$:

$$K = \frac{A_d \cdot \left[(35.7 - \frac{0.032 \cdot H}{AD}) - t_{cl}\right]}{0.18 \cdot I_{cl}} \tag{2.20}$$

The radiation component is given by:

$$R = A_{\text{eff}} \cdot \varepsilon \cdot \sigma \left[(t_{cl} + 273)^4 - (t_r + 273)^4\right] \tag{2.21}$$

Where:

- $A_{\text{eff}} = f_{\text{eff}} \times f_{\text{cl}} \times A_{\text{Du}}$ because all clothed surfaces do not exchange the same way, total A_d. Where f_{cl} is the ratio of clothed to exposed body surface found in clothing ensemble tables.
- ε = emittance of outer surface of clothing
- σ = the Stefan-Boltzmann constant $(4.96.10^{-8}$ in $kcal/m^2hrK^4$
- t_{cl} = temperature of outer surface of clothing
- t_r = mean radiant temperature

After substituting the appropriate numerical values, we get:

$$R = 3.4 \times 10^{-8} \cdot A_d \cdot f_{cl} \left[(t_{cl} + 273)^4 - (t_r + 273)^4 \right] \tag{2.22}$$

The convection component is given by:

$$C = A_d \cdot f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \tag{2.23}$$

Where:

- h_c = convection conductance (kcal/m^{2}h°C)

The magnitude of h_c (in kcal/m^{2}h·K) depends on air velocity v in $m.s^{-1}$:

The criterion (crit) is $2.05(t_{cl} - t_a)^{0.25}$ (or in $W/m^2.K$: $1.762(t_{cl} - t_a)^{0.25}$) is given by:

If crit $> 10.4 \cdot v^{0.5}$, then : h_c = crit
If crit $< 10.4 \cdot v^{0.5}$, then : $h_c = 10.4 \cdot v^{0.5}$ or in W/m^2 : $8.9 \cdot v^{0.5}$

The final double equation (2.12) gives the basis of the PMV index. Substituting the above expressions of skin temperature 2.14 and heat loss by sweating 2.15. into the "double equation" (2.12), as well as , writing $M(1-\eta)$ for H, and dividing each term by A_d, the full comfort equation, as named by Fanger in [119] becomes:

$$\begin{gathered} \tfrac{M}{A_d}(1-\eta) - 0.35\left[43 - 0.061\tfrac{M}{A_d}(1-\eta) - p_a\right] \\ -0.42\left[\tfrac{M}{A_d}(1-\eta) - 50\right] - 0.0023\tfrac{M}{A_d}(44 - p_a) \\ -0.0014\tfrac{M}{A_d}(34 - t_a) \\ = \\ \frac{35.7 - 0.032\frac{M}{A_d}(1-\eta) - t_{cl}}{0.18 \cdot I_{cl}} \\ = \\ 3.4 \times 10^{-8} \cdot f_{cl}\left[(t_{cl}+273)^4 - (t_r+273)^4\right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{gathered} \tag{2.24}$$

It is mandatory to solve the left part of the double equation 2.24 to obtain the expression of the unknown t_{cl}. An iteration is necessary to solve T_{cl}, the clothing surface temperature, expressed :

$$\begin{gathered} \mathrm{t_{cl}} = 35.7 - 0.032\frac{\mathrm{M}}{\mathrm{A_{Du}}}(1-\eta) - 0.18\mathrm{I_{cl}}\left[\frac{\mathrm{M}}{\mathrm{A_{Du}}}(1-\eta) - \right. \\ 0.35\left[43 - 0.061 \cdot \frac{\mathrm{M}}{\mathrm{A_{Du}}}(1-\eta) - \mathrm{p_a}\right] - 0.42\left[\frac{\mathrm{M}}{\mathrm{A_{Du}}}(1-\eta) - 50\right] - \\ \left. 0.0023\frac{\mathrm{M}}{\mathrm{A_{Du}}}(44 - \mathrm{p_a}) - 0.0014 \cdot \frac{\mathrm{M}}{\mathrm{A_{Du}}}(34 - \mathrm{t_a})\right] \end{gathered} \tag{2.25}$$

To calculate the PMV, it is necessary to evaluate the thermal load (TL) defined by Fanger as

$$\mathrm{TL} = \mathrm{H} - E_{\mathrm{diff}} - E_{\mathrm{rsw}} - E_{\mathrm{resp}} - \mathrm{L} - \mathrm{R} - \mathrm{C} \tag{2.26}$$

Solving this equation allows for calculating an index representative of the positive or negative thermal load experienced by the subject. Fanger then proposed the calculation of the Predicted Mean Vote (PMV) index, which was once again determined empirically on a new sample by Nevins for sedentary people and McNall for people in activity [143].

This thermal load has been correlated in lab experiment, leading to the mean sensation vote PMV, it is given by [15]:

$$\mathrm{PMV} = \left(0.352 \exp\left(-0.042 \frac{M}{A_D}\right) + 0.032\right) \times \mathrm{TL} \tag{2.27}$$

Which in W/m^2 gives :

$$\mathrm{PMV} = \left(0.303 \exp\left(-0.036 \frac{M}{A_D}\right) + 0.028\right) \times \mathrm{TL} \tag{2.28}$$

Now replacing with the expressions of thermal load, expression in W/m^2:

$$\mathrm{PMV} = \left(0.303 \exp\left(-0.036 \frac{M}{A_D}\right) + 0.028\right) \times (H - \ \mathrm{Ediff} \ - E_{\mathrm{rsw}} \ - E_{\mathrm{resp}} \ - \mathrm{L} - \mathrm{R} - \mathrm{C}) \tag{2.29}$$

$$\begin{aligned} \mathrm{PMV} \ = & \left[0.303 \exp\left(-0.036 \frac{M}{A_D}\right) + 0.028\right] \cdot \\ & \left\{ \begin{array}{c} \frac{\mathrm{M}}{\mathrm{A_D}}(1-\eta) - 0.35\left[43 - 0.061\frac{\mathrm{M}}{\mathrm{A_D}}(1-\eta) - \mathrm{p_a}\right] - 0.42\left[\frac{\mathrm{M}}{\mathrm{A_D}}(1-\eta) - 50\right] - 0.0023\frac{\mathrm{M}}{\mathrm{A_D}}(44 - \mathrm{p_a}) - \\ -0.0014\frac{\mathrm{M}}{\mathrm{A_D}}(34 - \mathrm{t_a}) - 3.4.10^{-8}.\mathrm{f_{cl}}\left[(\mathrm{t_{cl}} + 273)^4 - (\mathrm{t_r} + 273)^4\right] + \mathrm{f_{cl}}\,\mathrm{h_c}\,(\mathrm{t_{cl}} - \mathrm{t_a}) \end{array} \right\} \end{aligned} \tag{2.30}$$

The PMV is represented on ASHRAE's 7-point scale [-3, -2, -1, 0, 1, 2, 3] centred on thermal neutrality, where negative and positive values, respectively, give an increasing cold and increasing hot thermal sensation. Aware that the theoretical mean thermal sensation could not represent the variability of a given population, Fanger proposed another index to establish the statistical distribution of satisfaction based on the predicted thermal sensation vote. It highlights, as shown in figure 2.9, that 5% of the population will remain Dissatisfied even with a $PMV = 0$. It translates in another indice named Predicted Percentage Dissatisfied (PPD), given by the following relationship:

$$PPD = 100 - 95 \exp\left[-\left(0,03353 \cdot PMV^4 + 0,2179 \cdot PMV^2\right)\right] \tag{2.31}$$

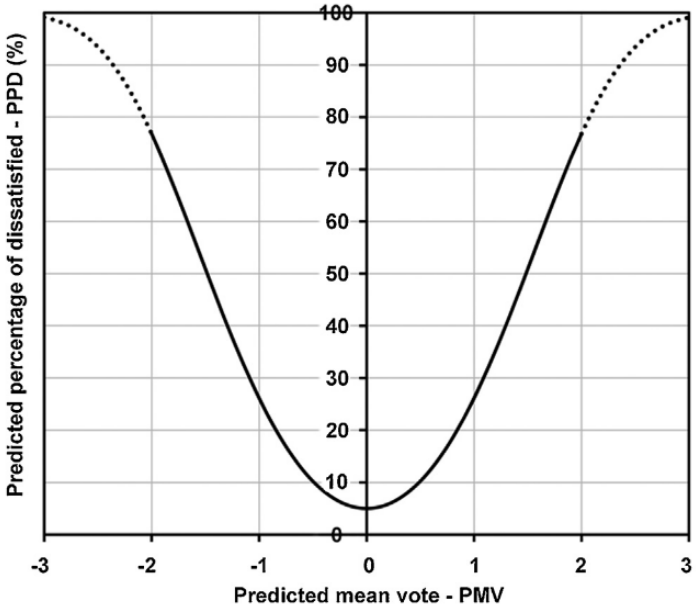

Figure 2.9: *PPD function of the PMV reproduced from* [144]

ISO 7730 and exEN15251 propose three categories of thermal environments for buildings: A, B, and C. The latest update of EN16798:2019 (exEN15251) adds a fourth category (IV) and renames the three previous ones. Their American (ASHRAE 55), English (CIBSE guide A), or Chinese (GB/T 50785) equivalents have different recommendations and only one or two categories (IV = the least demanding, II = the most demanding). Each of these is expressed in PMV and PPD as in the following Table 2.3:

	PMV	PPD	Standards
A (I)	[-0.2:+0.2]	<6%	exEN 15251, EN 16798, ISO 7730
B (II)	[-0.5:+0.5]	<10%	exEN 15251, EN 16798, ISO 7730, CIBSE, GB/T 50785
C (III)	[-0.7:+0.7]	<15%	exEN 15251, EN 16798, ISO 7730
(IV)	[-1.0:+1.0]		EN 16798, GB/T 50785

Table 2.3: *PMV-PDD categories in different standards*

The Predicted Percent Dissatisfied Due to Draft (PD or PPDpd) was developed by Fanger to predict the number of dissatisfied cases due to unwanted cool air movement across the neck (mainly due to cool air blowing through air conditioning nozzles located above the occupants). The Ankle Draft (AD or PPDad) is the equivalent of the Predicted Percent Dissatisfied model of Fanger's cool air draft risk model, but for air movement at the ankles. It thus fills the gap for cooling systems with floor distribution or recirculating and homogenizing ventilation. This method only applies to air velocities below 0.2 m/s at 0.1 m above the floor [145], [146], hence far from Natural Ventilation (NV) and Ceiling Fan (CF) operations. One could also mention other indices, aiming to characterise local discomfort, namely those related to radiant surface symmetry and air movement nuisance in conditioned spaces, as well as the vertical temperature gradient of a room [147]. This latter was developed in the context of

building heating, which justifies its exclusion from further investigation in this thesis.

Overall, the PMV is one of, if not the most, employed Thermal Heat-balance Models worldwide for assessing thermal comfort and sizing conditioning systems. It has proven efficient and accurate in its neutral range but remains inconsistent when conditions fall outside of it, especially while trying to predict warm sensations [98], [107], [117], [148], [149]. According to Gagge etal. [121], PMV index was derived for conditions in the +/-3 range at normal ambient vapour pressure between 1-2 kPa, approximating 40-60% relative humidity. Attention to the evapotranspiration equation highlights the simplification made by the authors regarding sweating capacity to dissipate heat in warm conditions. Indeed, equation 2.15 is a function of the body surface and internal heat production H of the body; hence, at fixed metabolic rate, sweating rate remains constant.

As described in by ISO 7730 [95], Fanger's model is applicable for indoor conditions comprised in $10 < t_{db}$,$[^{\circ}\mathrm{C}] < 30$, $10 < t_r$,$[^{\circ}\mathrm{C}] < 40$,$0 < v_r$,$[\mathrm{m/s}] < 1$, individual parameters comprised in $0.8 < met$,$[\mathrm{met}] < 4$, $0 < clo$,$[\mathrm{clo}] < 2$. Furthermore, the standard limit its applicability to $-2 < PMV < 2$.

Gagge's 2-node model and associated indices

In parallel with Fanger's work, Gagge and Stolwijk, both members of ASHRAE, provide a more detailed approach by proposing a two-node model of exchange between the human body and its environment. The Gagge model is also known as the Two-Pierce two-node model, named after the foundation employing the two scientists at Yale University. It is based on the heat balance equations previously developed by Stolwijk, Hardy, Gagge and Nishi [88]. Heat and mass exchange is modelled between the body and the skin layer, the clothed skin layer and its environment. It is conceptualized in two concentric cylinders representing the two nodes for calculation. The central cylinder represents the first thermal compartment composed of muscles, skeleton and subcutaneous tissues; the second outer cylinder is composed of the skin in contact with the environment as shown in the original figure of Gagge (Fig. 2.10, [120]). As mentioned by [136], the fact that there are only two radial nodes in the Gagge model implies that the skin represents the combined conductive and convective heat transfer influenced by metabolic rate (muscle insulation changes with activity). In contrast to very detailled multi-node models, the heat flows do not pass from one compartment to another, because compartments are lumped systems.

The heat transfer from the body core to the skin, and then from the skin to the environment, is described in [107], [120], [142] and entirely reproduced from [15].

The body's metabolic rate M (in watts) represents the internal energy production. Part of this energy is converted into mechanical work. The mechanical efficiency is given by:

$$\eta = \frac{\text{work}}{M} \tag{2.32}$$

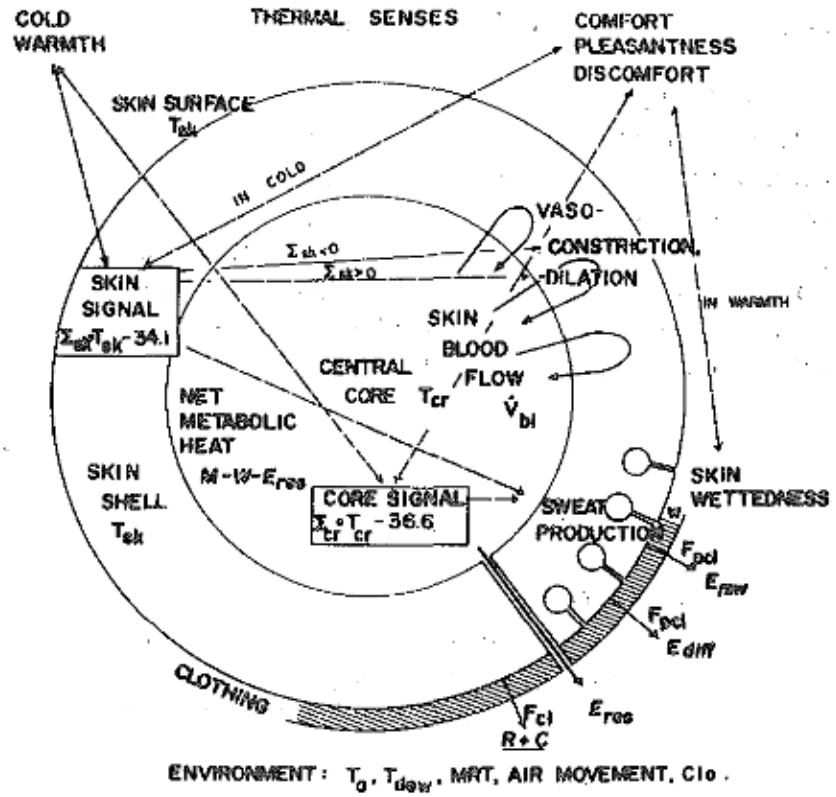

Figure 2.10: *Gagge's two-node model representation* [120]

The dissipated energy is the remaining part :

$$M(1-\eta) \tag{2.33}$$

which can be expressed by unit of body surface area based on Dubois area A_D :

$$\frac{M(1-\eta)}{A_D}, \quad \text{in} \quad W/m^2 \tag{2.34}$$

Heat is lost by evaporation three ways:

- E_{diff} due to vapor diffusion through the skin
- E_{rsw} due to evaporation of regulatory sweating from the skin
- E_{resp} due to respiration latent heat loss

These components can be estimated as follows:

$$E_{\text{resp}} = 0.0173M(5.87 - p_a) \tag{2.35}$$

with:

- $5.87kPa$: saturation vapor pressure at lung temperature (35°C)
- p_a = vapor pressure of ambient air

The sensible heat loss is given by:

$$C_{\text{resp}} = 0.0014M(34 - t_a) \tag{2.36}$$

where :

- $34\,^{\circ}\text{C}$ is the exhaled air temperature
- t_a = ambient air temperature , or dry buld temperature t_{db}

Since these two quantities do not reach the skin surface, the remaining heat M_{sk} is transferred to the skin for dissipation by convection and radiation :

$$M_{\text{sk}} = M(1 - \eta) - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a) \tag{2.37}$$

In the following equations, several heat transfer coefficients (conductances) are used (all in W/m^2K, except h_e in W/m^2kPa):

- h_r = radiation conductance (from surface to Mean Radiant temperature t_r)
- h_c = convection conductance (from surface to air)
- $h = h_r + h_c$
- h_{cl} = clothing conductance
- h_e = evaporation heat loss coefficient

The maximum possible evaporative heat loss from the body surface is:

$$E_{\text{max}} = 16.7h_c(p_{\text{sk}} - p_a)F_{pcl} \tag{2.38}$$

where:

- p_{sk} is the saturation vapor pressure at mean skin temperature
- p_a is the vapor pressure of ambient air (kPa)
- 16.7 is the *Lewis relation* in $K.kPa^{-1}$, representing the ratio of evaporative and convective heat transfer coefficients at sea level
- F_{pcl} is the vapor permeation efficiency from skin through clothing (non-dimensional)

Then, the evaporative sweating is expressed as a proportion (skin wettedness) of the maximum possible evaporative sweating (defined from convection coefficient/air velocity):

$$E_{\text{rsw}} = w_{\text{rsw}}E_{\text{max}} \tag{2.39}$$

Hence, skin wettedness $w_{\text{rsw}} = \frac{A_{\text{sw}}}{A_D}$ is introduced as the fraction of body surface covered by a film of sweat (A_{sw}) relative to the *DuBois* body area.

The ratio $\frac{E_{\text{sk}}}{E_{\text{max}}}$ is w, the average wettedness of the skin. When E_{sk} is taken as the evaporation heat loss necessary to maintain thermal equilibrium of the body, then the ratio $\frac{E_{\text{sk}}}{E_{\text{max}}} \times 100$ has been used as an index of heat stress.

From the area covered by clothing the sweat will evaporate by diffusion:

$$E_{\text{diff}} = (1 - w_{\text{rsw}})\,0.06E_{\text{max}} \tag{2.40}$$

But in the absence of regulatory sweating, if $E_{rsw} = 0$ (Generally, for resting subjects, if $40\% < RH < 60\%$ and $T_{db} < 20$řC, $E_{resp} + E_{diff}$ is about 20-25% of the metabolic rate M).

$$E_{\text{diff}} = 0.06\, E_{\max} \tag{2.41}$$

The total skin evaporation, adding the above two terms, is:

$$E_{\text{sk}} = E_{\text{diff}} + E_{\text{rsw}} = (0.06 + 0.94\, w_{\text{rsw}})\, E_{\max} \tag{2.42}$$

or substituting the Emax expression 2.38:

$$E_{sk} = 16.7\,(0.06 + 0.94 w_{rsw})\, h_c (p_{sk} - p_a) F_{pcl} \tag{2.43}$$

The sensible heat loss from the body surface is given by:

$$R + C = h(t_{\text{sk}} - t_a) F_{cl} \tag{2.44}$$

where: - F_{cl} is the insulation value of clothing $= \frac{1}{1+0.155 h I_{cl}}$, where I_{cl} is in clo units.

Substituting equations (2.37), (2.39), and (2.44) into the thermal balance equation, and neglecting conduction transfers gives:

$$\begin{aligned} S = M\,[(1-\eta) - 0.0173\,(5.87 - p_a) - 0.0014\,(34 - t_a)] \\ -16.7\,(0.06 + 0.94\, w_{\text{rsw}}).h_c (p_{\text{sk}} - p_a) F_{pcl} - h(t_{\text{sk}} - t_a) F_{cl} \end{aligned} \tag{2.45}$$

Internal variables such as temperature and skin wettedness can be determined dynamically (considering heat storage). Temperature is supposed to be uniform in each of the compartments. Gagge's model is generally used in a 60-minute procedure loop if willing to calculate the Standard Effective Temperature (SET) described in the following paragraph. It starts from neutral conditions in terms of core and skin temperature, and evaluates the influence of the environment and metabolism on energy balance. At each calculation step, generally one minute, the two-node model evaluates the need to implement thermoregulation by checking the deviation of the core temperature and its normal state. Core and skin temperatures, skin wettedness and metabolic heat production are then reassessed accordingly. The evolution of the model characteristics is mentioned in [150]. Vellei et al. [140] mention the most up-to-date versions in their article as well as several studies on the performance of the model, namely good accuracy for neutral as well as hot or very hot conditions, less good performance for very cold (<5°C). A drop in performance is also noted for activities with high internal heat production [3.5-7 MET], which is not a concern in this work. Nevertheless, in low activity conditions in a [1-1.2 MET] range, Takada et al. [151] showed that it effectively predicts the skin temperature for steady state conditions, confirming Doherty et al.[152] finding about low accuracy in high metabolic conditions. Parsons [107] mentions that due to its calculation procedure based on a time step of one minute, it is possible to conveniently determine the

physiological constants over the chosen duration, making the model more dynamic than the steady state equations of Fanger. Unlike Fanger's approach, Gagge's model is valid for transient conditions and in environments corresponding to the extreme right side of the thermal sensation scale (warm and hot) [140].

Gagge two-node model came alongside equivalent temperature indexes and sensation model. The earliest New Effective Temperature (ET*), to differentiate to Youglou's "ET", corresponded to the dry buld temperature of a uniform enclosure at 50% relative humidity, which produces the same heat exchanges as the actual environment. ET* lines are represented on a "tweaked" psychometric chart, with operative in abscise to account for radiation, $ET* = T_{db}$ at $50\%RH$. maximum summer comfort is ET*=26°C for $0.5clo$ and $0.2m.s^{-}1$, each 0.275 $m.s^{-}1$ increase correspond to and increase of $+1K$. The whole procedure to plot the ET* curves on the chart is developed in [15].

Nowadays, Standard Effective Temperature (SET) is a common index. It was developed at the beginning of the 1970s and last updated in 1986 [121], [153] to standardise the ET* for given clothing and activities. Its original definition by [121] is :" *Standard Effective Temeprature (SET*) is defined as the dry bulb temperature of a hypothetical isothermal environment at 50% RH in which a human subject, while wearing clothing , standardized for activity concerned, would have the same skin wettedness (w) and heat exchange at skin surface as he would have in the actual test environment.*" Above environmental compensation for the heat exchange, the SET now includes compensation of the type of activity (metabolism) and clothing. It is mentioned that an inverse change of clothing value can compensate for an increase in metabolism. In normal conditions, SET and ET* are equal, but the difference increases when ET* increases. SET is a first index to give an equivalence for any combination of environmental factors, clothing and activity [15]. The calculation process of SET from a standardized environment is given by [154] and represented in Figure 2.11. An equivalence table is given to match the ASHRAE sensation scale, it is available in [15], [107] and is reproduced in Table 2.4.

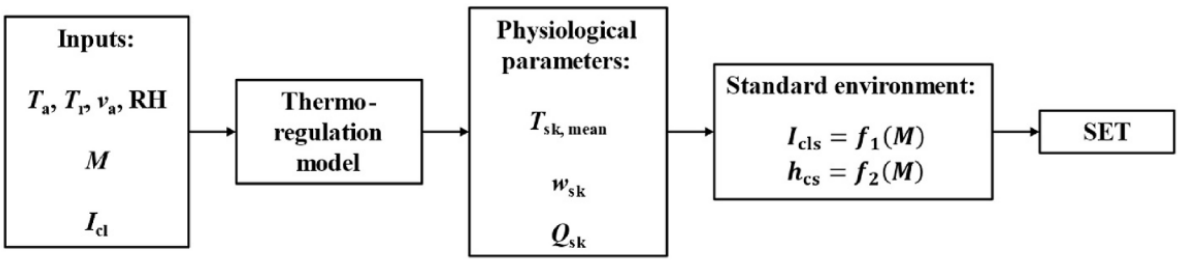

Figure 2.11: *SET calculation process reproduced from* [154]

Table 2.4: *Correspondence table of thermal sensation and physiological responses at different SET temperature ranges*

SET (°C)	Scale Value	Thermal Sensation and acceptability	Mean Body Temperature (°C)	Physiological State, Sedentary Person
> 37.5	> 3	Very hot, very uncomfortable	> 36.7	Failure of regulation
34.5–37.5	[2 : 3[	Hot, very unacceptable	36.8	Profuse sweating
30.0–34.5	[1 : 2[	Warm, uncomfortable, unacceptable	36.6	Sweating
25.6–30.0	[0.5 : 1[	Slightly warm, slightly unacceptable	36.5	Slight sweating, accepted vasodilation
22.2–25.6	[-0.5: –0.5[	Comfortable and acceptable	36.3	Neutrality
17.5–22.2	[-1: -0.5[	Slightly cool, slightly unacceptable	35.8	Vasoconstriction
14.5–17.5	[-2: -1[	Cool and unacceptable	35.0	Slow body cooling
10.0–14.5	[-3: -2[	Cold, very unacceptable	34.3	Shivering

Perspiration, sweat secretion, and the rise in body temperature are strongly associated with discomfort in warm and humid environments. The Discomfort Index DISC, introduced by Berglund and Gagge [155], is a regression model based on skin wettedness. It represents the thermoregulatory strain required to restore thermal balance through sweating. To match the ASHRAE 7-point thermal sensation scale, Gagge, in collaboration with Winslow, proposed a calibrated version of DISC [15], [155].

DISC applies only to warm conditions and is defined as:

$$\text{DISC} = 5 \times (w - 0.06) \tag{2.46}$$

where w is the skin wettedness.

An alternative formulation expresses DISC as a function of Standard Effective Temperature (SET) [15], [155]:

$$\text{DISC} = 0.00543 \times (SET - 17.5)^{2.12} \tag{2.47}$$

This regression enables DISC to be estimated directly from SET values under warm conditions.

In parallel, Gagge proposed a Thermal Sensation index (TSENS), sometimes written TS or t_{sens}. Its construction is similar to Fanger's PMV, but it extends the classical 7-point scale to a 10-point scale ranging from -4 (very cold) to $+4$ (very hot), and $+5$ (painfully hot).

The model is based on body temperature thresholds that depend on metabolic rate M:

$$
\begin{aligned}
t_{bm_l} &= \frac{0.194}{58.15} \cdot M + 36.301, \; with\, M \; in \; W.m^{-2} \\
t_{bm_h} &= \frac{0.347}{58.15} \cdot M + 36.669,
\end{aligned}
$$

$$
t_{\text{sens}} = \begin{cases} 0.4685\,(t_{\text{body}} - t_{bm_l}), & \text{if } t_{\text{body}} < t_{bm_l} \\ \dfrac{w_{\max} \cdot 4.7\,(t_{\text{body}} - t_{bm_l})}{t_{bm_h} - t_{bm_l}}, & \text{if } t_{bm_l} \leq t_{\text{body}} < t_{bm_h} \\ w_{\max} \cdot 4.7 + 0.4685\,(t_{\text{body}} - t_{bm_h}), & \text{if } t_{\text{body}} \geq t_{bm_h} \end{cases} \tag{2.48}
$$

These thresholds define three physiological regions:

- $t_{\text{body}} < t_{bm_l}$: no regulatory sweating and no warm sensation,
- $t_{bm_l} \leq t_{\text{body}} < t_{bm_h}$: regulatory sweating occurs,
- $t_{\text{body}} \geq t_{bm_h}$: high thermoregulatory stress.

The t_{sens} regression originates from work conducted at Kansas State University by Nelvins, McNall, and Rohles, and was later reproduced by Gonzalez, Nishi, and Gagge for comparison with DISC in warm conditions [153]. At that time, the model was referred to as a *Thermal Discomfort Vote* (*TDV*), which may slightly differ from the later standardized Thermal Sensation Vote (TSV) terminology. Figure 2.12 illustrates the comparison between the KSU TSENS regression and DISC (PDV line), as also reproduced in later publications by Gagge.

More recently, several studies [102], [156], [157] have referenced a Predicted Thermal Sensation (PTS) index derived from SET. PTS is attributed to the relationship between thermal sensation and SET presented in McIntyre's work [114], as discussed by Gao et al. [156].

The PTS model is defined as:

$$
\text{PTS}_{McIntyre} = 0.25 \times \text{SET} - 6.03 \tag{2.49}
$$

This formulation corresponds to an 8-point thermal sensation scale ranging from -3 (very cold) to $+4$ (very hot). However, the original dataset used to derive this regression is not clearly identified in the literature. Moreover, this PTS formulation was not explicitly included

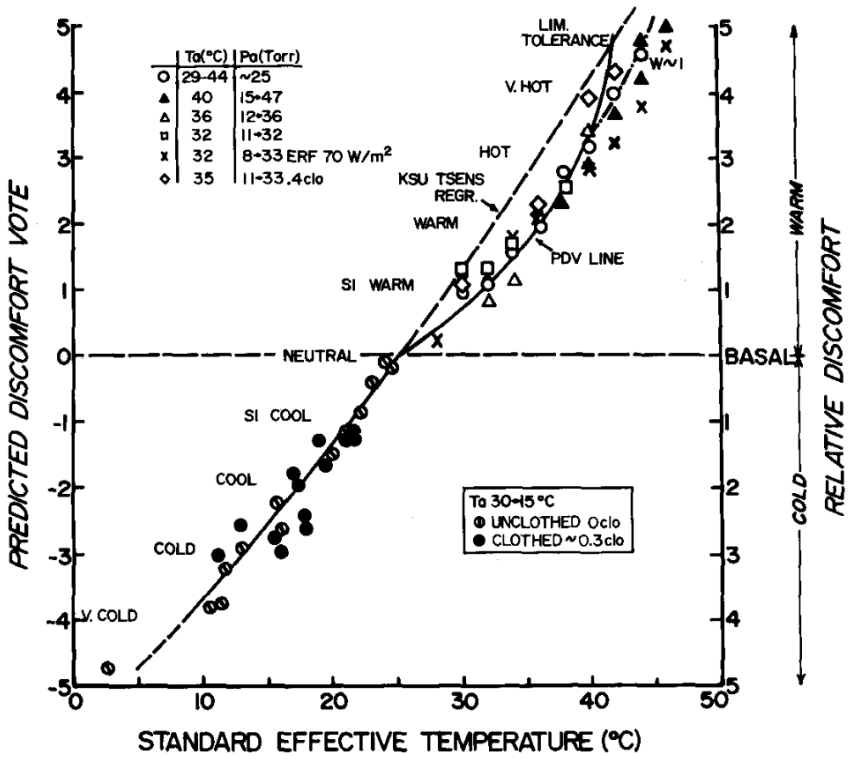

Figure 2.12: *Original discomfort vote model t_{sens} (KSU TSENS REGR) and DISC (PDV LINE) by Gagge* [142], [153]

in Gagge's later synthesis work [121].

The three indices differ in physiological basis and domain of applicability:

- **DISC**: based on skin wettedness (or SET regression), applicable to warm conditions only, and aligned with the ASHRAE 7-point scale.
- $t_{\mathbf{sens}}$ **(TSENS)**: based on body temperature thresholds and regulatory sweating, covering the full thermal range with an extended 10-point scale.
- **PTS**: a linear regression model based solely on SET, associated with an 8-point sensation scale.

DISC quantifies thermoregulatory strain due to sweating, t_{sens} reflects physiological thermal sensation linked to body temperature regulation, and PTS provides a simplified SET-based predictor of thermal sensation.

2.2.4 Adaptive regression-based Models (AM) of thermal comfort

Towards the end of the 1990s, research showed that the analytical approach was suitable in summer in air-conditioned and hermetically sealed spaces but reached its limits when the building was cooled by natural ventilation or in high humidity conditions, which is typical of a tropical climate [18], [158]. New concepts have emerged from the observation that the thermal sensations obtained from the Predicted Mean Vote, initially validated in laboratory

conditions where subjects are passive, were not representative of real votes in naturally ventilated buildings. In these buildings, occupants can adapt to restore their comfort and are, therefore, defined as active occupants. Early Studies [17], [18], [158] have shown that in a naturally ventilated building, in a climatic context with higher temperatures, individuals are predisposed to a greater capacity to adapt to their environment. This is known as adaptive comfort, and is not only based on the occupant's 'thermal' physiology, but on their ability to adapt based on close past climate history [17]. Behind this concept of adaptability, three main components are considered [159]:

- The **behavioural component** consists of the possibility of personal adaptation (changing clothing beyond the predefined normative value of 0.5 CLO in summer and >1.0 CLO in winter according to ISO7730), technical adaptation (turning on a fan, lowering the blinds, opening a window), or cultural adaptation (taking a nap, changing one's schedule). It also includes the notion of so-called active self-acclimatisation, where the subject voluntarily reduces their metabolism to compensate for prolonged exposure to heat.
- The **physiological component** consists of adaptation of the human body's thermoregulatory responses (shivering, sweating, changes in blood flow). It is considered non-linear and broken down into two categories: multigenerational (genetic) or monogenerational (physiological) adaptation. There is also the concept of passive acclimatisation, which considers the body's ability to lower its metabolism in extreme heat conditions, particularly in the case of prolonged heat exposure.
- The **psychological component**, for its part, involves considering the subject's need or level of expectation. This component can be influenced by a socio-cultural context ("right to cold, for example") and also be based on the fact that the body and the brain have a multi-scale temporal thermal memory (preference for different thermal sensations in summer and winter, for example, or increased demands in air-conditioned buildings).

The 2004 revision of the ASHRAE standard addresses these concepts by proposing an adaptation of the comfortable temperature range that is dependent on the average monthly outdoor temperature. Recent developments in standards propose this Adaptive Model (AM) method for buildings that are not heated or mechanically cooled. Since the mid-2000s, local variants have also been found in European (EN16798), Chinese (GB/T 2000), British (CIBSE) and Dutch (ISSO74) standards, as illustrated by the chronology in Figure 2.13. Also, two models for naturally ventilated buildings were integrated into the National Building Code (IMAC) for India's specific regional climatic conditions [159]. However, research on adaptive regression models AM was initiated much earlier. Humphreys in 1978 demonstrated the linear relationship between the preferred temperature in naturally ventilated buildings and the outside temperature through a meta-analysis of 30 satisfaction surveys of right-here-right-now comfort votes [107]. Webb and Nicol also contributed to this novel approach of adaptability in hot climates [102]. However, it was not until 1998 that De Dear and Brager presented their work, which involved conducting international-scale satisfaction surveys on thermal

comfort on behalf of ASHRAE and proposing a generalizable linear regression model of comfort temperature as a function of outside temperature. The RP-884 database (ASHRAE Global Comfort Database I) compiled from these surveys allowed the authors to highlight the behavioural and psychological adaptation of voters and to establish the first equation (Eq. 2.50of the adaptive model) [115], [122], [160].

$$T_{comf} = 0.31\ T_{out} + 17.8°C \tag{2.50}$$

With T_{out} the predominant average outside temperature that could originally have several forms (average temperature, sliding temperature, Effective temperature, etc.).[56]

Nicol and Humphreys gave its European equivalent a few years later, in 2007, for the European standard EN 15251. It is based on the SCAT project (Smart Control and Thermal Comfort Project), which brought together 26 buildings from European countries in France, Sweden, Greece, Portugal, and Great Britain. The European database is much smaller than the American RP884 database [123].

$$T_{comf} = 0.33\ T_{rm} + 18.8°C \tag{2.51}$$

With T_{rm}, the running mean temperature over a month.

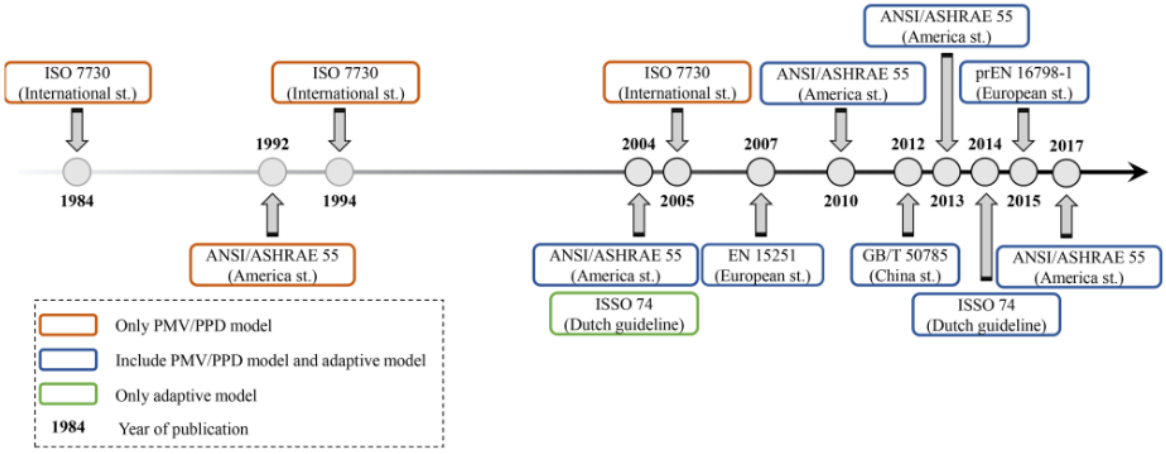

Figure 2.13: *Timeline for integrating the adaptive model alongside PMV/PPD in regulatory documents*

Although similar in formulation, the two regression models differ on several applicative topics. The ASHRAE model is based on international data prior to 1998 and has not been updated in the standard to date [78]. In contrast, EN 15251 regression utilises more recent data, but it is only collected in European buildings. It is therefore more directly applicable on this continent. In addition, (exEN 15251) EN 16798 allows for the inclusion of buildings with a low-consumption cooling system, such as mechanical ventilation or an earth-to-air heat exchanger, which is not possible in ASHRAE. The ASHRAE regression is only applicable for naturally ventilated buildings. The way of considering and calculating the outdoor

temperature T_o or T_{rm} also differs and was the subject of lengthy debates before the first publication in 2004 in the ASHRAE 55 standard, as mentioned by Carlucci et al. [56]. Today, to consider physiological adaptation (ie, subject climate history) on the scale of the previous day or week, current standards have adopted Humphrey's work to incorporate a decreasing weighted average of the previous days via the "running mean temperature," also known as the "prevailing mean outdoor air temperature". It is essential to note that adaptive comfort models do not directly consider relative humidity, although it is a significant factor in a humid tropical context. The original model [115] by De Dear and Brager used the New Effective Temperature ET* to account for the effects of humidity, a solution not retained by the ASHRAE Committee for more streamlined calculations. The concept of an adaptive model is now firmly established in standards and has undergone several amendments, including ASHRAE 55:2020, which extended the range of outdoor temperatures from [15°C: 33.5°C] to [10°C: 33.5°C], and the earlier EN 16798-1 (ex-EN 15251), which extended the range of its regression model for the cool part to align with ASHRAE, thus allowing the [10°C: 30°C] range.

The assessment is based on an acceptability index according to two categories for ASHRAE 55 (bands of 5° or 7°C around comfort temperature and three categories for EN 16798 (5, 7, 9°C around Tcomf), whose limits are given in table 2.5. The adoption of the adaptive model is also effective in the British (CIBSE), Chinese (GB/T 50785), Indian (IMAC), and Dutch (ISSO 74) standards, whose requirements differ from the American and European versions. Figure 2.14 reproduces the AM regressions and limits for the leading standard that are described in [102]. It is worth noting that the EN 16798 AM model and its American counterpart 55:2023 limit its use exclusively in cases where a building has no mechanical heating or cooling system. Otherwise, the ISO7730 PMV-PPD indices should be used. Correcting the indoor comfort upper acceptability limit is possible when the building is equipped with a fan with individual control for the occupant only. It is built on air speed stepped predefined "cooling effect" allows the upper limits 80% and 90% acceptability of ASHRAE AM to be raised by fixed values of 1.2°C ($v > 0.6$ m/s), 1.8°C ($v > 0.9$ m/s) and 1.2°C ($v > 2.2$ m/s). (Table 5-12 of 55:2023 standard [104]. According to EN 16798 [42], increased air velocity is considered during summer conditions when the indoor temperature reaches 25°C and occupants have complete control. Fixed temperature correction values are consistent with the American counterpart. The ASHRAE 55:2023 mentions the predefined cooling effect is based on SET calculation, while the foundation of EN 16798 AM is based on the original work of Arens [61] and Nicol [124] and Humphreys [18] on the evaluation of cooling related to air movement as a function of the operating temperature (T_{op}). It is expressed by equation 2.52. Also, it is worth mentioning that neither standard recommends an air speed over 0.8 $m.s^{-1}$ to avoid moving papers from desks.

$$\mathrm{T} = \mathrm{T_{op}} - 7 + \frac{50}{4 + 10\ \mathrm{v}^{0.5}} \tag{2.52}$$

From figure 2.14, the EN 16798 Adaptive model offers the highest hot upper limit. ASHRAE 55's AM upper limit is two degrees lower, but can be applied to outdoor conditions up to T_{rm} of

33.5°C, when the European standard limits it to 30°C. GB-T AM follows a different construction with a greater regression slope.

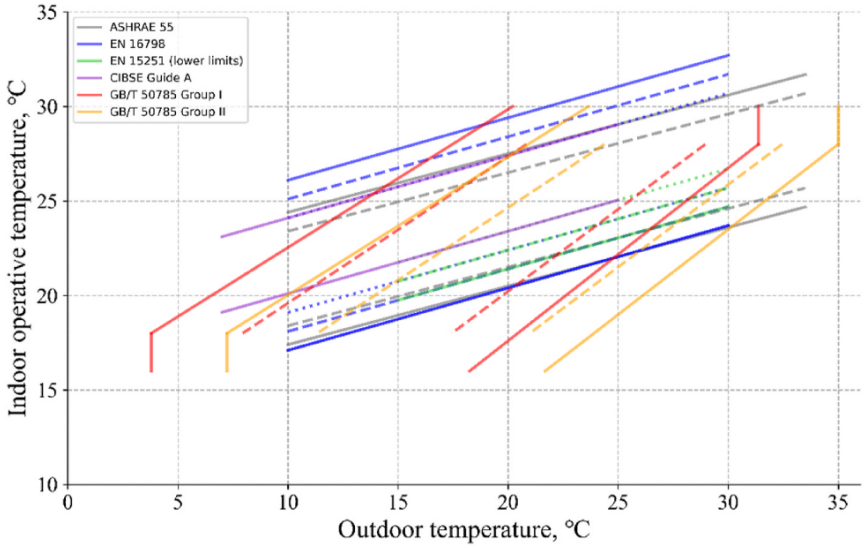

Figure 2.14: *Supersposition of different AM regression for non mechanically heated or cooled buildings, reproduced from* [102]

Table 2.5: *EN 16798 Thermal Comfort Guidelines*

Condition	Regression
Category III - upper limit	$0.33\ T_{rm} + 18.8°C + 4°C$
Category II - upper limit	$0.33\ T_{rm} + 18.8°C + 3°C$
Category I - upper limit	$0.33\ T_{rm} + 18.8°C + 2°C$
Optimum comfort temperature	$0.33\ T_{rm} + 18.8°C$
Category I - lower limit	$0.33\ T_{rm} + 18.8°C - 3°C$
Category II - lower limit	$0.33\ T_{rm} + 18.8°C - 4°C$
Category III - lower limit	$0.33\ T_{rm} + 18.8°C - 5°C$

Finally, under the aegis of the Berkley Lab (Centre for Built Environment) and the University of Sydney (Indoor Environmental Quality Laboratory), the project to consolidate a database over several decades was launched and recently published in its version 2.1 (June 2022). This launch marks a significant milestone in the ongoing development of new adaptive approaches for buildings. The ASHRAE Global Comfort Database II (AGCDBII), beyond bringing together previous comfort survey studies with the most recent ones, notably RP-884, offers an invaluable source of open-source data ($>$ 100,000 votes), fully standardised. It comes along with an online visualisation tool to explore the data [161]. The details of the database are available in a collegial publication by Földvàry Licina et al.[109]

2.3 Latest developments in the modelling of thermal comfort

2.3.1 Overview

The engineering and architecture-built environment disciplines have both contributed differently to the comfort modelling theory in building. The first one is based on a deterministic approach of the simple balance of heat production and heat transfer in the human body, which is analogous to the load calculation in a thermal zone HVAC [115]. This theory is derived from the assumption that thermal sensation is directly related to human body thermal load [102]. The second, the adaptive model, suggests that people's sense of thermal comfort depends on their context and expectations rather than on physical and measurable variables and that adaptation is the key [115]. As mentioned by de Dear et al. [102], [115] *the adaptive and heat balance approaches to modelling thermal comfort are complementary rather than contradictory. At some level, the static heat balance model can be considered as being partially adaptive in the behavioural sense since it accounts for clothing, activity level and indoor climatic parameters which can be adjusted by the occupants* [*8*]. Thermal Heat-balance models and indices such as those of Fanger (PMV-PPD), Gagge (Standard Temperature Effective SET), as well as the Adaptive Models of de Dear and Nicol, have been the subject of numerous reliability studies since their integration in standards listed in [157].

The last two decades of research have been productive in model modification, adaptation, and combination to propose alternatives to the duality PMV-Adaptive Model.

2.3.2 Regional approach of the Givoni (BBCC) zones

Among the recent studies based on Givoni's work from the 1970s, two in particular focus on comfort zones in a hot and humid climate. The work of Lenoir et al. [63] focuses on a case study in the French overseas department of La Réunion. The satisfaction survey is already illustrated in chapter 1. It mainly focuses on a population of students in the first positive-energy bioclimatic building (NZEB) in the tropical zone, illustrated by 1.6 and designed to operate with natural ventilation all year round in Saint Pierre de la Réunion. The author proposes a new comfort zone based on occupant votes. The maximum temperature of 32°C proposed by Givoni for naturally ventilated buildings in hot "developing" countries is revised downwards (30°C). However, it is shown that the upper limit of specific humidity can be extended to 21 $g.kg^{-1}$ of dry air. These results are understood for an average air speed of 1 m/s and in the context of a metabolic activity close to 1 met for young subjects (students) lightly dressed (< 0.6 clo). Kumar et al.'s [134]research focuses on a study in India involving 32 naturally ventilated sites (2,610 satisfaction voting samples), providing a baseline for evaluating ASHRAE 55:2013 (Givoni-based) natural ventilation comfort zones. The study shows that occupants are generally comfortable at temperatures well above the ASHRAE and Givoni guidelines for naturally ventilated buildings. The authors propose comfort zones with still winds up to 32°C and with high air velocities up to almost 35°C. However, the analysis also shows that although comfortable in summer, the preference for more than 30% of voters

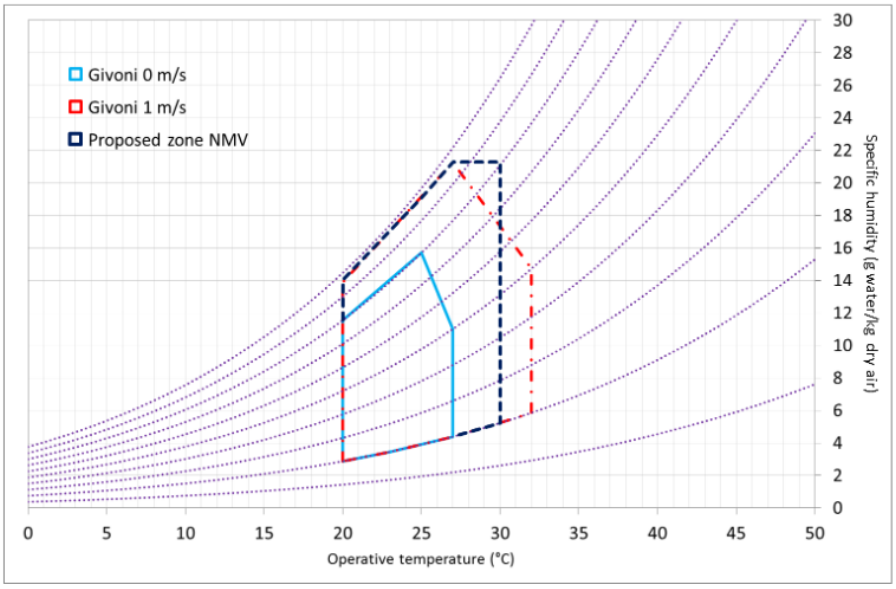

Figure 2.15: *Lenoir Mechanical Natural Ventilation (MNV) over the original still air and NV zones on the Building Bioclimatic Comfort Chart*

is for a cooler environment. Furthermore, unlike Lenoir, or even Givoni and ASHRAE, who push the upper limit of specific humidity to 21 g of water/kg of dry air (Lenoir) and 95% relative humidity (Givoni / ASHRAE), Kumar argues that the upper limit cannot exceed 80%. They are given for a standard office activity (1-1.2 m) and a maximum clothing of 1.2 clo.

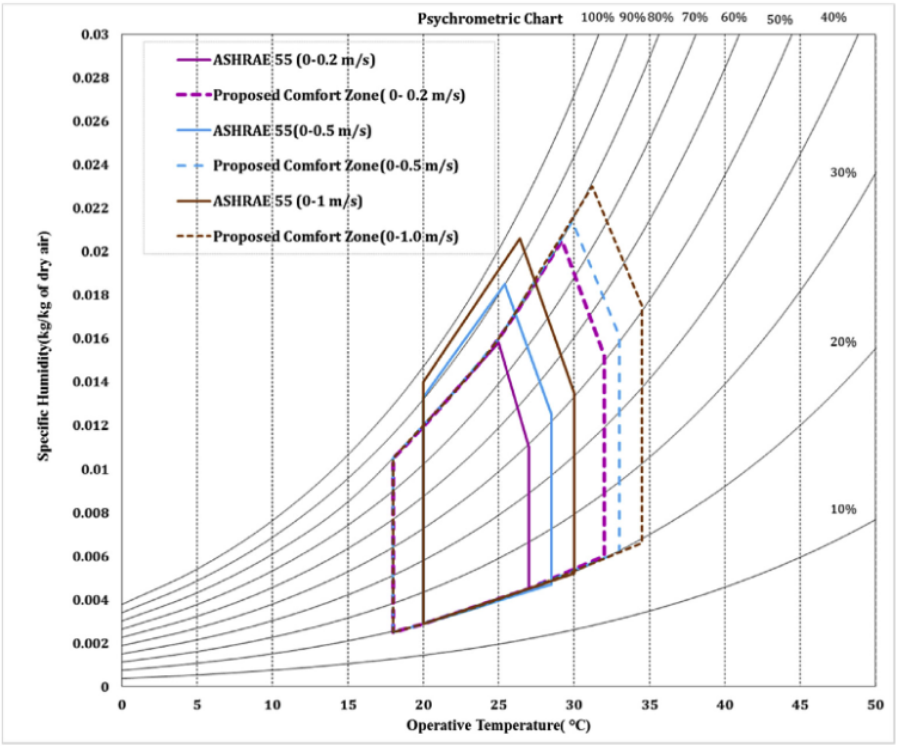

Figure 2.16: *Kumar et al. adaptive Naturally Ventilated zones for indian population* [134]

Recently, Herb et al. [162] investigated the original Givoni Bioclimatic chart and more refined method of building energy simulation for the purpose of early-stage design of energy-efficient buildings. Their study reveals significant discrepancies concerning overheating hours related to numerous passive design options and climate typology. Further, for 10% of the three hundred cases, it highlights that the original BBCC is unable to identify the AC needs when simulation does. Hence, they conclude by advocating BEM for the early-stage design process, even if it is more time-consuming and propose an alternative automated BEM tool, which is still under development. Also noteworthy is a recent contribution by Teitelbaum et al.[163], [164] who propose a graphical tool, allowing to represent the resolution of either the radiant temperature or the air speed to define dynamic comfort zones on the humid air diagram as illustrated by Figure 2.17. It provides a more complete approach than the classic ASHRAE zones defined as target zones for the sizing of air conditioning systems. The consideration of individual variables (MET, CLO) is also possible in the extended psychrometric chart.

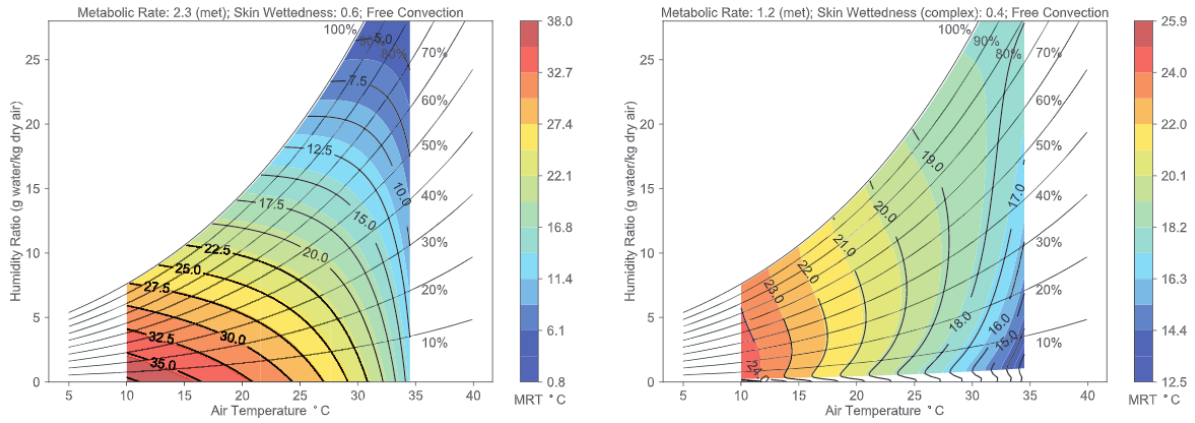

Figure 2.17: *Teteilbaum et al. design tool for radiant cooling base on BBCC* [163], [164]

2.3.3 Modified Heat-balance equations or sensation model

This approach aims to improve the prediction of analytical models by modifying the core equations of the comfort model or providing an alternative sensation model.

Gagge's PMV_{gagge} and PMV^*/PMV_{set} (1986):

Gagge pioneered this approach, modifying the equations to calculate the PMV as early as 1986, at the same time, the SET procedure was finalised and published. He proposed replacing the heat loss and gain in the PMV equation with those of the two nodes in PMV_{gagge}[128], [149].The resulting PMV is named PMV_{gagge} or PMV^* [121] and is specifically designed for humid environments and the 20-40°C temperature range. It combines both the stress to the environment and the strain from sweating (by means of skin wetness) [141]
In the PMV^*/PMV_{set} , dry buld temperature is replaced by SET*, which, according to the author, is a better representative temperature of the enthalpy of the "humid-clothing

environment" around the skin's outer surface [121].

ASHRAE's $PMV_{adjusted}$ or PMV_{ce} (2013):

The Cooling Effect (CE) is introduced by ASHRAE 55 from the year 2013 [102] for air velocities in the range 0.15 - 2 m/s. It is calculated using Gagge's two-node model, specifically the SET index, because it can provide a physiological response of evaporative cooling by means of enhanced convection[102]. It is expressed in degrees and is used in the calculation of the adjusted PMV (PMV_{adj}: PMV adjusted, or PMV_{CE}). When subtracted from the air temperature and the mean radiant temperature, it yields the same SET temperature for a condition of $0.15\ m.s^{-1}$. It has been available as an online tool since 2013 [165]. Recent studies have shown similar poor performance in prediction against the traditional PMV formulation. (one third of good prediction) [148], [149].

Omidvar's PMV_{new} (2020):

Another, much more recent attempt to modify PMV was that of Omidvar [166], who proposed modifying the equation for heat loss due to evaporation of transpiration in Fanger's model. He starts from the observation that the poor performance of the original model for hot environments would be due to the notion of expectation of Fanger and Toftum [167] (see $ePMV$) but also mainly to the fact that the calculations related to perspiration are very simplified. Indeed, the evaporation equation of the original model is dependent only on metabolic activity and becomes negligible during the low activity of a sedentary person ($M\ [1 : 1.1\,met]$), such as rest, sitting, or low office activity, like typing. He, therefore, introduces an additional term to account for basal loss through perspiration, proposing a new version of the PMV model, named PMV_{new}

Zhang's modified Fanger's equations (2020, 2021) :

Zhang et al. also propose to improve Fanger's PMV along two axes:

- The modification of the skin temperature calculation was proposed in 2020 in [168]. The authors propose the latter using skin temperature calculated via the Gagge model and obtained with SET, which offers a more advanced approach through the implementation of detailed equations for human body thermoregulation. The prediction is improved by 56% to 62% depending on the building type.
- The modification of the skin wetness calculation was proposed for 2021 in [169]. Just as for skin temperature, wetness is determined by the Gagge model. Evaporative heat losses at the skin are more detailed than with the simplified Fanger model. The prediction is improved by 32% to 64% compared to the original PMV, validated against the ASHRAE Global Comfort Database II for different climates and building/air conditioning types.

Ji's, Du and Jia's modified Gagge model, procedure or sensation model :

It is noteworthy that several recent studies have questioned both the model itself and the sensation prediction model. These are described in 2.3.5. Ji et al. questioned the SET calculation procedure in [150] and proposed a corrected one for Metabolism higher than 1 met for elderly people [170]. Du et al [171] revisited the SET calculation procedure in order to deal no resting activities, i.e high metabolic rates cases. Jia et al. [154] also proposed a Universal Standard Effective Temperature based on another corrected Standardised environment for assessing thermal comfort with different high metabolic rates. Finally, Ji et al. [172] also propose a thermal sensation vote of the form $PTS = a.SET + b$ for different climate type among which the hot and humid equations 2.53, 2.54, 2.55, are reproduced hereafter :

$$PTS_{Ji,\text{TropicalSavanna}} = 0.2208 \times SET - 5.7274 \tag{2.53}$$

$$PTS_{Ji,\text{HumidSubtropical}} = 0.2273 \times SET - 5.5563 \tag{2.54}$$

$$PTS_{Ji,\text{WetEquatorial}} = 0.2010 \times SET - 5.137 \tag{2.55}$$

Schiavon and Tartarini *Use Fan During Heat Wave* model

Based on Gagge equations, the recent Use Fans During Heatwaves [21] model was developed by Schiavon and Tartarini with the aim of challenging the limitations of American standards [104] regarding the use of fans to manage extreme heat. It allows testing the conditions under which the use of a fan is beneficial and does not pose health concerns for the occupants. Gagge's heat balance equations is used to determine a humidity-dependent temperature.

Vellei's Gagge-based thermal sensation models (2019, 2020, 2024):

Finally, another example, based on the Gagge model, could be particularly interesting for tropical climates. Indeed, the two-node model has received positive feedback from several studies regarding its adequate performance for assessing comfort in hot conditions, unlike the original Fanger PMV, which remains effective only in its neutral zone. In this sense, Vellei et al.[140], [173] propose a modification of Gagge's two-node thermophysiological model by applying the computational accuracy of Fiala's multi-node, multi-segment model for the dynamic thermal sensation prediction. This is particularly valid for rapid changes in skin temperature conditions (e.g., rapid increase in metabolism). The latter model performs well in steady-state and dynamic conditions without requiring a local skin temperature measurement as input. Finally, to improve the dynamic prediction of thermal comfort in rapidly changing environments, a new DPD (Dynamic Percentage Dissatisfied) index has been developed,

primarily based on the structure of Fanger's PPD. In 2024, the same authors introduced a new prediction model to evaluate transient thermal conditions based on physiological signals calculated using the two-node models. The next Dynamic Mean (thermal sensation) Vote DMV is derived from steady-state and transient experiments (1610 exposures). It outperforms the PMV outside of its neutrality range while maintaining a low computational cost, being based on the two-node model. It is accompanied by a Static Mean Vote SMV model for those conditions. Details of the calculation and the whole procedure are available in [174].

2.3.4 Adaptive model modification

Orosa and Oliveira's PMV_n regression model (2010):

Another proposal for PMVn, not to be confused with the PMVn of Humphreys and Nicol (see next section), is proposed by Orosa and Oliveira[175]. It aims to consider humidity more accurately, but this time without taking into account the outside temperature, which is the very principle of the adaptive model. The Fanger equations disappear to give a PMV formula closer to a pure adaptive regression model, according to two variables: air temperature and water vapour pressure. The relationship is given by:

$$PMV_n = -5.151 + 0.202t + 0.553p_v \tag{2.56}$$

Although validated in a warm Mediterranean climate, the authors limit its applicability to young populations, in conditions of temperatures below 25°C, clo of approximately 0.5 and results centered on neutral [-0.4; +0.8].

Vellei's Relative Humidity dependant AM (2017):

One of the main drawbacks of the adaptive model is the inability to consider the relative humidity of indoor conditions, which is particularly problematic for tropical climates. On this subject, Rodriguez et al.[10] cite several studies based on ad hoc surveys that suggest that relative humidity sometimes has an adverse effect on thermal comfort, with the optimal range being 50-60%, and sometimes has a negligible impact if temperatures do not exceed 26°C. Finally, for the tropics, the optimum humidity is around 73%, or within the range (62.2-90%), according to two other studies suggesting that populations in these regions are more likely to accept high levels.

To our knowledge, Veillei et al.[176] are the only ones who have proposed an alternative adaptive model that considers relative humidity. It was determined based on the ASHRAE RP-884 database which, after data cleaning, consisted of 39 naturally ventilated buildings in 8 climates for 8257 voting observations. After highlighting the influence of humidity on thermal sensation recorded in several studies, the authors reanalyze RP-884 to validate this postulate using statistical tools. They select the Random Forest model for its best prediction performance and evaluate the influence of input variables on the prediction. Among the 6 input parameters (Operating Temperature, Outdoor Temperature, Relative Humidity, Air Velocity, Metabolism,

and Gender), relative humidity is the third most influential parameter, behind operative and outdoor temperatures. Using a K-means classification algorithm, three humidity categories are defined (<40%, 40%<RH<60%, >60%), from which three new regressions with roughly the same slope are derived, as shown in Figure 2.18. However, some assumptions can be questioned, namely, (1) although relative humidity influences the RF predictions by 14%, air speed comes just behind at 12%. The question arises of removing this last variable from the set of influential variables. It is worth noting that the authors do not mention the possibility of evaluating cooling by "Cooling Effect", and therefore raising the upper limits of acceptable temperatures, as possible for the original ASHRAE model. At this level, it is easy to imagine that the upper limits for the original model adjusted for the "cooling effect" broadly encompass the new upper limit for RH> 60% proposed by the authors. [177] mention that Vellei et al. *found that the adaptive approach overestimated overheating by 30% over 13 global locations. To include more parameters important to thermal comfort would reduce the error of the adaptive approach, e.g., by 56%, with the inclusion of the relative humidity* [42].

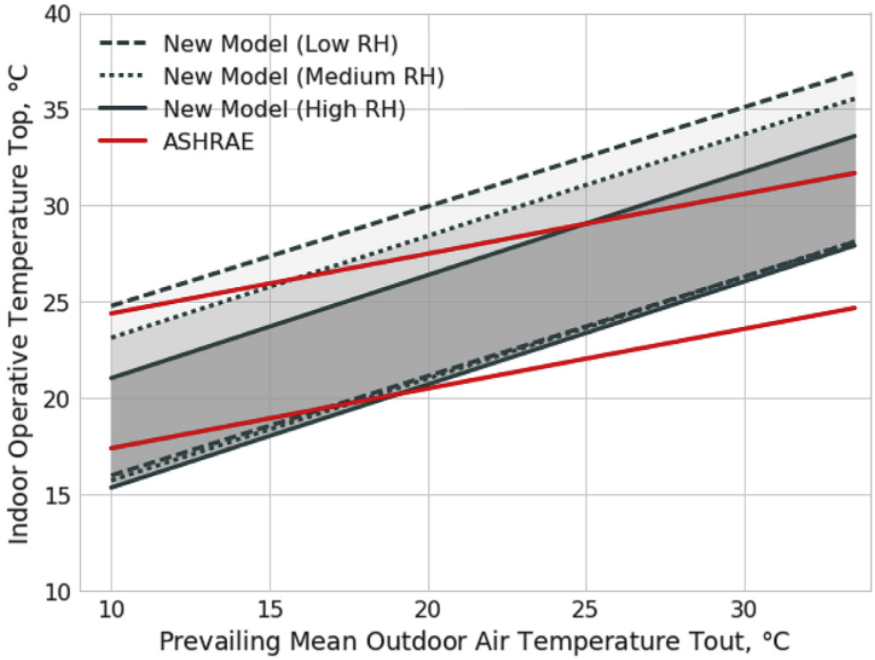

Figure 2.18: *Vellei Adaptive Comfort Model compared to ASHARE's AM 80% acceptability limits*

Regional AMs propositions (2020):

The two pioneering standards in the adoption of the adaptive model, the American ASHRAE 55 and EN16798 (formerly EN 15251), have enabled the model to be widely disseminated. The publication of the work of De Dear and Brager on RP-884, Nicol and Humphrey on SCAT, cited above, as well as their complete databases and methodologies for deriving the model, either by linear regression or by the Griffith method, have enabled the scientific community to fully appropriate this knowledge and make their contribution to it. To date, several proposals for adaptive models have been listed, putting the two generic American and European models in competition. Yao et al. [102] have exhaustively listed them

in their recent article in 2022. Each addresses a specific country, climate, or building type. All these studies present different regression results as shown in Figure 2.19. This shows the diversity of possible Adaptive Model response.

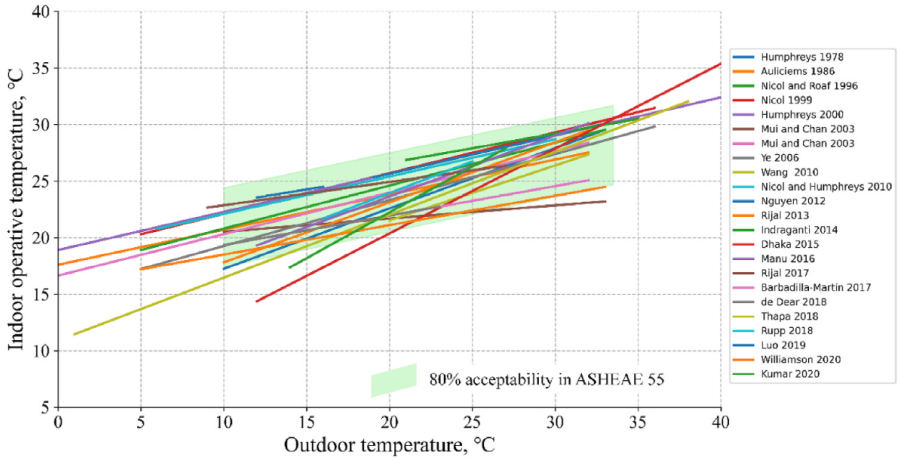

Figure 2.19: *Adaptive Model Regression superposition for different studies, reproduced from Yao et al.* [102]

Parkinson's SET-based Adaptive Model (2020): This latest version is described in the Adaptive Thermal Heat-balance models section 2.3.5

2.3.5 Adaptive Thermal Heat-balance models

Soon after the adoption of the adaptive model in the standards, the idea of applying this concept to address a gap in analytical models led to a new adaptive-heat-balance approach. It highlights a potential for improvement for a better consideration of the three factors of physiological, psychological, and behavioral adaptation by analytical models. The objective of this research was to attempt to rationalize the adaptive approach by heat-balance equations, hence combining it with a physiological response embodied by analytical models.

Fanger and Toftum Adjusted Predicted Mean Votes with Expectancy Factor $ePMV$ (2002):

Fanger himself is the first to be concerned about the accuracy of his prediction of his PMV model in the case of naturally ventilated buildings in hot tropics. Fanger and Toftum [167] first provide an answer to this question by introducing the expectancy factor (ePMV Eq. 2.57, e: expectancy factor). The ePMV is based on two hypotheses: (1) occupants in hot discomfort situations naturally tend to lower their activity level, which results in a drop in metabolism at the PMV input, and (2) the expectations of occupants in an un-air-conditioned building in a hot climate depend on the majority cooling typologies in the area. For this matter, the authors introduce a 6.7% reduction in metabolism per degree of PMV/TSV (> 0) and a PMV-ISO7730 correction factor e between 0.5 and 1. The value 1 represents the highest expectations, i.e.,

a region with high air conditioning penetration. The value of 0.5 corresponds to the lowest expectations in areas where air conditioning is uncommon. However it is stated by Zhang at al. [177] that it only partial account for thermal adaptations because most of it is psychological adaptation, minoring other type of adaptation. That is, as they mention in their article, contrary to what other research from Liu et al and Jing et al. state. Indeed, psychological adaptation would only account for 50% and other types (physiological and behavioural) as 50%, of which parts are dependent on ambient conditions.

The original article mentions an order of magnitude of the "e" coefficients according to the cities studied as follows, determined from a survey of 3,200 observations in Brisbane, Bangkok, Athens, and Singapore. They reported in the following table 2.6 but it's is not clear from where these coefficients were obtained [157]:

$$\text{ePMV} = e.\text{PMV} \tag{2.57}$$

Alternatively, it is also possible to derive the e expectancy factor from field survey recorded Thermal Sensation Vote (TSV) according to Gao et al. [156] with the following expression (N begin the sample size):

$$e = \frac{\sum_{i=1}^{N} (\text{TSV}_i \cdot \text{PMV}_i)}{\sum_{i=1}^{N} (\text{PMV}_i)^2} \tag{2.58}$$

Expectation	**Location (Classification of non-air-conditioned buildings)**	**Warm periods**	**Expectancy factor, e**
High	In regions where air-conditioned buildings are common	Occurring briefly during the summer season	0.9–1.0
Moderate	In regions with some air-conditioned buildings	Summer season	0.7–0.9
Low	In regions with few air-conditioned buildings	All seasons	0.5–0.7

Table 2.6: *Expectation factor e for non-air-conditioned according to the level of penetration of air conditioning, reproduced from* [167]

Although occupant expectations are a matter of psychological adaptation mechanisms, the simplified correction of PMV using $ePMV$ would deserve to be replaced by a quantitative approach, integrating the spatial and temporal dynamics of air conditioning penetration.[79]. $ePMV$ calculation is based on ISO7730 version of PMV and does consider the elevated air speed method of the PMV_{ce}. It is also worth noting that the $ePMV$ model is primarily designed for the case of a building with no mechanical system for heating or cooling installed.

Humprheys' new proposed $nPMV$ or PMV_{new} (2002):

At the same time as Fanger and Toftum with the ePMV, Humphreys and Nicol, the progenitors of the European adaptive model, proposed a regression equation intended to reduce the biases of the original ISO 7730 PMV. It involves determining a coefficient dependent on the outside temperature (like the adaptive model), humidity and the operative inside temperature.[178] This approach is validated on 16,762 observations in office buildings. This is a proof-of-concept for improving the original PMV, as the authors specify in their articles and it should not be generalized. The regression obtained is as follows :

$$\begin{aligned} D_{\text{PMV ASHRAE}} &= -4.03 + 0.0949\, T_{\text{op}} + 0.00584\,(\text{RH}\%) \\ &\quad + 1.201(\text{ met } \times \text{ clo }) + 0.000838\, T_{\text{out}}^2 \\ \text{PMV}_{\text{new}}\,(nPMV) &= 0.8\,(\text{PMV} - D_{\text{PMV ASHRAE}}) \end{aligned} \tag{2.59}$$

The study focuses on reducing PMV bias, particularly the strong bias induced by outdoor climate conditions, which the new formulation allows. An important point to note, however, is that, unlike the studies by De Dear and Brager, the authors find no distinction in responses between voters in AC or NV buildings. There would certainly be a difference, but it could be attributed to the variety of buildings rather than the cooling system implemented. They explain the good performance of the original PMV over a narrow neutral temperature range by the simple fact that it is used in the case of sizing air-conditioned buildings with this criterion. A revision of the PMV, as demonstrated in a proof of concept, could make it generalizable to all cooling typologies and reduce the bias induced by outdoor climate conditions adaptation. The authors also highlight the reason why the PMV could fail to predict consistent sensation in daily conditions, namely, regarding its core equations.

Yao's adaptive rational Predicted Mean Vote noted $aPMV$ (2009) :

In 2009, as part of the redesign of the Chinese standard (GT/B), Yao et al.[179] proposed a new way to integrate the notions of adaptability (psychological and behavioural) into the ISO7730 PMV. The concept is based on the principle of negative feedback control, given that an occupant will respond to a thermal ambience to restore thermal comfort consciously or unconsciously [179], [180]. Therefore, it is based on two pillars: (1) the steady state includes physiological adaptation in a "black box", while psychological and behavioural adaptations will cause an "adaptive feedback" linked to the stimuli of environmental conditions. We start from the basic postulate that the PMV can be written:

$$PMV = G \times \delta \tag{2.60}$$

We then obtain, according to the black box theory, a circular formula:

$$aPMV = G \times \delta - aPMV \times K_\delta \times G \tag{2.61}$$

With:

- G is the transfer function corresponding to the thermoregulation and thermal sensation system,
- δ is the stimuli
- K_δ is the psychological and behavioural coefficient -induced by the stimuli- giving an adaptive feedback (i.e., clothing flexibility, windows, fan use...)

After several mathematical manipulations and assumptions describe in [179] we obtain a final form of the $aPMV$ with the term λ, the adaptive coefficient, positive for hot environments, negative for cold environments.

$$aPMV = \frac{PMV}{1 + \lambda.PMV} \tag{2.62}$$

To obtain the term λ, it is necessary to compare the field survey actual Thermal Sensation Vote (TSV) to calculated PMV and derived the term using a least-squares method (Eq. 2.63,(N begin the sample size and i the vote)) This approach remains heavily dependent on large in situ surveys to determine the adaptation coefficient, which makes it impractical for designers because it is not very generalizable[79]. Nevertheless, $aPMV$ calculation is based on the ISO7730 version of PMV and does consider the elevated air speed method of the PMV_{ce}. Based on [128], [179], recommended fixed values by the authors for λ are 0.293 for a generalised modelling warm conditions (0.125 in cool conditions PMV<0) [181]. The model is integrated alongside the adaptive model in the Chinese standard which has typical λ coefficients depending on the climatic zones. Otherwise, it widelly cited with more than 50 reference but remains almost exclusively used in research in Asia [102].

$$\lambda = \frac{\sum_{i=1}^{N} 1/\mathrm{TSV}_i - \sum_{i=1}^{N} 1/\mathrm{PMV}_i}{N} \tag{2.63}$$

Gao's extended and adaptive SET models $eSET/aSET$ or $ePTS/aPTS$ (2015):

Following the proposals of Nicol (ePMV) [167]and Yao (aPMV) [179], Gao proposes to transpose precisely the same two methodologies and apply them to the calculation of the SET temperature and PTS index based on SET. It has the advantage of benefiting from the better consideration of the influence of air speed and relative humidity by calculating the SET. While these models are often mentioned as $eSET$ (extended SET) and $aSET$ (adaptive SET) models, they are actually modified PTS based on McIntyre equation 2.49 . Both models allow a better prediction than $aPMV$ and $ePMV$, but still face the same problems of applicability and validity presented by the latter two, namely the need for a large a priori database of votes to produce the corrective coefficient. Generalisation remains a question posed by this kind of model.

The procedure to obtain the e and λ coefficient is the same as for Yao and Fanger's previous contribution but the PTS (Eq. 2.49) is used instead of the PMV (N being the sample size and i the vote):

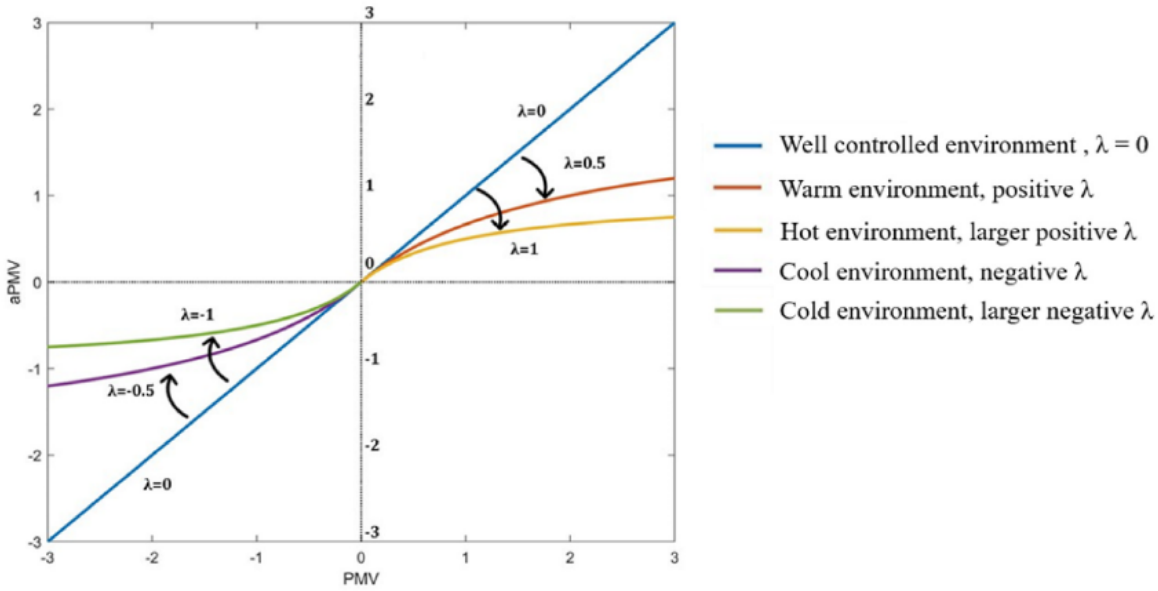

Figure 2.20: *aPMV corrective coefficient illustration according to indoor conditions, reproduced from* [102]

$$e_{\mathrm{s}} = \frac{\sum_{i=1}^{N} (\mathrm{TSV}_i \cdot \mathrm{PTS}_i)}{\sum_{i=1}^{N} (\mathrm{PTS}_i)^2} \tag{2.64}$$

$$\lambda_{\mathrm{s}} = \frac{\sum_{i=1}^{N} 1/\mathrm{TSV}_i - \sum_{i=1}^{N} 1/\mathrm{PTS}_i}{N} \tag{2.65}$$

The resulting Predicted Thermal Sensation, respectively, extended SET and adaptive SET Predicted thermal sensation can be expressed as follows:

$$\mathrm{ePTS}\ (or\ \mathrm{eSET}) = e_{\mathrm{s}} \cdot \mathrm{PTS} \tag{2.66}$$

$$\mathrm{aPTS}\ (or\ \mathrm{aSET}) = \frac{\mathrm{PTS}}{1 + \lambda_{\mathrm{s}} \cdot \mathrm{PTS}} \tag{2.67}$$

For those in search of generalised coefficients, it is advisable to use Gao's original paper reproduced hereafter in section 2.3.5 for the adaptive and extended PMV and SET models. While not explicitly mentioned in their study, it seems to be assumed only for a warm

environment. According to [182], fixed value from early Fanger and Toftum [167] study can also be used as a rough estimation of the expectancy factor e (see also Table 2.6) :

	Range of indoor air velocity	e or λ
Extended PMV model	$0 - 0.2$ m/s	0.974
	$0.2 - 0.8$ m/s	0.770
Adaptive PMV model	$0 - 0.2$ m/s	0.029
	$0.2 - 0.8$ m/s	0.167
Extended SET model	$0 - 0.2$ m/s	1.363
	$0.2 - 0.8$ m/s	1.330
Adaptive SET model	$0 - 0.2$ m/s	−0.213
	$0.2 - 0.8$ m/s	−0.195

(2.68)

Schweiker's $ATHB$ Framework for PMV and SET/PTS (2015,2022) noted PMV_{ATHB}/PTS_{ATHB}:

Schweiker and Wagner's [157], [183] proposal is entirely different in its approach. It involves modifying the inputs of analytical models by considering the notion of behavioural (clothing) and psychological (metabolism) adaptation, derived from two individual variables (Icl and MET) as inputs to a model based on heat balance equations: PMV ($ATBH_{pmv}$: Adaptive Thermal Heat Balance PMV) or PTS ($ATHB_{pts}$: Adaptive Thermal Heat Balance PTS).

According to several studies in their article [183], occupants adapt their clothing and behaviour according to the outdoor and indoor temperatures. Another interesting aspect is that the concept incorporates the notion of psychological adaptation through a new PSYCH indicator correlated with pulse rate measurement. It reflects users' perceptions of flexibility and control over their environment to restore comfort. This principle is well explained in Yao's review, but unfortunately, it was observed during on-site surveys, making it less easily applicable to designers. Nevertheless, validation of the model on laboratory surveys in Germany (BTGA-box and LOBSETR-facility) and on the RP-884 demonstrated good performance compared to the original PMV and the adaptive model, both on air-conditioned and naturally ventilated buildings, as mentioned by Yao et al[102]. According to de Dear [79], this approach is the most promising in addressing individual adaptation processes related to thermal comfort. Still, the approach lacks a theoretical foundation and would be beneficially complemented by investigating the expectation concept. Other points of vigilance concern the validity domains of the coefficients proposed for MET reduction and the low variability of the data used to estimate the coefficients. Schweiker and Wagner have recently updated and extended the applicability of their 2015 theory [184]. They propose revising the approach to considering the two environmental variables MET and Icl for adaptability. They now include new context-related variables such as cooling type, climate, building typology, and envelope characteristics. These variables modify the relationship between indoor and outdoor environments and influence physiological adaptation. The study is based on the complete

ASHRAE Global Comfort Data Base II dataset.

Nine models combining running mean outdoor temperature Trm, metabolism, and context variables were tested. Two of these were selected for evaluation:

- ATHBpmv (2022: updated 2015 version), function of running mean temperature and adjusted metbolism and clothing
- ATHBxpmv (ATHBpmv 2022 extended to take into account building type, cooling type, and season),

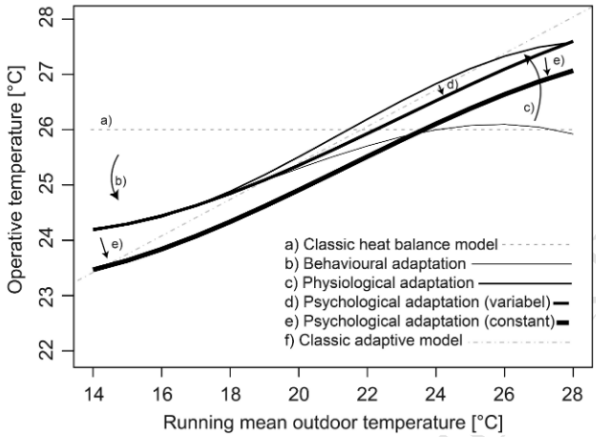

Figure 2.21: *Schweiker and Wagner's different adaptation types' influence on Thermal Heat Balance model output*

The models perform well in arid and temperate climates (groups B and C). The model seems to perform better than the PMV for extreme conditions, but this performance decreases from 27°C. However, it increases with increasing humidity. Air speed does not significantly affect performance, but note that the referenced climates use it less frequently than tropical climates. Although redundant with the average running outdoor temperature, including the season helps explain a greater variance. Finally, the overall performance is also dependent on the accuracy of the analytical model supporting the coupled ATHB model. Unfortunately, Group A (tropical climate) is not mentioned in the article, and the adjustable clothing value is limited to 0.46 clo, as in the Shiavon model [105]. Both models rely on the ASHRAE Global Comfort Database II to regress the adjusted clothing value.

Zhang's PMV with inversely predicted metabolism (2020), noted PMV_{Zhang}:

The inverse determination of metabolism to better take into account physiological adaptation is proposed in 2020 in [185]. Metabolism becomes a function of room temperature and air velocity and is determined through an optimization algorithm (variable metric algorithm); it becomes a new input to the Fanger model. The developed grey-box model improves the prediction of TSV by PMV by 41 to 52%, depending on the building type. The methodology is validated based on the ASHRAE RP-884 database.

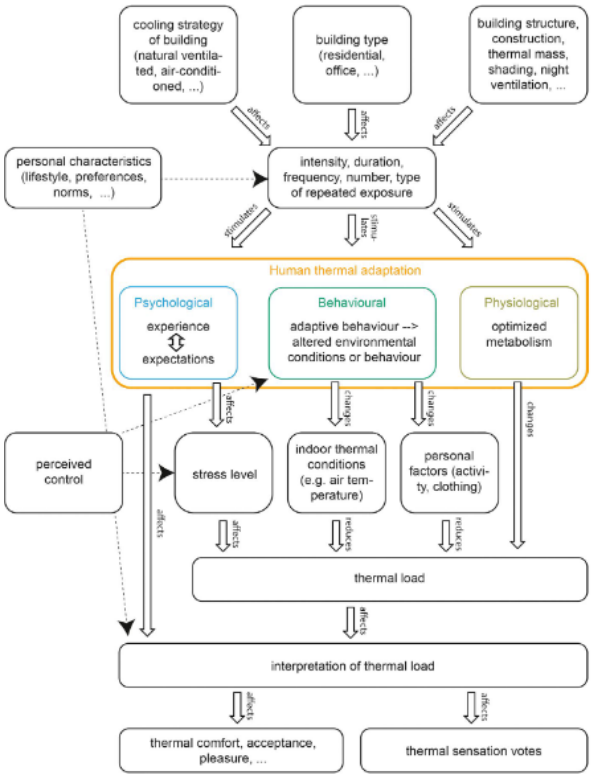

Figure 2.22: *Schweiker and Wagner's Adaptive THM framework*

Zhang's improved algorithm to determine the adaptive coefficient of Yao's (2009) $aPMV$ (2019) -

Zhang et al. [180] propose an alternative algorithm to calculate the adaptive coefficient, but it remains within the same framework.

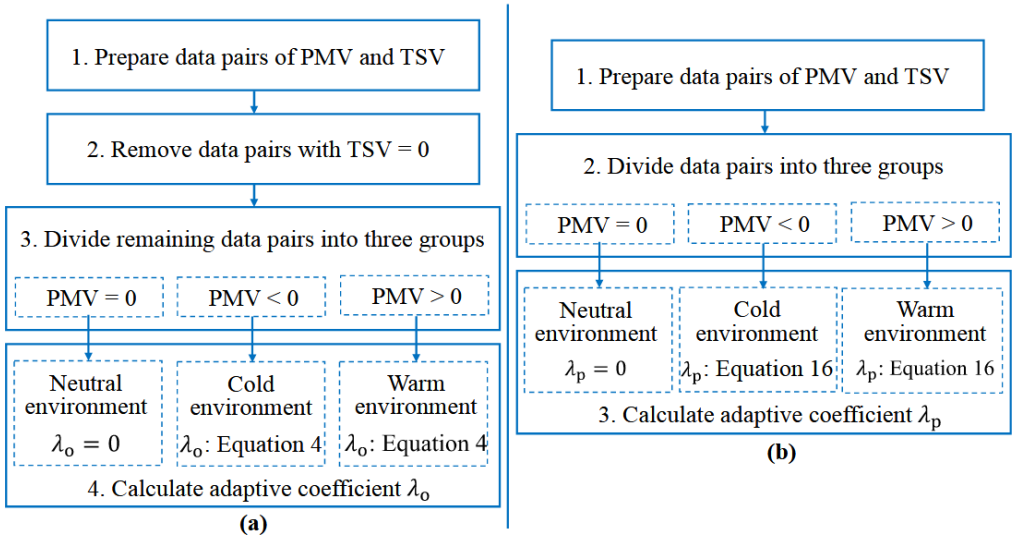

Figure 2.23: *Comparison of Yao and Zhang algorithms for calculating the adaptive coefficient*

$$\lambda_{\mathrm{p}} = \frac{\sum_{i=1}^{n} TSV_{\mathrm{i}} - \sum_{i=1}^{n} \frac{TSV_i^2}{PMV_{\mathrm{i}}}}{\sum_{i=1}^{n} TSV_{\mathrm{i}}^2} \tag{2.69}$$

Zhang's new extended PMV (2020) proposition $ePMV_p$ with variable expectency coefficient:

In 2020, Zhang et al. [177] proposed an extended PMV by multiplying it by a factor linearly dependent on the ambient temperature, like the adaptive model, unlike Nicol's ePMV which is fixed according to the air conditioning habits in the region where the study is located. The ambient temperature can be the air temperature, globe operating temperature or sliding outdoor temperature. According to the author, it allows to take into account the three categories of adaptations but also the dynamics of thermal adaptation. Unlike Nicol's original ePMV, intended for NV buildings and Yao's aPMV intended for AC buildings, the new ePMV is intended to be adapted to the three typologies of AC, NV and MM buildings. The proposed ePMV gives performances of +75 and +65% for naturally ventilated buildings, respectively, compared to the original PMV and Nicol's ePMV. For air-conditioned buildings, it provides the following performance: +75% compared to the original PMV, +90% compared to the original ePMV, +90% compared to the new PMV from Humphreys. His proposed $ePMV$ model is names $ePMV_p$ with corresponding e_p factor and two propositions are made for both NV and AC buildings.

$$\mathrm{ePMV}_p = e_{\mathrm{p}}.\mathrm{PMV} \tag{2.70}$$

$$e_p = a.T + b \tag{2.71}$$

With a and b defined as follows:

$$a = \frac{\sum_{i=1}^{n} PMV_{\mathrm{i}} TSV_{\mathrm{i}} \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}} - \sum_{i=1}^{n} PMV_{\mathrm{i}} TSV_{\mathrm{i}} T_{\mathrm{i}} \sum_{i=1}^{n} PMV_{\mathrm{i}}^2}{\sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}} \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}} - \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}}^2 \sum_{i=1}^{n} PMV_{\mathrm{i}}^2}$$

$$b = \frac{\sum_{i=1}^{n} PMV_{\mathrm{i}} TSV_{\mathrm{i}} T_{\mathrm{i}} \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}} - \sum_{i=1}^{n} PMV_{\mathrm{i}} TSV_{\mathrm{i}} \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}}^2}{\sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}} \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}} - \sum_{i=1}^{n} PMV_{\mathrm{i}}^2 T_{\mathrm{i}}^2 \sum_{i=1}^{n} PMV_{\mathrm{i}}^2}$$

$$ePMV_{\mathrm{p,\ NV}} = (0.0058T + 0.3132)PMV \tag{2.72}$$

$$ePMV_{p,\ \mathrm{AC}} = (-0.0570T + 1.4557)PMV \tag{2.73}$$

Zhang's new extended PMV (2020) proposition $arPMV_p$ with variable adaptive coefficient:

In two other publications, Zhang et al. [180], [181] implement another algorithm to determine the adaptive coefficient with a shift in variable to avoid minimising the influence of neutral TSV values. $arPMV$, again, remains consistent with this approach at the $aPMV$. It is also developed for $ePTS$ and $aPTS$ in the next paragraph.

$$\begin{aligned} x_1 &= \frac{1}{\mathrm{PMV}} \\ x_2 &= \frac{1}{T} \\ y &= \frac{1}{\mathrm{TSV}} \end{aligned} \tag{2.74}$$

$$\begin{aligned} q &= \frac{\sum_{i=1}^{n} \frac{x_{1,i}x_{2,i}}{y_i^2} \sum_{i=1}^{n} \frac{1}{y_i^2} + \sum_{i=1}^{n} \frac{x_{2,i}}{y_i^2} \sum_{i=1}^{n} \frac{1}{y_i} - \sum_{i=1}^{n} \frac{x_{1,i}}{y_i^2} \sum_{i=1}^{n} \frac{x_{2,i}}{y_i^2} - \sum_{i=1}^{n} \frac{1}{y_i^2} \sum_{i=1}^{n} \frac{x_{2,i}}{y_i}}{\sum_{i=1}^{n} \frac{x_{2i}}{y_i^2} \sum_{i=1}^{n} \frac{x_{2,i}}{y_i^2} - \sum_{i=1}^{n} \frac{x_{2,i}^2}{y_i^2} \sum_{i=1}^{n} \frac{1}{y_i^2}} \\ p &= \frac{\sum_{i=1}^{n} \frac{1}{y_i} - \sum_{i=1}^{n} \frac{x_1}{y_i^2} - q \sum_{i=1}^{n} \frac{x_2}{y_i^2}}{\sum_{i=1}^{n} \frac{1}{y_i^2}} \end{aligned} \tag{2.75}$$

But to avoid dividing by zero, just like in original $aPMV$, the following formulation is proposed though PMV and TSV variable substitution:

$$\begin{aligned} PMV' &= PMV + 5 \\ TSV' &= TSV + 5 \end{aligned} \tag{2.76}$$

$$\begin{aligned} q' &= \frac{\sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{\mathrm{PMV}_i' T_i} \sum_{i=1}^{n} \mathrm{TSV}_i'^2 + \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} \sum_{i=1}^{n} \mathrm{TSV}_i' - \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{\mathrm{PMV}_i'} \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} - \sum_{i=1}^{n} \mathrm{TSV}_i'^2 \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'}{\mathrm{T_i}}}{\sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} - \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i^2} \sum_{i=1}^{n} \mathrm{TSV}_i'^2} \\ p' &= \frac{\sum_{i=1}^{n} \mathrm{TSV}_i' - \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{\mathrm{PMV}_i'} - q' \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i}}{\sum_{i=1}^{n} \mathrm{TSV}_i'^2} \end{aligned} \tag{2.77}$$

$$\mathrm{arPMV} = \frac{\mathrm{PMV}'}{1 + \left(q' \frac{1}{T} + p'\right) \mathrm{PMV}'} - 5 = \frac{\mathrm{PMV} + 5}{1 + \left(q' \frac{1}{T} + p'\right) (\mathrm{PMV} + 5)} - 5 \tag{2.78}$$

Zhang et al. [181] propose coefficients for NV buildings and AC buildings based on field survey data in China. They are as follows:

Building type	p'	q'
NV (naturally ventilated)	0.034	-0.646
AC (air-conditioned)	0.240	-5.326

Zhang's updated adaptive rational $ePTS_p$ and $aPTS_p$ with variable adaptive coefficient (2020):

In 2020, Zhang et al.[182] studied the improvement of the accuracy of Gao's aSET and eSET (from which aPTS and ePTS are derived) and proposed a new formulation based solely on PTS. In other words, the coefficients "e" and "a" respectively "expectancy factor" and "feedback theory from cybernetics" are not applied to the calculation of SET but to the calculation of PTS. Compared with the original PTS, conventional ePTS and aPTS (from Gao, 2015) are 6-36.5% more accurate. Zhang's new proposal is 29.4-77% more accurate. This study has been validated on naturally ventilated and air-conditioned buildings of RP-884. The procedure for determining "variable adaptive coefficient" e and λ coefficient from field study is the same as for $ePMVp$ and $arPMVp$ mentioned hereinabove, the main difference lying in substituting the PMV_i by the PTS_i

$$\begin{aligned} PTS' &= PTS + 5 \\ TSV' &= TSV + 5 \end{aligned} \tag{2.79}$$

$$\begin{aligned} q' &= \frac{\sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{\mathrm{PTS}_i' T_i} \sum_{i=1}^{n} \mathrm{TSV}_i'^2 + \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} \sum_{i=1}^{n} \mathrm{TSV}_i' - \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{\mathrm{PTS}_i'} \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} - \sum_{i=1}^{n} \mathrm{TSV}_i'^2 \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'}{\mathrm{T_i}}}{\sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i} - \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i^2} \sum_{i=1}^{n} \mathrm{TSV}_i'^2} \\ p' &= \frac{\sum_{i=1}^{n} \mathrm{TSV}_i' - \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{\mathrm{PTS}_i'} - q' \sum_{i=1}^{n} \frac{\mathrm{TSV}_i'^2}{T_i}}{\sum_{i=1}^{n} \mathrm{TSV}_i'^2} \end{aligned} \tag{2.80}$$

Concerning the extented PTS models, two options are compared. The conventional $ePTS_c$ and proposed $ePTS_p$ are defined as well as his "adaptive" counterpart $aPTS_c$ and proposed $aPTS_p$:

$$ePTS_{\mathrm{c},\,NV} = e_{\mathrm{c}} \times PTS = 0.5880 \times PTS \tag{2.81}$$

$$ePTS_{\mathrm{p,NV}} = \left(0.0050\, T_{\mathrm{op}} + 0.7403\right)(PTS + 5) - 5 \tag{2.82}$$

$$aPTS_{\mathrm{c,NV}} = \frac{PTS}{1 + 0.1315 PTS} \tag{2.83}$$

$$aPTS_{\mathrm{p,NV}} = \frac{PTS + 5}{1 + \left(1.1281 \frac{1}{T_{\mathrm{op}}} - 0.0197\right)(PTS + 5)} - 5 \tag{2.84}$$

The same process est reiterated for AC building with equivalent propositions:

$$ePTS_{\mathrm{c,AC}} = 1.9097 PTS \tag{2.85}$$

$$ePTS_{\mathrm{p,AC}} = \left(0.0256 T_{\mathrm{op}} + 0.1905\right)(PTS + 5) - 5 \tag{2.86}$$

$$aPTS_{\mathrm{c,AC}} = \frac{PTS}{1 + 0.9937 PTS} \tag{2.87}$$

$$aPTS_{\mathrm{p,AC}} = \frac{PTS + 5}{1 + \left(5.8232 \frac{1}{T_{\mathrm{op}}} - 0.1946\right)(PTS + 5)} - 5 \tag{2.88}$$

Parkinson's SET-based Adaptive Model (2020):

The release of the open-source ASHRAE Global Comfort Database II in 2018 [109] gave the opportunity to the research community to confront the latest field survey data, especially for MM building, with adaptive models based on the first version of the database (RP-884 [186]). Parkinson et al.[78] suggest that the Adaptive Model is applicable to all types of building types and operations (AC, NV and MM). They found that the neutral temperature determined by the regression model is more likely to be 1-2°C higher in Asian countries than in Western countries. They mention that mixed-mode operation should be more relaxed in AC setpoint definition, abandoning the deal-band-like AC 2K setpoint of traditional control, even when mechanical cooling is available. This implies adapting the setpoint based on seasonal fluctuation of outdoor conditions. They propose a mixed-mode building-specific model (Eq. 2.89), among three SET-based regression models for NV, AC, and MM (Fig. 2.24). These models provide a neutral SET function of the outside running mean temperature. They offer a broader range of neutral conditions options, given that the SET is calculated from the Gagge two-node model and that other parameters such as relative humidity, air velocity, or clothing are considered in the ideal neutral SET-setpoint. Nevertheless, the authors do not define a comfortable range around the neutral SET, i.e., acceptability upper/lower limits, similar to the original Adaptive Model (AM) of De Dear and Brager. As a result, it tempers its direct adaptation in building control, necessitating further investigations.

$$\mathrm{SET}_{\mathrm{Neutral,\ Parkison}} = 0.16\, T_{\mathrm{out}} + 22.6 \tag{2.89}$$

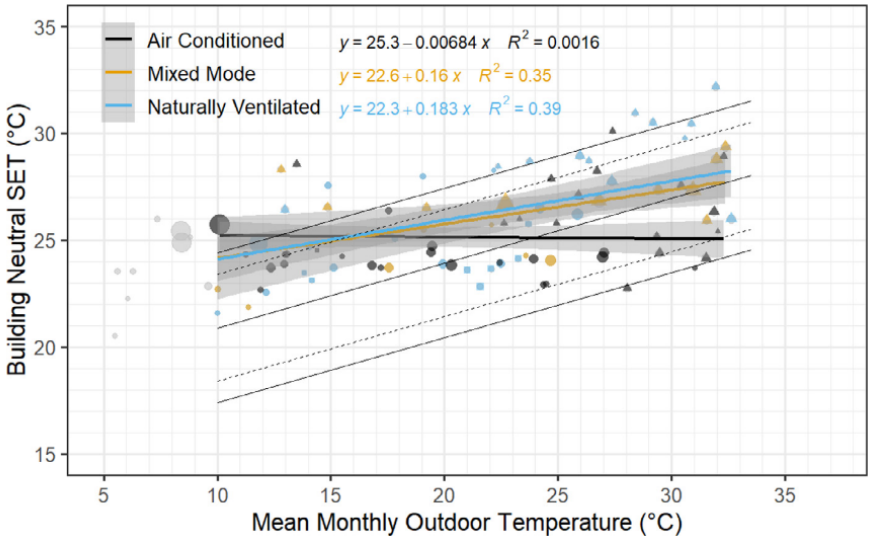

Figure 2.24: *Parkinson's Standard Effective Temperature-based Adaptive regression model built from Ahasrae Global Comfort Databse II* [78], [109]

2.4 Conclusive remarks

The second research question of this thesis is to assess the most relevant comfort models to simulate mixed-mode operation in Building Energy Models in tropical summer. After providing minimal background regarding thermal comfort to the reader, the aim of this chapter was to perform an extensive literature review of comfort modelling techniques for the built environment and evaluate if some of them were directly applicable to Mixed-Mode operation. This review has shown that the literature is abundant in solutions. It describes the traditional Thermal Heat Balance approaches of Fanger and Gagge dating from the 1970s and 1980s and still in use today. The emergence of a revolutionary *adaptive* approach by De Dear and Brager, Nicol and Humprehys late 1990/beginning of the 2000s, addresses the question of naturally ventilated buildings in opposition to Air-conditioned ones. It also highlights the past two decades of very active research in the field of thermal comfort to try to solve the drawbacks of the aforementioned traditional approaches. It could be by modifying or adjusting Thermal Heat-balance Models model equation and calculation procedure, or regionalising data-based adaptive model or providing a more refined one, and, ultimately, trying to combine both adaptive and thermal heat balance approaches. The latter is made possible by the publication of SCAT, RP884 and lastest version of ASHRAE Global Comfort Database II.

While numerous off-the-shelf options are available to researchers, it remains at this stage challenging to select one model for this application.

As stated previously in section 1.3.1 by Parkinson et al.[78], there is no agreement on which model to use for Mixed-mode applications. Parkinson's study is, to our knowledge, the only one proposing a model dedicated to MM operation. Built on the ASHRAE Global Comfort Database II, this updated version of the Adaptive model uses the Standard Effective

Temperature as a comfortable, adaptive temperature. It has, however, some drawbacks, namely the absence of a comfort band, making it not trivially applicable to building control.

Furthermore, while the applicability to MM cooling is not explicitly mentioned, it could be an error to disregard the abundant options highlighted in this review. They deserve a more refined analysis to challenge their applicability to our case study of mixed-mode cooling in tropical conditions.

To delimit our analysis and facilitate model selection for MM application, we implement the following methodology:

- (1) Define selection criteria tailored to the case study to narrow the choice of comfort models based on an extensive literature review presented above.
- (2) Quantitative analysis: Set up a comfort survey in a tropical Mixed-mode building to assist in the model selection,
- (3) Model sensitivity: confirm, via sensitivity analysis techniques, that the selected model can handle MM controllable parameters.

Chapter 3 will describe the experimental setup that will serve as a basis for Chapter 4 for model selection.

3
Experimental Study

This chapter describes the experimental aspect of an on-site field experiment on which this thesis is based. Actual recorded data regarding energy, environmental conditions and occupant feedback regarding overall comfort conditions helps identify many characteristics of underrated and underused mixed-mode operation. A long-term field survey was conducted from January 2023 to December 2024, during which two periods of comfort and ambience surveys were programmed to match tropical summer conditions. These are conditions in which users have difficulty relying solely on natural ventilation and fans to maintain their comfort. Hence, they tend to use AC systems. This long-term campaign helps in selecting an appropriate comfort index and understanding the energy and comfort consequences of using a fan in conjunction with air conditioners.

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3.1 Case study description

3.1.1 Overall context: Cooldown Project

This PhD thesis on-site experimentation was jointly led with the COOLDOWN Project Team. COOLDOWN [187] is a French National Research Agency funded project which overarching objective is to *"define tools and methodology to optimize the successive and/or combined use of passive, soft and active solutions to maximize controlled comfort for occupants while minimizing energy consumption in summer, hot seasons or heat waves to face the climate change impact on buildings with a focus on existing office buildings."* The project is funded under reference ANR-22-CE22-0014 in the category AAPG2020 Category CE22-Transport and mobility, construction in urban and peri-urban areas.

The Project Team is composed of:

- Two state-owned industrial and commercial organizations: **CEA** (**Project leader** (French Alternative Energies and Atomic Energy Commission) and the **CSTB** (Scientific and Technical Center for Building)
- Two academic research labs (**LOCIE** from Savoie Mont-Blanc University and **PIMENT** from La Reunion University)
- An industrial company: **BLUETECK**
- A consulting firm in sustainable design of building: **Laboratoire d'Ecologie Urbaine Reunion**

COOLDOWN is a 48-month-long project. It started in January 2022. Its work plan is articulated around 4 work packages. Foundations of CoolDown will be set in WP1, starting with an update of the state of the art on cooling systems, occupant acceptability, and comfort, followed by some occupant surveys. WP1 will also include the demonstration task with four office buildings in real different climate areas (Auvergne-Rhônes-Alpes, Centre, La Réunion (2 buildings)). These buildings are used throughout the project as use cases for the technical Cooldown development and for their implementation, to gather actual feedback on their efficiency. WP2 and WP3 are dedicated to technical developments. WP2 aims to optimise the combined use of passive, soft and active cooling systems in term of sizing and control strategies. WP3 aims to develop a methodology to ensure the actual performance of hybrid cooling strategies, taking occupants' acceptability into account. Throughout the project, WP4 is dedicated to management and dissemination; it ensures the project's progress and the overall coherence of the research carried out and the dissemination of the results.

Because some aspects of the field survey were jointly led with other stakeholders, it is important to mention their role. While the accurate description will be provided in the following sections and subsections, here is a brief description of the joint collaboration regarding the field survey on which this thesis is based.

- The CEA team had already developed a comfort vote application, which was jointly adapted based on our study requirements. It is described in section 3.3.1.
- Within the CSTB, the PULSE laboratory specialises in sensory response monitoring of occupants. Their role was to develop a physiological measurement campaign to match corresponding votes and update the CSTB-owned Neuro-Physiological NTHM model described in [188]. It was led during specific weeks of this thesis's long-term surveys. Those campaigns are mentioned as PULSE campaign in the following chapter and are described in section 3.2.
- Two buildings have been subject to a comfort survey and physiological measurement campaign in La Reunion in the COOLDOWN project. The Ilet du centre Building, which is described in [189], and the Co-architecte Building, which is described in [80] and in the following section. In total, 23 subjects were implicated in the joint study between PIMENT Lab, CEA, CSTB, and LEU Reunion.

This thesis focuses exclusively on the Coarchitects building and on Subjects 9–23. Data from the joint PULSE campaign are partially used; however, the physiological measurements conducted during this campaign are outside the scope of the present study. The PULSE campaign is nevertheless described in the following section, as it coincided with several comfort survey periods and provided a specific measurement context for the subjects who participated in the comfort surveys.

Whereas the COOLDOWN Project is a broad collaboration, the entire field survey, except for a few complementary topics such as physiological measurements, has been conducted exclusively by the PhD candidate. **The following experimental tasks are integral to the thesis work and constitute its scope. It consists of:**

- **Selection of MM-operated building and subject recruitment**: Co-architectes building and team.
- **CEA's Comfort application adaptation to tropical context**: Functionality gap analysis, requirements documentation, development testing with CEA, and on-site deployment.
- **Experiment setup**: Requirements analysis, selection of sensors for energy use, ceiling fan use, indoor environmental quality (IEQ), and comfort stations.
- **Equipment**: sourcing, configuration, and on-site installation.
- **On site experimentation**: installation, configuration, follow up and troubleshooting.
- **Data collection**: On-site raw data collection, such as Energy loggers, comfort stations, IEQ sensors, and their upload on the PIMENT Lab database, in collaboration with the Lab engineer
- **Data set**: consolidation of the metadata and the dataset
- **Statistical Analysis**

3.1.2 Building location and climate

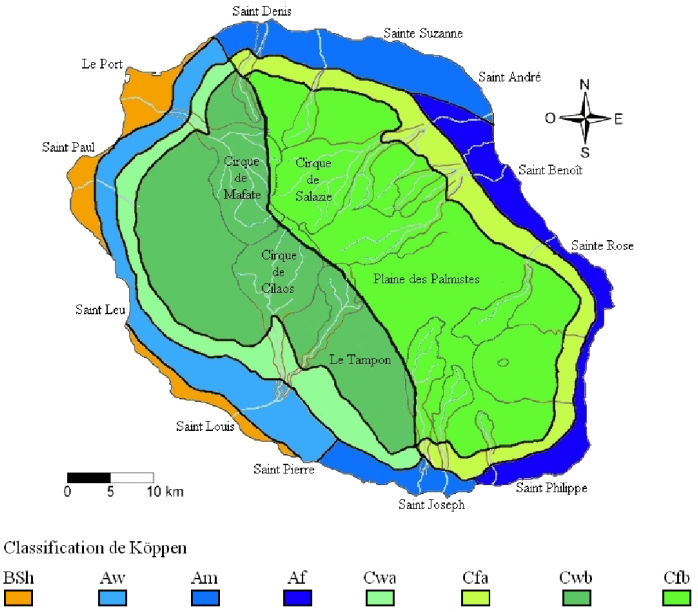

Figure 3.1: *Reunion Island climate map according to Köppen classification* [190] *build from* [52]

The experimental support building is located in the southern coastal city of Saint-Pierre, Reunion Island. La Reunion is situated at 21°S latitude between the well-known islands of Mauritius and Madagascar. While far from Europe, this French outermost territory is a fast-developing and innovative region, especially in the field of tropical building design. One of the significant research and innovation axes of the regional strategy is *Sustainable development and tropical buildings for bioclimatic and resilient cities in intertropical zones*. It aims at reducing the environmental impact of the AEC industry, which accounts for more than 25% of the whole energy use. Those objectives have to be tackled considering the difficult tropical climate conditions. Overall, the climate of La Reunion is characterised by high temperature and humidity year-round with alternating dry and wet seasons as described in section 1.2.1. Nevertheless, La Reunion faces different tropical conditions due to its distinct topography, which ranges from sea level to more than 3000m high, and because of the trade winds that bring moist air from the ocean. On the eastern side of the island, trade winds blow strongly and condense as they cool, reaching the peaks. The city of Saint-Pierre is at the bottom of the abrupt slope of the *"Piton de la Fournaise"* volcano on the south-western side of the island. Thus, it benefits from dryer conditions. The climate of the building site is difficult to state as one can easily see on the Koppen map in Figure 3.1. There is an in-between climate between the wet and windy *Am* type, the drier *Aw* type, and the non-tropical categorised Arid *Bsh*. The wind regime and the local topography, consisting of several deep ravines, highly influence the Saint-Pierre communal lands. Located in the small village of Terre Sainte, the case study is officially in the Aw zone. The average annual daytime temperatures [7 a.m. to 6 p.m.] do not drop below 23°C for Saint-Pierre.

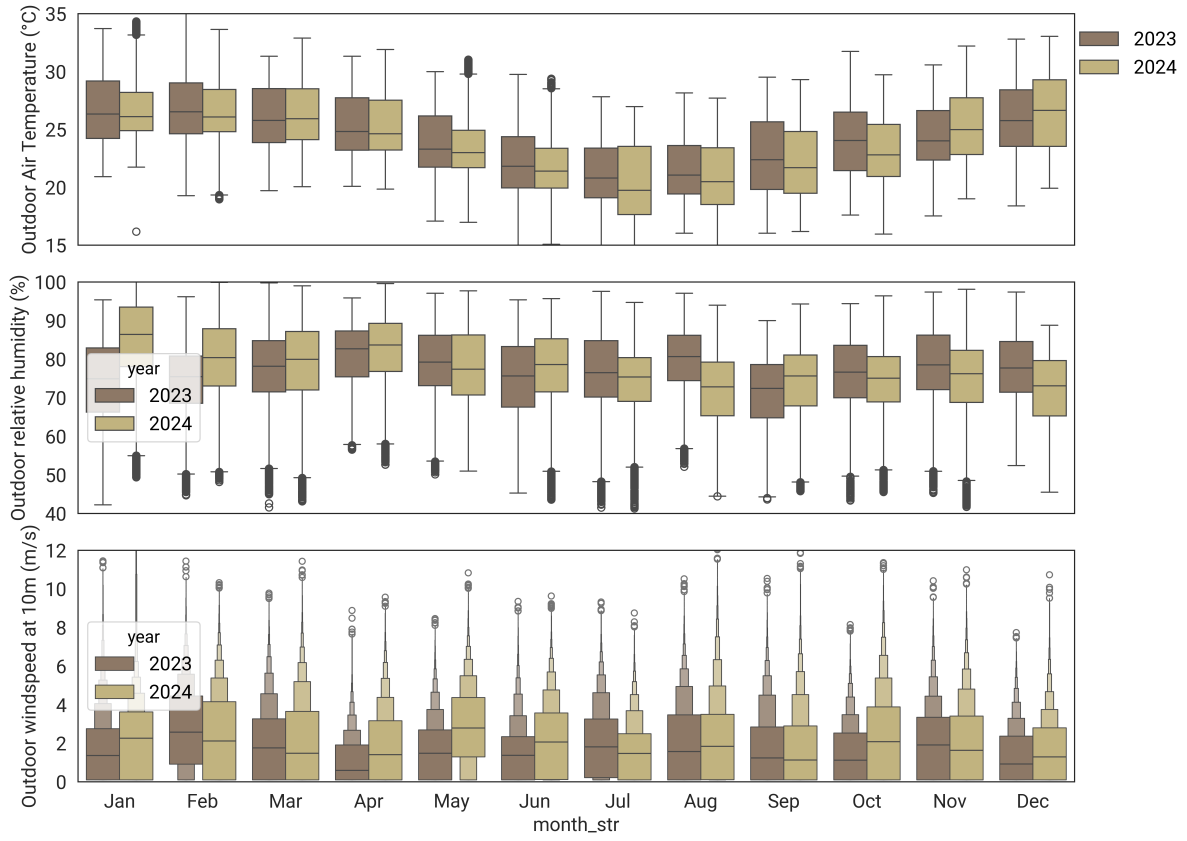

Figure 3.2: *Outdoor Monthly distribution of temperature, relative humidity and air velocity at the closed (1km) meteo station (IUT Terre-Sainte)*

Figure 3.2 shows the monthly outdoor condition distribution recorded at 1 km from the studied site. It presents plots for temperature, relative humidity, and wind speed in a box plot for both 2023 and 2024 throughout the year. A windrose for 2023 is described in figure 3.3. Overall, climatic conditions follow a similar seasonal cycle in 2023 and 2024. Median temperatures remain high in austral summer (November to March, between 26-28 °C) but with extremely high temperatures up to 32-34°C range. In winter (June to September), dispersion is narrower and the median drops to 20-22°C. The average annual daytime temperatures [7 a.m. to 6 p.m.] do not drop below 23°C for Saint-Pierre. Relative humidity is often in the 70-85% range, but numerous outliers around 45-55% show drier short periods. Wind speed presents low to medium medians at around 1.5-3 $m.s^{-1}$ but with a high intensity peak over the 8-10 $m.s^{-1}$ range. 2024 appears slightly warmer than 2023, but in summer, the temperatures are equivalent. Relative humidity is less critical in December and November 2024 but far more important in January-February and March, by almost 10%, drawing extreme humidity conditions in the 82-92% range during that period (summer comfort survey period). Overall, the conditions align with a tropical coastal climate, featuring high temperatures in summer and high relative humidity throughout the year. Exclusive S-SE (fig 3.3 trade winds provide sufficient potential for natural ventilation of spaces, making the mixed-mode cascade cooling a good option for this area.

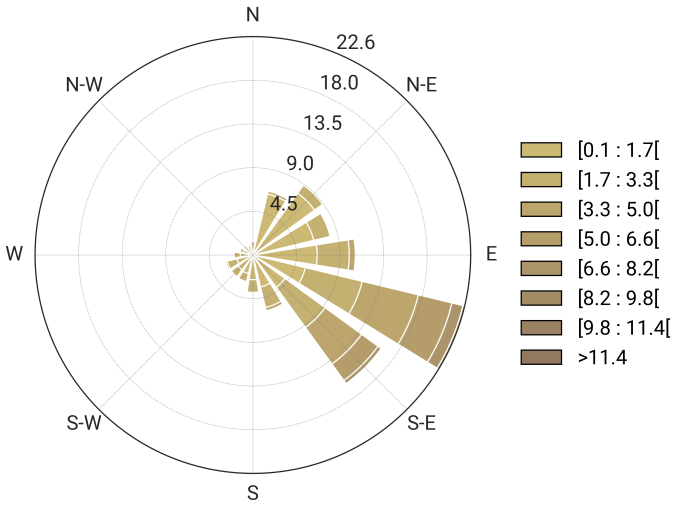

Figure 3.3: *Windrose of recorded velocities at 10m at the closed (1km) meteo station (IUT Terre-Sainte)*

3.1.3 Building's description

The building, as shown in figure 3.4, is an old concrete structure —a two-floor house from the 1980s, approximately 150 square meters in size— located by the sea. It was renovated in 2018, enlarged, and converted into an office (100 m^2) for an architectural agency and a fully equipped self-catering accommodation. It is typical of many offices in La Réunion Island for small companies with fewer than 30 employees. Its location is not subject to road infrastructure acoustic nuisance as its North-east (NE) access is via a one-way road with very little traffic.

The NE facade is almost blind and is next to a vacant lot. Its South-east (SE) facade is next to an individual dwelling. Only the two spaces could be subject to acoustic nuisance with a North-West (NW) oriented window facing a restaurant's cuisine. As it is a renovated house, it is not subject to any applicable energy efficiency standard in La Réunion. The renovation consists of a wooden extension (4-desks naturally ventilated space) on the south-west (SW) façade of the original house. It also serves as vertical access to the first-floor office. On the plot side, it is worth mentioning the 2m-high gate and extensive tropical vegetation that shade the SE, SW, and NW ground-floor facades.



Figure 3.4: *Outdoor view of the case study building, Co-architectes Agency showing NV multi-office louver-type facade (center), MM Openspace with opened French-type double windows (right), and MM single office (upper right) facing its veranda*

The main blind façades are oriented to the north-east (NE) and north-west (NW), and are not shaded or insulated. The main open façades are S-SW-oriented, facing a green courtyard. Most ground-floor ceilings are shaded from the sun (great tree) or do not get direct sunlight as they are not in contact with the outdoors (first floor, rooftop veranda). Since specific spaces are single-oriented, they do not have natural cross ventilation for users' comfort. These users have access to ceiling fans that can be combined with air conditioning for the hottest periods. There are four main spaces illustrated in Figure 3.6 and are described in Table 3.1. A Mixed-Mode single office located on the first floor with double panes glazed openings and a glazed window, a Mixed Mode meeting room located on the ground floor with one double panes

glazed openings, a four desks NV fully cross-ventilated space (wood construction extension) and eight desks Mixed Mode office with three double pane door-windows openings on a single façade as illustrated by figure 3.4. All spaces have ceiling fans (brand: Hunter, model: Industrie II 132 cm). Mixed-mode spaces are not cross-ventilated; therefore, they are also equipped with split air conditioning units. Control of ceiling fans and AC thermostats is at the user's discretion. The ceiling fans offer three different rotation speeds. The office administrator limits the thermostat threshold for the AC unit at 26°C per the local Reunion Island standard for offices and commercial buildings PERENE:2009 [191]. This setpoint is also recommended in Manzano-Agugliaro et al. [192] review of bioclimatic strategies for thermal comfort. The IT room is also conditioned, but the door remains closed all the time; the cooling temperature setpoint is set at 27°C all year long.

In the thesis, only the sedentary working spaces have been studied. Namely, the MM Single Office, the MM Openspace, and the NV multioffice were part of the comfort and energy studies. The MM meeting room and the IT Room have not been studied from a comfort perspective, but their energy use is described in the energy use section later in this chapter. The building was chosen for the following reasons, sorted by importance :

- From an architectural point of view, the renovated building is not appropriate for providing users with natural cross ventilation all year round because of its configuration and construction details. Only the new wooden extension can do so. During the refurbishment, it was impossible to break the wall and install new windows on the blind facades due to town planning regulations. Most spaces have single-sided openings and are poorly configured for beneficial natural cooling when temperatures rise. It thus makes a good candidate for a mixed-mode building application, coupling ceiling fans and air conditioning when climatic conditions deteriorate. Also, from an AEC industry perspective, working on a renovated building brings more constraints than a new one to ensure flawless execution. With the densification of urban areas and land scarcity, the next generation of architects will spend more time refurbishing old buildings than designing new ones.
- From a case study point of view, back in 2022, when the PhD thesis field survey was initiated, there were only a couple of MM buildings with this configuration, offering the users the possibility to use both a ceiling fan and air-conditioning simultaneously. This narrowed our choices in terms of demonstrative building. The Co-architectes building was the closest to the Lab, and the users were enthusiastic about taking part in such a study, which is definitely something to consider when choosing a case study.
- The building is in the scope of MM application. According to Brager et al. [69] taxonomy, the building can be considered as *"Zoned"* because it is composed of NV spaces and MM spaces. It can also be described as *"Changer over"* because the cooling system in use is different according to the season. NV + Fans is mainly used in mid-season (sometimes in winter season if necessary), AC + Fans is used in summer season at the highest temperature peak, NV + Fans is also used during the hot season if sufficient.

Furthermore, it can be considered a Fan-First scenario operated building as described by Malik et al. [22] because occupants initially try to maintain their comfort using only the effect of air movement.

- The building operation pushes further the MM operation. While most research studying MM operation [22], [47] highlights comfort and energy gain from the 22-24°C range to 26-27°C, the Co-architectes AC already operates at a minimal cooling setpoint of 26°C. It was interesting for this thesis to study a well-established MM operation driven by the team's adaptive opportunities. From the perspective of understanding the extent to which an MM operation can benefit energy use, the Co-architectes operation was a good candidate.
- Its location, on the seaside in an Am tropical climate type and in a fast-developing economic area of the island, was in the scope of our study.

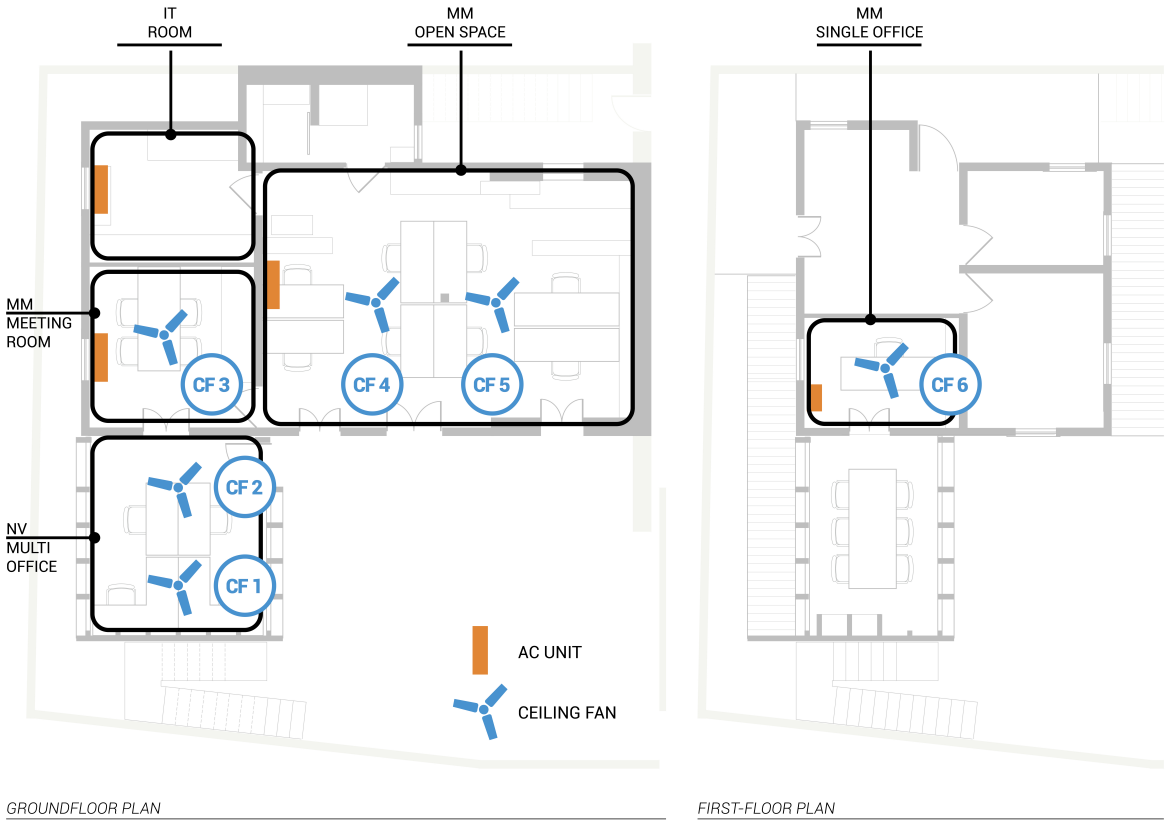

Figure 3.5: *Space layout plan and cooling systems of both floor of the study case building*

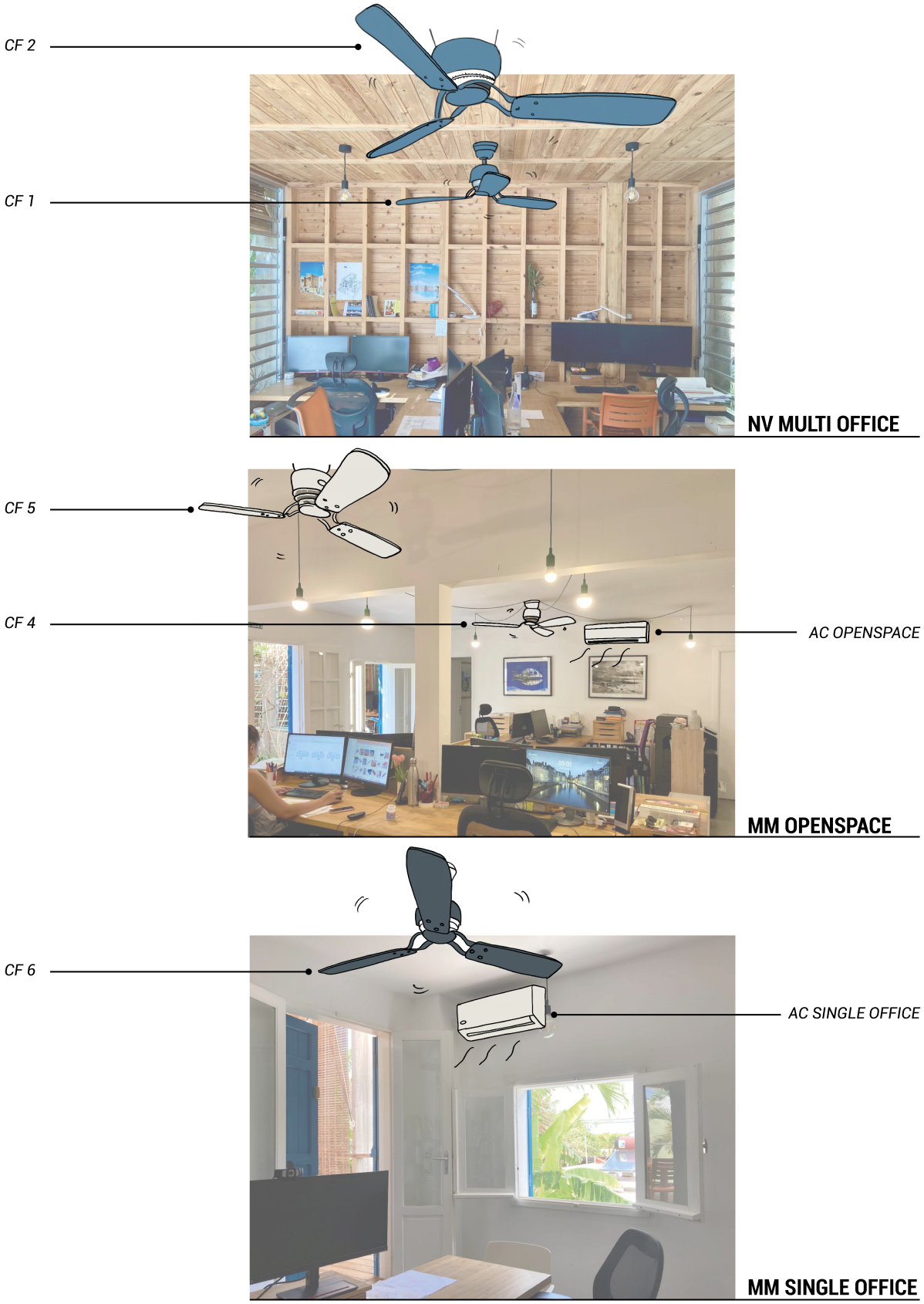

Figure 3.6: *Views of Coarchitects indoor working spaces and available windows, ceiling fans and air-conditioning units*

Table 3.1: *Working spaces characteristics*

Space	**MM Open Space**	**NV Multi Office**	**MM Single Office**	**MM Meeting Room**	**IT Room**	**Bathroom**
Surface $[m^2]$	44	17	8	13	8	–
Desks / Users	8	4	1	7 max	–	–
$m^2/pers$	5.5	4.25	8	–	–	–
Wall Construction	Uninsulated concrete	Timber frame	Uninsulated concrete	Uninsulated concrete	Uninsulated concrete	Uninsulated concrete
Wall finish	white stucco	wood cladding / grey corrugated sheet metal	white wood cladding	white stucco	white stucco	white stucco
Roofing	no exterior*	Shaded by veranda	Insulated metal sheet	no exterior*	no exterior*	no exterior*
NW openings	0.5×0.5m glazed louvred windows	–	–	–	–	–
SW openings	–	2.3×2.1m glazed louvred windows	1×1.4m French window door	–	–	–
SE openings	three 2×1.4m French window doors	–	0.7×0.7m windows	1×1.4m French window door	–	–
NE openings	–	2.3×2.1m glazed louvred windows	–	–	–	–
Shade	awning	venitian blinds	veranda	pivot shutter	-	-
NV	Single sided	Crossed	Lateral	Single sided	–	–
AC	Split	–	Split	Split	Split(27°C)	–
CF **	2	2	1	1	–	–
*CF ** command*	1 wall mounted switch	2 IR remote control	1 wall mounted switch	1 IR remote control	–	–

** some spaces roofing are connected to a touristic flat and so have no exterior roof*
***All ceiling fans are identical, each with three speed settings.*

3.1.4 Building's occupants and their adaptive opportunities

CO-Architectes is an architectural firm based in La Réunion and Mayotte, specialising in tropical bioclimatic architecture. The 15 employees of Co-architectes participated in the study at varying levels of involvement. Thirteen of them are architects, and two are executive assistants. They all originate from Reunion Island or from the French mainland. Most of them lived on the island for at least six months before entering the study. Due to their daily involvement in designing sustainable living and working spaces for people in Reunion Island and Mayotte, the team exhibits a particular environmental awareness. It could be seen as a limitation regarding the generalizability of our findings, but it might also highlight more ambitious goals for MM operation to lower energy use.

Over the 15 subjects, **referenced as subjects 09 to 23**, 10 are females, and 5 are males between 23 and 50 years old. Females average 38.6 years old (sd 10.4 y.o) with a median of 36 years old. Males average 35.2 years old (sd 6.1 y.o) with a median of 33 years old. Between 2023 and 2024, turnover affects the consistency of the sample, with subjects 17 and 21 present only in 2023 and subjects 20 and 23 present only in 2024. Nevertheless, all comparisons made between 2023 and 2024 in the following sections of results will be based on a relatively consistent sample of subjects, as 74% of the studied population took part in both 2023 and 2024 studies.

Regarding personal adaptive opportunities, the occupants can freely adapt their activities within the scope of office work. They can stand up and go outside to feel a fresh breeze, move around the office from their chair, or even have a cold glass of water to cool down. Clothing habits are also very flexible. Subjects can dress as they like, as long as they remain dressed casually. Light fabrics such as dresses, skirts, and pants are allowed for women. For men, shorts and a t-shirt are allowed. Wearing sock-free shoes, open shoes, or sandals is pretty standard; even removing shoes while working at the desk is a common habit among the team when clients are absent. Since most employees come to the office on foot or by bike, a shower is available for their use. It is sometimes used early in the morning, after lunchtime, or following a sports break.

Regarding the building comfort system controls, users have full control over all comfort systems to maintain their comfort. There is no automation in place in the building. In hot conditions, windows remain open from the beginning of the day unless the AC is ON. This is also the case with ceiling fans turned on at low speed upon arrival. Solar shades are manoeuvrable at the user's discretion but remain a community decision. The same rules apply to the fan's higher speed configuration and air conditioning.

All equipment and commands are described in Table 3.1. The main differences for the three studied working spaces are introduced hereafter:

- Subjects in the MM openspace do not have access to natural cross ventilation. Openings are single-sided, all positioned on the same wall. It benefits from three large double-pane

French-type openings that can be shaded by an awning. An air conditioning system and two ceiling fans with independent remote controls are available for the occupants' use. Actioning a system is a community decision-making.

- Subjects in the NV Multioffice do not have access to air conditioning but benefit from fully opposite-sided operable louvre-type windows to regulate airflow in the space. There are a total of 8 controls per façade. Actioning a system is a community decision-making process, but because louvres involve many controls, they can be easily fine-tuned for one or two people. Nevertheless, the two ceiling fans have the same switch, so they can only run simultaneously.
- The case of the single office is different, as a single person makes the decision for all adaptive opportunities. The office has two lateral openings with movable shades, an air conditioning unit, and a ceiling fan.

3.2 Data acquisition

Between January 2022 and December 2024, the energy consumption of cooling systems was systematically recorded. During this period, summer seasons were selected for more detailed investigations focusing on indoor comfort and environmental conditions. Additionally, as part of the Cooldown Project—though beyond the scope of this thesis—physiological measurements such as skin temperature and heart rate were collected while assessing occupants' thermal comfort [85].

The experimental setup and data acquisition serve several purposes:

- (1) The first objective of the in-use data collection was to evaluate energy use and comfort of our case study of the NV+CF+AC mixed-mode building with an active population to understand to what extent it is possible to push Mixed-mode application. All comfort surveys of 2023 were performed without any behavioural rules. Hence, the use of window openings, fans, and AC was at the discretion of the users.
- (2) The second objective of the in-use data collection was to evaluate energy use and comfort in the absence of air movement provoked by ceiling fans in order to deepen the understanding of the role of CF in maintaining comfort in MM operation. Two test weeks in 2024 were conducted without the use of ceiling fans. Hence, users could maintain their comfort relying only on the Window opening and the AC.
- (3) The final objective was to collect a significant amount of hot conditions votes with IEQ measurements to serve the model selection methodology of chapter 4

3.2.1 Field survey types and scope of the present study

There are four types of field measurement with different levels of detail over the 2-year period. Some measured variables are specifically dedicated to this thesis work, some to the cooldown project, and some others to both.

- **Level 1 - ENERGY**: The first level of measurement is regarding AC and CF energy use. It was measured during two complete years, 2023 and 2024, to get an overview of the cooling demand energy. **This survey is part of this thesis work.**
- **Level 2 - LOCAL AMBIENCE**: The second level of measurement concerns the couple Temperature/Relative humidity locally on desks. During this period, users had the opportunity, but no obligation, to vote for their comfort. **It was intended for the cooldown projects and is not part of this study**
- **Level 3 - IEQ / COMFORT**: The third level of comfort survey applies to a full environmental variable and comfort vote. During this period, voters are strongly encouraged to provide feedback on thermal comfort via an application that appears on their computer eight times a day. During these periods, users are fully adaptable to maintain their comfort. During the *Level 3* data collection weeks, all cooling equipment could be used at the user's discretion. **This level is fully part of this thesis work and intermediate campaigns are labelled** $I0i$
- **Level 4 - IEQ/COMFORT/PHYSIO (Pulse)**: The last *level 4* is based on *level 3* with extra physiological measurements. It occurs in 2023 over 3 weeks, during which users are fully adaptable, and in 2024 over 2 weeks, during which users do not have access to ceiling fans. During this period, users were required to vote between 4 and 8 times a day when at their desks. During C01, C02, and C03 weeks (2023), Natural ventilation, Ceiling Fan use and Air-conditioning were all allowed. During C04 and C05 weeks (2024), only NV and AC were allowed (*'NO CF" test weeks*). **While physiological measurements are outside the scope of this thesis, IEQ measurement is used in the creation of the comfort dataset and is labelled** $C0i$**.**

To summarise, this thesis work makes use of a level 3 (IEQ / COMFORT - $I01$ **to** $I08$**) survey for about 4 months over two summers (2023/2024), during which 5 weeks have been dedicated to extra physiological measurements (level 4 IEQ/COMFORT/PHYSIO** $C01$ **to** $C05$**). Energy use is recorded during two years to match the level 3 and 4 survey and provide an energy use overview of the building over the whole recording period.**

Table 3.2: *Field measurement types description*

	1 ENERGY	**2 LOCAL AMBIENCE**	**3 IEQ COMFORT**	**4 IEQ COMFORT PHYSIO**
Project	**This thesis**	Cooldown	**This thesis**	**This thesis** + Cooldown
Responsible	M.Boulinguez	PIMENT	M.Boulinguez	M.Boulinguez (+PULSE Lab)
Type	Longitudinal	Longitudinal	Longitudinal	Cross-sectional
Periods	01-2023/12-2024	01-2023/03-2024	02/2023-05/2023 03/2024-05/2024	C_{01}(13-18/02/2023) C_{02}(20-25/03/2023) C_{03}(27-31/03/2023) **'NO CF" test weeks:** C_{04}(26-29/02/2024) C_{05}(18-22/03/2024)
AC-CF Energy Use	x	x	x	x
CF usage		x*	x*	x*
Environmental control		x	x	x
Local T/RH		x*	x*	x*
Zone Temperature			x	x
Zone Rel.Humidity			x	x
Zone Globe temp.			x	x
Zone Airspeed			x	x
User clothing		x	x	x
Comfort votes		Optional	Strongly encouraged	Mandatory
Heart Rate				x
Skin/Core Temp.				x

(*) *The recorded data is partial and cannot be used reliably for the selected periods of this thesis*

3.2.2 Data types and Method of acquisition

Personal data protection

Energy use, fan usage, AC usage, comfort votes are part of personal data that are regulated under the General Data Protection Regulation - EU 2016/679 agreement [193]. Before any field study intervention, a questionnaire was sent to the users to secure their consent by signing a GDPR-compliant agreement. Thus, they were informed of the study's content, their involvement, and how the Cooldown project and this thesis would utilise their personal data. CSTB-PULSE and LEU Reunion have archived the paper agreement, and all data have been anonymised. A blank copy of the GDPR agreement is provided in the appendix.

Basic identifier and respondent's personal information

The basic identifiers, as per ASHRAE Global Comfort Database coding convention, are recorded as follows:

- **Year:** each record is dated with a GMT+4 timestamp.
- **Season:** Season will be defined by the timestamp, but for this thesis study, all votes used are recorded in the summer season
- **Climate:** Climate is defined as Am according to Köppen Geiger Climate Classification (KGC)
- **City, Country :** Building Co-architectes is located in Saint-Pierre, La Reunion, with coordinates $21°20'39''S\ \ 55°28'48''E$
- **Building types :** Office building
- **Building operation :** Mixed-mode operated building
- **Respondant:** Each subject has a unique identifier SUi with subscript i from 09 to 23. It was given at the beginning of the field survey.
- **Age, Sex, Weight, Height:** These informations are mentioned in the GDPR agreement, recorded at the beginning of the survey. The ages mentioned in the results are the recorded age in 2023. No change of $+1y.o$ was made for ages in 2024 for the analysis.

Energy and usage

As part of this thesis work, we implemented a power metering system illustrated in Figure 3.7. Multivoies (Omegawatt) is a French-manufactured multi-output electricity metering system which allows for a detailed analysis of energy use. The system is modular and compact enough to be installed in the existing electrical switchboard. It comes with a variety of miniature, openable, flexible sensors to measure each outgoing circuit. For installation convenience, ours is equipped with a 0-90A mini amp clamp at 2W resolution (0.2A). Records consist of energy use for ceiling fans and air conditioning units. Data is recorded at one-minute intervals and stored in the built-in storage. The system uploads the latest records to a private FTP server daily for remote monitoring. Every three months, backup data is collected on-site via WiFi. The actual electrical installation is a mix of old and new wiring diagrams. Hence, it

was not possible to record each ceiling fan equipment individually because they are wired to the same switch. The detail for each meter is mentioned hereafter:

- **Meter 1:** AC from the IT room
- **Meter 2:** AC from the Meeting room
- **Meter 3:** AC from the MM Openspace
- **Meter 4:** 2 CF from the MM Open space + 1 CF from the Meeting Room
- **Meter 5:** 2 CF from the NV Multioffice + 1 CF from the MM Single office
- **Meter 6:** AC from the MM Single office

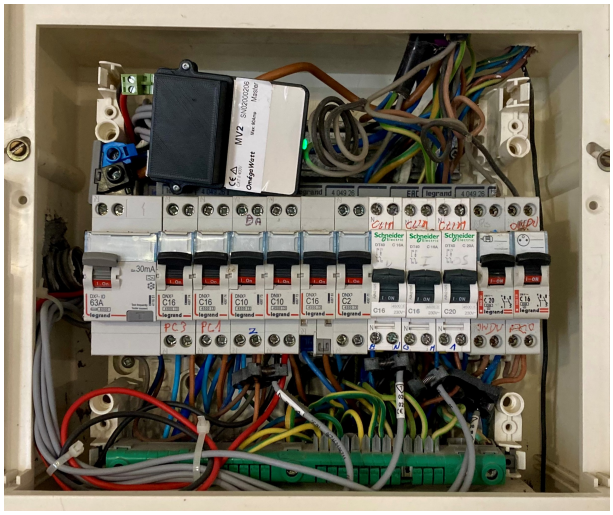

Figure 3.7: *View of the Omegawatt energy meter temporary installation on the existing MM Openspace electrical board*

Regarding ceiling fan usage, accelerometers were initially installed on each fan to detect its operation. Unfortunately, due to unknown technical issues, a significant amount of data was lost during the transfer from the IOT outsourcing company to the lab database. Hence, it was not possible to detect the individual usage of ceiling fans.

Meteorological data

The outdoor environmental data were collected from a weather station at the Southern Campus of the University of Réunion, located in the same municipality as the study site, at approximately 1 km distance, at a comparable altitude. The measured variables include outdoor air temperature, relative humidity, wind speed, and wind direction at heights of 2 m and 10 m. Wind direction data at 10m is missing for the 2024 summer season due to sensor failure.

Indoor Environmental parameters

Environmental sensors (Dragino LHT65) recording dry bulb temperature and relative humidity were installed on all workstations for the Cooldown project, but were not used as part of this work. For recording an averaged zoned ambience, in accordance with zones of

Building Energy Models (BEM), each space was also equipped with an IEQ/comfort station, detailed in Table 3.3, which measured air temperature, globe temperature, relative humidity, and air velocity. The mean radiant temperature is post-processed and calculated from the globe temperature, air velocity, and dry bulb temperature, according to ISO 7726:2023 [194] and equation 3.1, where D is the globe diameter and ε is its emissivity. Recording environmental parameters on a long-term basis in an occupied building brings the constraint of available space for sensor placement. First, it was difficult to deploy more than a comfort station per workspace due to the available space around and between desks. The occupation density ranged from 4 to 8 $m^2/pers$ with very little space for circulating around desks. The tripod with attached sensors was placed in the centre of the room, in the middle of facing desks, away from direct solar radiation and architectural masks or internal partitions. With these constraints, it was impossible to respect the 0.3, 0.6, 1.1m high measurement [109]. Sensors were at the closest to 1.1m high.

$$T_r = \left[\left(T_g + 273\right)^4 + \frac{0.25 \times 10^8}{\varepsilon \times D} \times \left|T_g - T_a\right|^{\frac{1}{4}} \times \left(T_g - T_a\right) \right]^{\frac{1}{4}} - 273 \tag{3.1}$$

Supplier	Model	Probes	Measurements	Timestep
DeltaOhm	HD32.1 – Thermal Microclimate Data Logger	Combined temperature and relative humidity PT100 probe. Globe temperature probe Ø 150mm. Omnidirectional hot wire probe (0 °C – 80 °C)	T_{db}, T_g, V, RH	15 s
Testo	400	CO□ probe with temperature and relative humidity sensors. Globe temperature probe Ø 150mm TC type K. Hotwire thermo-anemometer	T_{db}, T_g, V, RH	15 s
Campbell Scientific + Testo	CR1000	Combined temperature and relative humidity PT100 probe. Globe temperature probe Ø 152mm. Thermal anemometer	T_{db}, T_g, V, RH	1 s

Table 3.3: *Overview of the equipments and sensors used for Indoor Environmental Quality (IEQ) data collection*

Application for Occupants' comfort, clothing and environmental controls

A survey application was designed to assess users' perceived comfort. It is illustrated with the screenshot of figure 3.8. The following parameters are recorded using different scales:

- Thermal sensation is used to describe the occupant's perception of their environment at the time of voting. This vote reflects the physiological aspect of comfort.
- Thermal preference is used to describe the occupant's preferred thermal conditions in the space they are exposed to. An occupant may feel "comfortable" but still prefer a slightly cooler or warmer sensation.
- Thermal judgment (comfort) provides additional insight into thermal sensation through a vote that reflects the psychological aspect of the occupant's thermal environment.

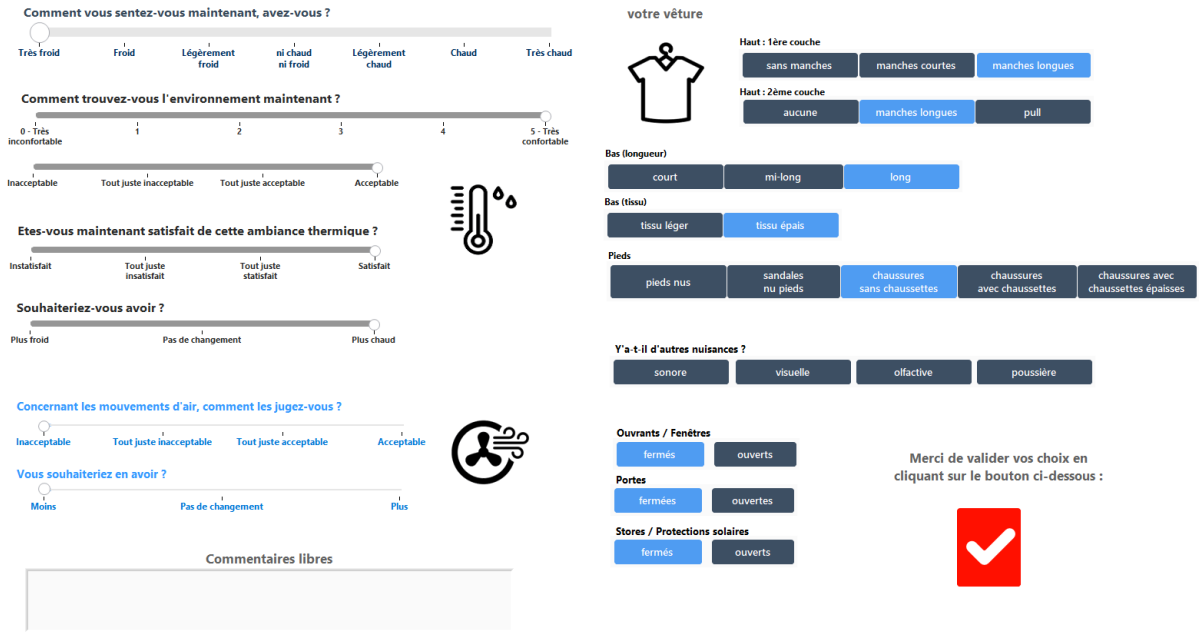

Figure 3.8: *Application developed to record occupants' comfort, clothing and environmental control, in French*

- Acceptability is used to determine whether the thermal condition of the space is considered acceptable. For instance, an occupant may feel slightly warm but still find the condition acceptable.

They are evaluated in real-time by Co-architectes employees via the in-app questionnaire. Air movement comfort is also assessed for each vote. The occupant is asked to evaluate the acceptability of air movements in the room, as well as to indicate their preference regarding air movement. The survey also includes questions about the presence of noise, visual, olfactory, and dust-related nuisances that could impact overall perception. An overall comfort assessment is conducted for each vote, combining all aspects covered in the survey.

The use of openings and shading devices is determined based on the occupants' comfort votes. They are required to complete the comfort state section shown in 3.8, which enables us to record whether solar protections, windows, and doors were used or not for each user vote.

The occupant's clothing level is also recorded in the survey. This data provides insight into the thermal adaptation strategies of users and allows for a better interpretation of the perceived comfort levels. Clothing garments for top, bottom, shoes and extra layers were recorded for each vote and translated to clothing values according to ISO 9920:2009 [100].

The presence of the occupants was not directly recorded. However, they were not allowed to vote unless they were seated at their desks. Furthermore, although this happened anecdotally, it was possible over the course of work weeks that the position of certain employees could change within the same space or from one workspace to another. Real-time updating of a metadata file allows the traceability of subjects within the building.

PULSE physiological survey description

Physiological measurement occurring during the 5 weeks (C01 to C05) of the Level 4 (Comfort Physio - PULSE) campaign consists of the following (equipment is illustrated in figure 3.9):

- Metabolism represents the energy produced by the body, which must be conserved in cold conditions or dissipated in warm conditions. Metabolism depends on the subject's activity in their environment. During "Level 4" weeks, employees wore a smartwatch that provided heart rate data to evaluate metabolic activity.
- Thermo-buttons were used to measure body temperature. They are strategically placed on each subject to determine an average skin temperature (forearms, shins, under the collarbone) and approximate core temperature (under the armpit)
- To evaluate near-body-surface boundary layer conditions, the same type of buttons was used to record air temperature, relative humidity, and mean radiant temperature.



Figure 3.9: *COOLDOWN-PULSE complementary physiological measurement equipment used during specific C_{0i} comfort survey weeks*

Sensory response is outside the scope of this thesis, but subjects' votes and other measurements taken during these periods are used in our analysis. For more information on the results, the reader is referred to the Cooldown publication in [86] focusing on 2023 summer.

3.2.3 On-site data collection risk management and Data preparation

Data preparation is a crucial task prior to any analysis. Maintaining consistency in data preparation prior to analysis is essential to ensure process reproducibility and minimise the risk of error and data loss. The following steps were implemented to achieve these objectives:

Step 1: Data collection and storage : Raw data collection and non-destructive storage preserve the origin of the data. Comfort station data were collected regularly, daily during level 3 and 4 campaigns and bi-monthly for other measurement periods. These data are archived with the original name from the measuring equipment to avoid any handling errors. Data from the voting application was saved directly to a network folder of the Co-architects

company to avoid requiring access to each subject's computers. It was also backed up daily or weekly with original file naming. Energy meter data was sent daily to an FTP server for regular monitoring. A manual data retrieval was performed on a monthly basis. These files are stored in a folder per measuring device or per subject studied.

Step 2: Data consolidation: This step is performed per sensor and is the second step involved in data preparation. For each device or subject, we created a file containing all of its data. This is a consolidated copy of the original data, thus avoiding any destructive manipulation of the raw data. At this stage, cleaning of the remaining inconsistencies is a manual process.

Step 3: Data preparation for analysis: To prepare a dataset for analysing votes and consumption, several subsets of data were created. Several Python scripts were developed to perform these steps.

- A metadata file enables us to specify the measurement periods, the subject's location, and the corresponding measuring equipment for each subject and each measurement campaign. This allows us to manage changes in office allocation or employee turnover/absence.
- An outdoor weather conditions file is created by a query from the laboratory server.
- A voting file, including all subjects, is created based on the subject files. The main difficulty encountered was the initial poor configuration of the application, with minor coding errors. At this stage, the script allows for the correction of the raw data based on the campaign period. Since each vote is timestamped, the closest time data (within 5 minutes) is also entered to standardise the correspondence with the measured data (ambience, usage).
- A clothing correspondence file was developed for upper- and lower-body garments to link the clothing selections available in the application with the types of fabrics commonly worn in Réunion Island (See tables in appendix B for reference). Based on this correspondence, minimum, maximum, and average clothing insulation values were assigned to each possible top–bottom clothing combination according to ISO 9920:2009. Footwear and additional clothing layers were also recorded for each survey response and converted into clothing insulation values in accordance with ISO 9920:2009. Full clothing combination insulation value is then calculated with equation 2.2.
- An indoor ambient measurement file is created to group all the measurement sensors with the same column header. The link to the location of the comfort station can be made using the metadata file.
- A file of air conditioning and ceiling fan usage is also created based on consumption.
- Finally, a final dataset allows all this data to be linked via the metadata file. Each time-stamped vote is linked to the data measured by the sensors and meters. For each vote with environmental measurements, the comfort indices are computed for further analysis.

While setting up the experimental part, we were able to seek advice from experienced researchers in the field of comfort and energy measurement, particularly in the PIMENT Lab and within the Cooldown project teams. Nevertheless, it is essential to keep in mind that the deployment and monitoring of the instrumentation and the human management of the interviewees are onerous, energy-intensive, and time-consuming tasks. We offer brief feedback hereafter:

As mentioned by Payet [195], preparation needs to be anticipated at least a year before the start of actual measurement. A good knowledge of equipment is required to meet the research question's needs. Budget anticipation is also required, as is a good understanding of the financial expense procedures within the institution to avoid any delays.

Full control of the data flow from acquisition to analysis also reduces the risks of loss or inconsistency. This thesis includes training on the equipment used by the owners (ESIROI Engineering School, CTSB PULSE, PIMENT Lab, LEU Réunion) or suppliers (OMEGAWATT, AMARIOT) and several tests before the study begins. Potential risks include data erasure, continuous measurement sensor shutdown, battery and power management, accidental damage risk reduction, FTP server maintenance, communications maintenance, and backups.

Recruiting study subjects is also a task requiring considerable investment and advanced planning. The first step is to integrate the employees' work methods to minimise the intrusive nature of the experiment. Then, it is necessary to present the work, the objectives, and the study constraints for the subjects, and adapt and sometimes find compromises, for example, by reducing the number of comfort stations due to a lack of space in order to limit the impact of the investigation on the study populations. In this process, several discussions or working meetings are necessary to gain the full group's support. Working with office workers in a real-world situation requires adaptability, as the slightest glitch in the machinery can put an end to all or part of the experiment, involving the loss of research data or worse, partial desengagement of the surveyed population.

Another aspect of working with subjects who have a role in the research context -in this case, the action of maintaining their comfort, including the use of air conditioning or ceiling fans- can also introduce bias. It is known that the subject being studied can act differently from their usual behaviour if they are aware of it. (*"Hawthrone effect"*as cited by Payet in her thesis [195])

Although we did our utmost to collect the necessary information for this research, we encountered some setbacks.

- The use of ceiling fans could not be accurately recorded with the desired level of detail due to poor data management from acquisition, transfer to the IoT provider's database,

and consolidation in the PIMENT laboratory database. The subcontracting firm for data acquisition was acquired, and the data was lost during the internal server transfer. This resulted in a loss of information on these systems for our research, highlighting the necessity to manage the whole data workflow.

- The change in financial spending rules within the university prevented us, due to a lack of information, from ordering the desired equipment in time and forced us to borrow some of the measuring equipment.
- The availability of the comfort measuring equipment required great flexibility, and the power failure of one of the devices caused a slight loss of data in the single office.
- The university's weather station did not record wind data for the first quarter of 2024 due to a sensor failure.
- The very low use rate of air conditioning in the summer of 2023 raised significant questions and prompted us to replicate part of the experiment in the summer of 2024. During the latter, we had the opportunity to partially eliminate the use of ceiling fans to better assess air conditioning usage. Although this provided additional valuable results, the thesis work was significantly impacted in terms of planning.

3.3 Comfort, Energy use and cooling systems usage descriptive analysis

3.3.1 Scope of this thesis study

As previously mentioned in section 3.2, the longitudinal survey is broken down into 4 levels (Level 1: ENERGY, Level 2: LOCAL AMBIENCE, Level 3: IEQ/COMFORT, Level 4: IEQ/COMFORT/PHYSIO), all described in Table 3.2. This thesis's scope is limited to Energy Metering (Level 1), IEQ and comfort survey of Level 3 and 4, while complementary physiological measurement is out of the scope of this thesis, as well as local ambience level (Level 2).

The vote breakdown per subject is graphically represented by the heatmap in Figure 3.10. It shows the vote count per year (with the upper plot for 2023 and the lower plot for 2024), per subject (y-axis), and per week of the year (x-axis). The numbers displayed on the plot represent the vote count. Those in white are from periods with both IEQ, Comfort vote, and physiological measurement. Those in black are from other votes with IEQ measurement (referred to as intermediate periods). First of all, the plot helps us to describe the presence of occupants over the two years of the survey. It is evident that subjects 22 and 23 were not part of the study in 2023 and that subjects 17 and 21 left the company in 2024. Over the two-year period, the subject population remains consistent, with 13 people over 15 appearing in both the 2023 and 2024 surveys. Secondly, for most surveyed occupants, and for both 2023 and 2024, the maximum number of votes is during the level 4 weeks (in white figures, weeks 7/12/13 of 2023 and 8/12 of 2024). This confirms the quasi obligation to vote several times a day, with a weekly count ranging from 15 to 37, accounting for subject absences due to out-of-office meetings and construction site visits. Outside of these periods, intermediate campaigns to

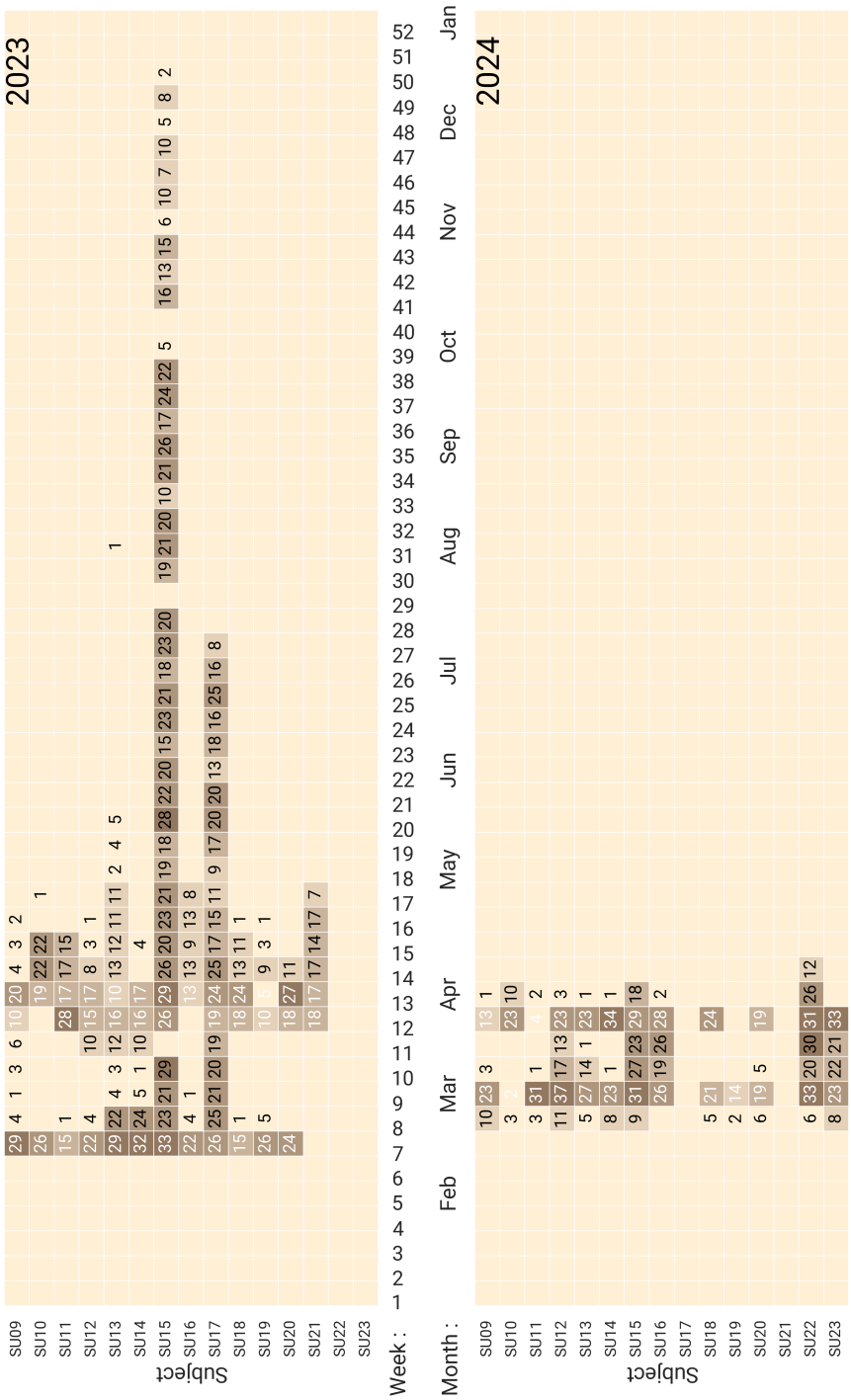

Figure 3.10: *Vote count breakdown per week/month for 2023 and 2024 in Co-Architects building*

enforce more flexible voting rules overall decreased the number of votes from a few to around 20. Two exceptions in 2023 demonstrate the active volunteering engagement of subjects 15 and 17 throughout the year, even though there was no obligation to vote. Nevertheless, the comfort application pop-up had to be uninstalled from the majority of subject computers after the summer period to avoid the distraction it causes. Describing the vote breakdown in more detail, 2023 shows an intense activity for subjects SU11, SU15, SU16 and SU17, which is stable year-to-year in 2024. Also stable year-to-year is the medium activity of subjects SU10, SU12, SU18, and SU20, while there is lower activity for subjects SU9, SU13, SU14, SU19, SU21, SU22, which present few cells with very low vote counts. Overall, while the vote window in 2024 is shorter, active profiles remain engaged and activity drops after the summer period (end of March, beginning of April). We used figure 3.10 to define the summer period of both years to analyse. **To account for the maximum number of respondents' implication, the 2023 summer period was defined between weeks 7 and 17, while the 2024 summer period was between weeks 9 and 13.**

Table 3.4: *Comfort vote counts according to the granularity of measurement for the Co-Architects building*

Campaign	Overall	3 IEQ/COMFORT	4 IEQ/COMFORT/PHYSIO (Pulse)
C01	299	**240**	236
C02	194	**169**	143
C03	239	**234**	200
C04	310	**286**	273
C05	284	**260**	237
$C0_i(Subtotal)$	1326	**1189**	1089
Intermediate	1806	**1250**	0
Total	3132	**2439**	1089
Selected Intermediate summer periods	1116	**722**	0
Total selected summer periods	2442	**1911**	1089

The vote breakdown for each campaign type of the Coarchitects building is described in Table 3.4. The first column *"Overall"* represents the number of votes recorded for the selected campaign. *Level 3* for IEQ/Comfort and *Level 4* columns that, in addition to level 3, have physiological measurement. It is noteworthy that the level 4 count is included in the level 3. We want to show the part of the votes that include both complete IEQ measurement and physiological measurement here. This is important to note as context because, during physiological measurement, occupants had to vote between 4 and 8 times a day, whereas the voting rule was more flexible during intermediate / level 3 periods. *Selected Intermediate summer periods* and the combined *Total selected summer* show the part of the data chosen for

this PhD study (2023: weeks 7-17 and 2024: weeks 9-13).

Two scopes are defined hereafter: the first is the most extensive scope, which is composed of the maximum number of votes in the predefined summer periods. The second narrowed down to the summer periods when IEQ measurements were available.

From the above-mentioned table 3.4, several key figures can be extracted. The total vote count recorded across all campaigns is 3132. Intermediate periods account for 57 % (1806) of the votes, and level 4 weeks for 43% of the votes (1326) (level 4 Ci periods during which extra sensory measurement is performed on subjects). When focusing on previously defined summer periods, the total count reached 2442 votes. **This is the most extensive dataset of our study, aiming at describing the building thermal comfort overall without IEQ-based analysis.**

When considering IEQ measurement, the overall vote count of 3132 decreased to 2439, composed of 1350 (77,9 % of the total count) and 1,089 with physiological measurement (34,8 % of the total count). While considering only level 3 and 4 surveys, these surveys account for 2439 votes, with 55 % (1250 votes) being for intermediate and 45 % (1089 votes) for C0i weeks. Physiological coverage within C0i (Level-4 vs. Level-3) is very high: for example, in C04, about 95 % of IEQ/Comfort votes are paired with physiological measurements, in C01, about 98 %, and in C02, about 85 %. As is easily understandable, all C0i weeks are selected in the 2023 and 2024 summer periods, so 100 % of level 4 votes are included in the survey. Narrowing the summer period of intermediate campaigns to account for population representativity brings us to use 722 intermediate votes. In total, 1911 votes are selected in this dataset with IEQ data. **This is the second, less extensive dataset aiming at model prediction-actual vote comparison or control IEQ-based analysis.**

Another aspect to evaluate the consistency of the recorded votes is to analyse their distribution by working hours. Let's recall that the office opening hours are from 7:00 am to sometimes 9:00 pm. However, most employees' typical working day starts around 8:00 and finishes at 6:00 pm, with a flexible 1-hour lunch break between 12:00 and 2:00 pm. Figure 3.11 presents, as a heatmap, the votes per working hour (x-axis) and per subject (y-axis). The last row consolidates the hourly votes for the whole surveyed population. First, it illustrates that there are almost no votes (1) before 7:00 am and very few after 7:00 pm. Overall, 92% of the votes are in the 9:00-5:00 period and 96% in the 9:00-6:00 period. The highest peak in votes occurs between 8:00 and 9:00 am, after employees arrive, with a minimum of 8 votes (subject 20) and a maximum of 48 votes (subject 15). In this highest hour, a total of 355 votes are recorded. Morning votes from 8:00 to 12:00 represent 44% (1083 votes), lunch time votes represent 11% (271 votes), and afternoon votes represent 40% of votes. As far the subject homogeneity is concerns, eight subjects (SU12, SU13, SU14, SU15, SU16, SU17, SU22, SU23) shows a broad hourly coverage (AM+PM), three others present some inconsistency in voting engagement with several time slots less- or uncovered (SU10, SU11, SU18). The four remainings shows a sporadic presence or engagement that could be explained by lots of

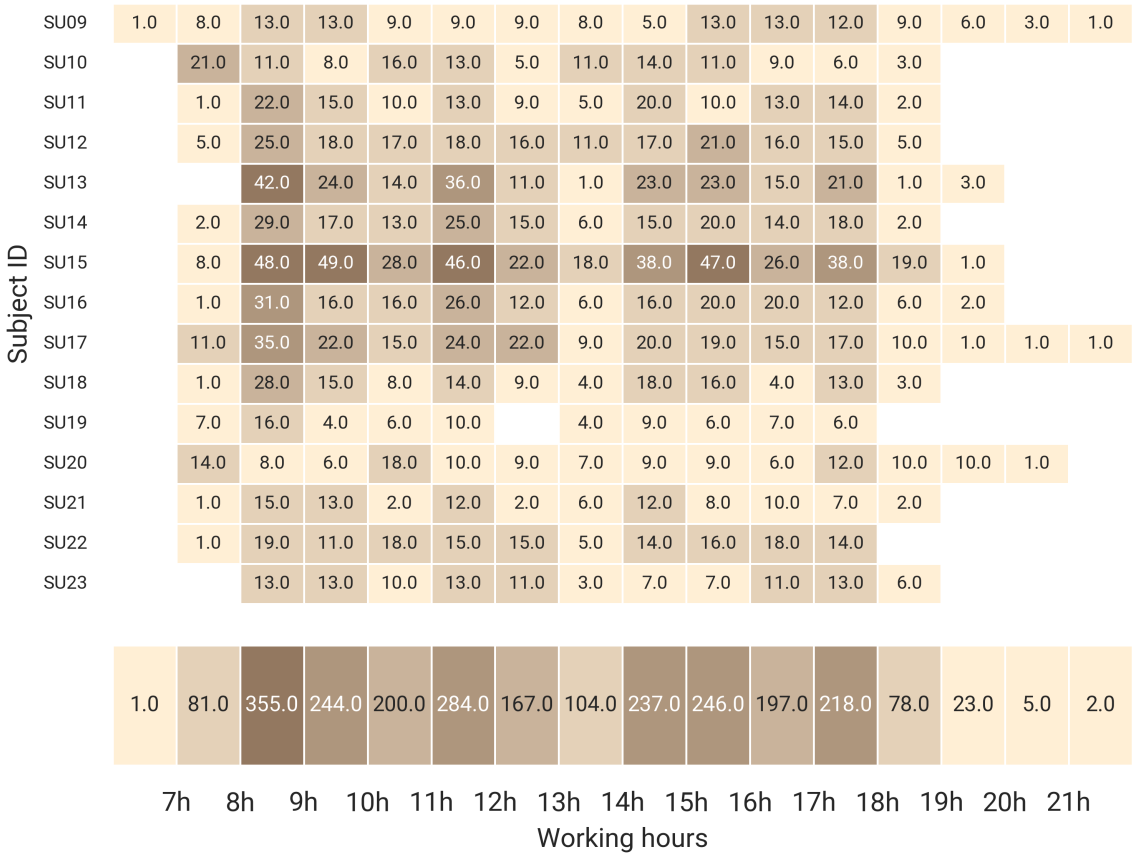

Figure 3.11: *Vote count breakdown per working hour per subject in the Co-Architects building*

out-of-office meetings (SU09, SU19, SU20, SU21).

To sum up, on how we created the two datasets for different purposes in this study:

- The dataset was overall composed of 3132 votes, but after selecting consistent summer periods, this was reduced to 2442 votes.
- When not interested in IEQ, we maximised the number of votes, choosing all entries of the selected summer periods. This led us to a total of 2442 votes. Those votes are used to describe how the building is (or is not) comfortable without any causal effect analysis of IEQ measurement. This is the most extensive dataset.
- It was nevertheless important to us to also maximise the number of comfort votes with IEQ measurements (level 3-4) and from a consistent population sample. Both IEA/Comfort votes with and without sensory measurement were included in this PhD study scope. Over those 2442 votes, we needed only vote with all IEQ measurements (T_{db}, RH, T_g, v), which reduced the number of exploitable votes to 1911. Of which, 57% (1089) are from specific level 4 physiological measurement, with a strong obligation to vote. This led us to 1911 votes used for IEQ-based analysis or *actual vote - model prediction* comparison (later described in chapter 4). This is the least extensive dataset in vote count, but with 100 % IEQ measurement
- Hence, votes are from approximately half of flexible voting rules and half of strong voting rules (Weeks $C0i$), which is a key aspect for ensuring data consistency.
- The daily vote distribution is balanced between morning and afternoon, with very few outliers outside of typical working hours. It is also consistent for the majority of surveyed occupants.

3.3.2 Temporal description of climatic conditions

Overview

On an annual scale, the three figures 3.12, 3.13 compare the measured outdoor and indoor temperatures, and the relative humidity of the building, respectively. Let's recall that meteorological data are recorded 1km away from the building location at La Reunion University (Campus of Terre Sainte). Additionally, plotted indoor conditions include the Mixed-mode Open-plan office, where the ambience was monitored over a year-long period.
The first two plots use a box plot to represent the monthly distribution of temperature and relative humidity. Boxplots allow for a quick overview of the distribution range between the extremum, the median value and all four quartiles. The main "box" represents 50% of the distribution, surrounded by the remaining lower and upper distribution tails, each of which accounts for 25%. Wind recorded velocity is plotted in a stripplot as in figure 3.14 and is described in the following paragraph.

Figure 3.12 shows that the indoor temperature (in brown) remains higher than the outdoor temperature (in yellow) throughout the year from February 2024 to April 2024. The low monthly variation in indoor temperature is a sign of a space that is thermally insensitive to

solar radiation (properly shaded). It should be noted, as previously mentioned, that the MM Openspace is constructed with a white concrete frame on the ground floor and is primarily protected from vegetation and solar screens. It is poorly ventilated, and the occupancy density is 5.5 m² per person, which is high. The electrical equipment doubles the internal heat gain of people with desktop workstations and dual screens.

Indoor temperatures are systematically above 26°C during the austral summer period (December to March). Fifty per cent of the readings were between 28 and 30 degrees, suggesting relatively low air conditioning usage, or at least with setpoints below 26°C. Internal temperatures regularly exceed 28°C during the off-season, particularly between May and June, and October and November. The low interior extremes are quite far from the temperature records at the weather station, which presumes that internal conditions are maintained when the office closes at night. The lack of night ventilation would not allow the space to cool down thoroughly, and/or the internal heat gains would be maintained during the night. In winter, from June to September, internal conditions remain in the 24-26.5°C range, which is typical of comfortable ASHRAE conditions, even if recorded low temperatures at the station are under 20°C, presumably at night, benefit from envelop thermal mass.

At the other extreme, the maximum exterior temperatures recorded appear to be well smoothed by the building envelope, and the interior conditions rarely exceeds the exterior conditions. However, the interior readings can be very unfavourable to occupants comfort, with peaks at 33°C and more in February 2023 and January 2024, for example. Note that during the summer period, although 50% of the interior conditions are between 28 and 30°C, 25% of the conditions recorded are between 30 and 33° in February, 30 and 32°C in March and April. The early-year period is particularly impacted by cyclonic conditions, with three cyclones occurring during the measurements: Freddy: February 4-24, 2023, Belal: January 12-19, 2024, and Candice: January 25-28, 2024, which explains the high extremes above 33°C.

Relative humidity, as shown in figure 3.13, conditions generally follow a reverse trend to temperature, with a typical range (50% of the distribution) around 70% relative humidity, plus or minus 5%. However, the range in both summer and winter is 45 to 90% relative humidity indoors. Outdoor weather conditions are 5 points higher than indoors, with distributions from 50 to 100%. The range is also greater, around 78% median at plus or minus 10%. The driest months are in the winter period from June to September, and the wettest, corresponding to the hottest conditions, are during cyclone periods. Comparing summer 2023 and 2024 highlights no difference in temperature with a median around 29°C for February, March and April but reveals an 8 to 10 percentage point difference in relative humidity, pushing the median of the former month around the 75% threshold.

Regarding air movement conditions, the figure 3.14 represents the recorded indoor air velocity at the centre of each room at 1.1m above the floor. A focus is made on the summer months only, where records were available, namely February, March and April of both 2023 and 2024 summers. The fully cross-naturally ventilated office presents air velocities up to 3 m/s for a few exceptions, but is mainly in the $[0: 1.8\ m.s^{-1}]$ range in 2023. The MM Single

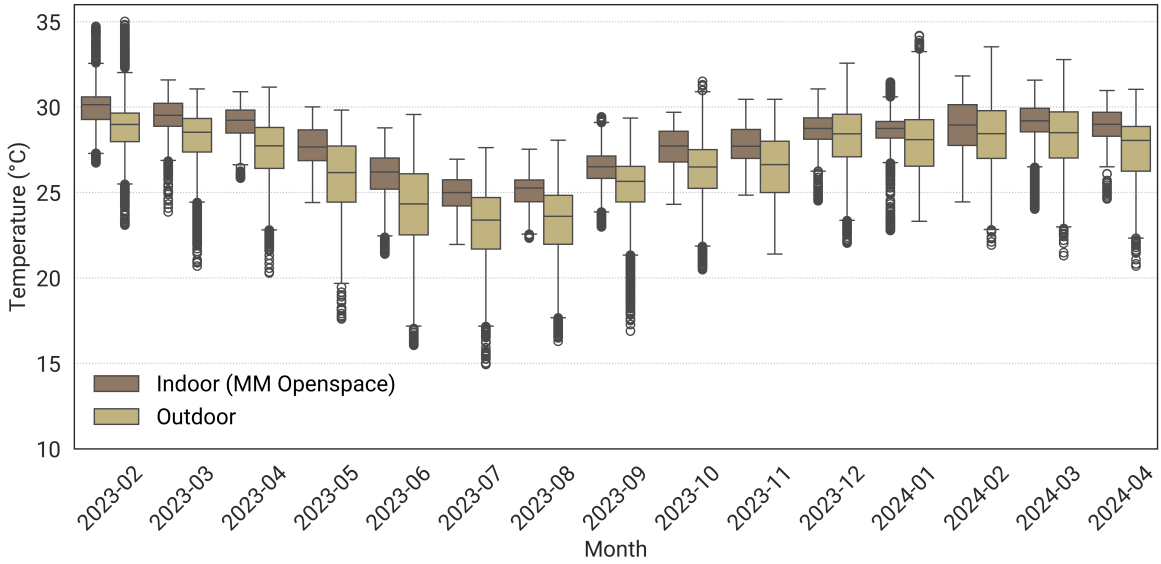

Figure 3.12: *Monthly comparison between mean indoor (MM Openspace) and outdoor temperature*

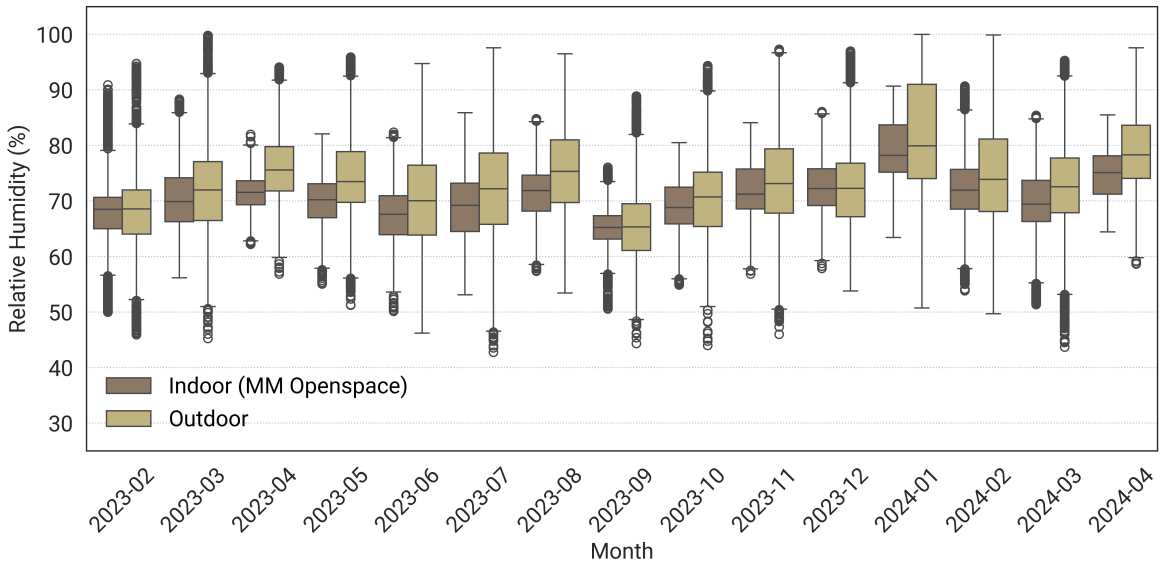

Figure 3.13: *Monthly comparison between mean indoor (MM Openspace) and outdoor relative humidity*

office has a record for 2023 only because of a last-minute equipment failure. It follows the same pattern as the NV multi-office, but with a slightly lower maximum velocity. For both spaces, the level of usage of the ceiling could be distinguished at around 1.2 $m.s^{-1}$, 0.6 $m.s^{-1}$ and 0.2/0.3 $m.s^{-1}$ for the NV multioffice. Points in between are the conjunction of the ceiling fan use and Natural ventilation passing through. It is a bit more difficult to see those patterns on the MM Single office while in use, given that a range of 0.5-0.8 $m.s^{-1}$ airspeed is still detectable. It is noteworthy that the single office has two lateral openings that can influence the ceiling fan airflow differently from the cross ventilation of the NV multioffice. Additionally, air conditioning can be used simultaneously with the ceiling fan, both blowing air on the sensor at the same time. The MM openspace shows a distinctive pattern in 2023 against the two other spaces. First, the range of recorded velocities is from 0.1 to 2.5 $m.s^{-1}$. It barely shows null velocities, mainly because a small NE facade jalousie window can remain open even if the office is empty (around 7:00, for example). Ceiling fan usage patterns can be distinguished at around 0.3/0.4 $m.s^{-1}$, 0.5/0.7 $m.s^{-1}$ and 1.2/1.5 $m.s^{-1}$. Again, in-between and over-placed points are a combination of both ceiling fan use and natural ventilation, and sometimes, air conditioning airflow. The 2024 pattern for the MM openspace can raise questions. Indeed, the recorded range of velocity is far less extended, up to 1.2 $m.s^{-1}$ only, so twice as less as in 2024. One can further note that $0m.s^{-1}$ records highlight the closure of the single jalousie window. Both patterns of ceiling fan use, giving 0.3/0.4 $m.s^{-1}$ and 0.5/0.7 $m.s^{-1}$, highlight the use of only two ceiling fan speeds. Because air velocities in the NV office and the MM open space are of the same order of magnitude, we assume it is not an equipment issue, even if the sensor might have been slightly displaced by a few centimetres. Hence, we can assume that NV+CF mode was far less used during summer 2024 than in 2023, depriving the space of a very high air velocity record. Plus, because of the use of AC, occupants might not have used the highest CF speed given, approximately 1/1.2 $m.s^{-1}$ to avoid draft. Regarding outdoor air velocity conditions, half of the winds are recorded between 0 and 4 $m.s^{-}1$ in summer, with a median above 2 $m.s^{-}1$. 50% of the time, conditions are above the 2 $m.s^{-}1$ threshold, which suggests favourable high trade winds for natural ventilation. Comparing the summers of 2023 and 2024 reveals different patterns. Despite the potential for external wind, indoor spaces exhibit almost no air movement, indicating a lack of ventilation or air circulation mechanisms. In winter, outdoor air velocity drops moderately at 1.5–2 m/s median, but remains significant. Meteorological data from the PIMENT Lab station cannot shed light on the discrepancy between 2024 NV Multioffice and MM Openspace because the direction sensor was out of order from February 2024.

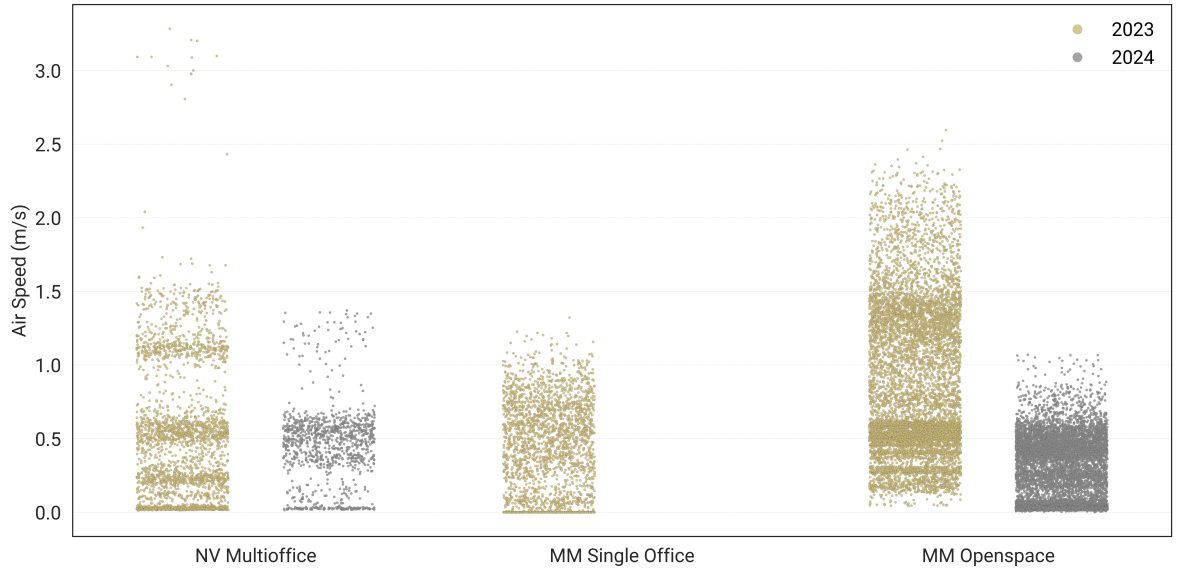

Figure 3.14: *Comparison of recorded mean indoor air velocity at 1.1 m in operated spaces from 7:00-21:00*

Typical days of selected periods

To better understand the climatic condition evolution throughout a day, figure 3.15 shows the evolution of temperature (solid line) and relative humidity (dashed line) of all three spaces (MM Single Office (blue), MM Openspace (green), and NV Multioffice (orange) over the course of the day from midnight to midnight. These are plotted against outdoor temperature and relative humidity recorded at the weather station (in black). Underplotted are the Adaptive model limits for EN16798, represented by red dotted lines, from the lower to upper line: neutral temperature, cat I, cat II, and cat III limits. The ASHRAE ones are plotted in dotted blue lines, respectively, from lower to upper lines: neutral temperature, 90 % acceptability and 80 % acceptability limits. The 27th of March 2023 is typical of a day with no air conditioning in use. Only outdoor conditions (black) and MM Open Space indoor (green) zones are plotted throughout the day; the other zones were not equipped with an IEQ station at night. Outdoor temperature starts from 22 °C around 6 am and abruptly rises to 27°C around 9 am. Users coming to the office already suffer from high temperatures in the morning. All spaces benefit from a temperature of around 26-27°C when windows are opened upon arrival at their desks. Then the outdoor temperature rises more slowly up to the 29-30°C range. Indoor conditions are similar, even if the zone orientation to the sun course, opening, and envelope composition differ. Until 12:00, indoor conditions remain in a 1K range for all three zones. MM openspace, being the least ventilated and the most densely occupied, remains the warmest of the three, quickly reaching the ASHRAE 90 % acceptability and catII EN16798 limits. NV multioffice is almost as densely populated as the MM Openspace and follows its trend in the morning. Nevertheless, it benefits from overheating discharge thanks to natural cross ventilation and wooden-built framing offering a climate-responsive envelope. While being at first floor level, the MM Single office remains cooler in the morning than outdoors but is subject to overheating when passing noon, following the same trend as the

wooden office, decreasing temperature when the sun goes down. It is worth mentioning that the MM Open Space is poorly ventilated (with no cross ventilation) during the day, as well as at night, considering the temperature does not significantly decrease to outdoor conditions. Other spaces, even if the data is not available for the whole night, show a clear decreasing trend from 17:00. Nevertheless, the indoor/outdoor temperature difference remains huge when the office is closed, suggesting poor evening ventilation, internal gains (IT equipment), and thermal mass storage.

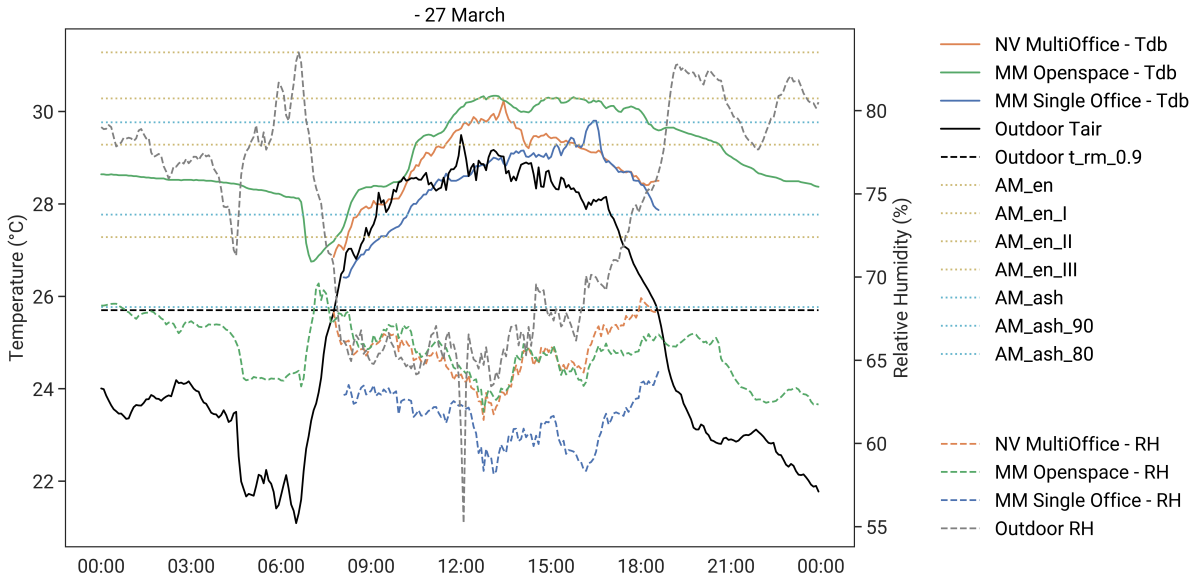

Figure 3.15: *Temperature and relative humidity of Co-architectes spaces against outdoor conditions for day 2023 March, 27 - typical NV usage with ceiling fan.*

Figures 3.16 and 3.17 show examples of air conditioning use during the day with two different usages. Figure 3.16 data is recorded during the full adaptive opportunities campaigns of 2023. At this stage, morning trends are similar to the day before (see figure 3.15), but the MM Single Office, with only one person deciding on cooling system use, starts using the AC at 27°C setpoint from 13:00 to almost 18:00. For AC use, it is mandatory that fans are also in use. Other spaces, while recording similar warmer indoor conditions, remain on the NV option, relying only on fans as a complement to cool down. Another typical example is given for the 2024 field survey on March 19. During this period, using a ceiling fan was not a viable option for maintaining comfort. With particularly hot outdoor conditions (up to 32°C), the common decision to use AC at a setpoint of 26°C is shown on 3.16 from 13:00 to 19:00 (green solid line). This action tended to lower relative humidity below 60% while the NV space remained around 70%. (MM Single Office occupant was absent on that particular day, so no ambience record was made). Both curve patterns when AC is ON are not the same because in the MM Singleoffice, the AC unit is dedicated to a single 8 m^2 office, so the sensor being close to the unit can precisely capture the behaviour of the cold airflow as illustrated by the blue solid line oscillation in Figure 3.16. In the MM openspace, the sensor is more than 5m far from the fan unit, and air can premix before reaching it. It is illustrated by the solid green line fuzzy

pattern from 12:00 on figure 3.17.

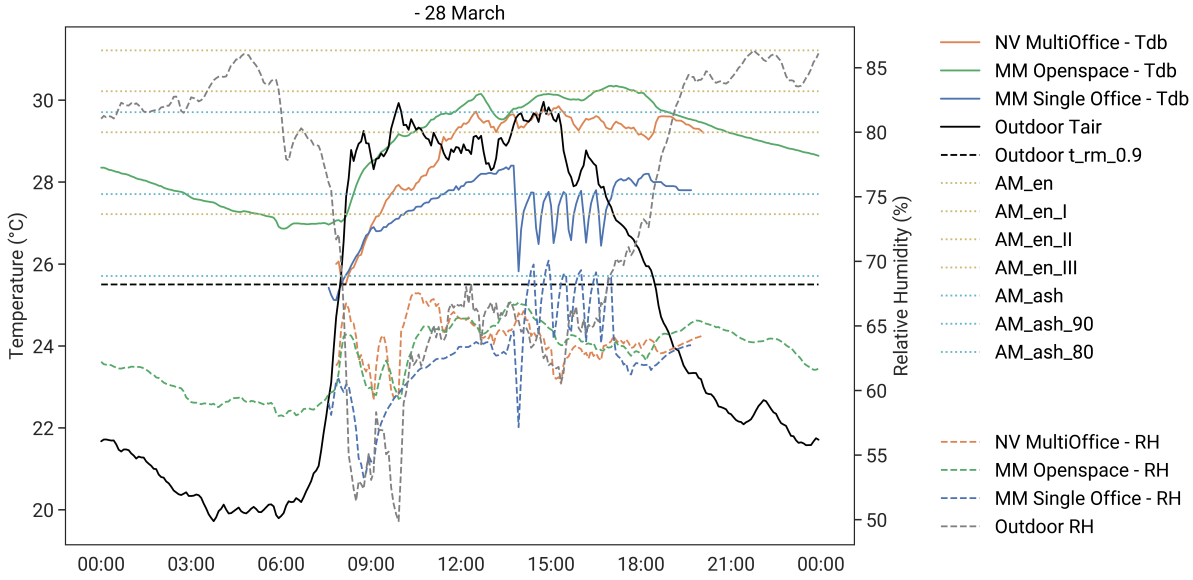

Figure 3.16: *Temperature and relative humidity of Co-architectes spaces against outdoor conditions for day 2023 March, 28 - typical AC usage with ceiling fan.*

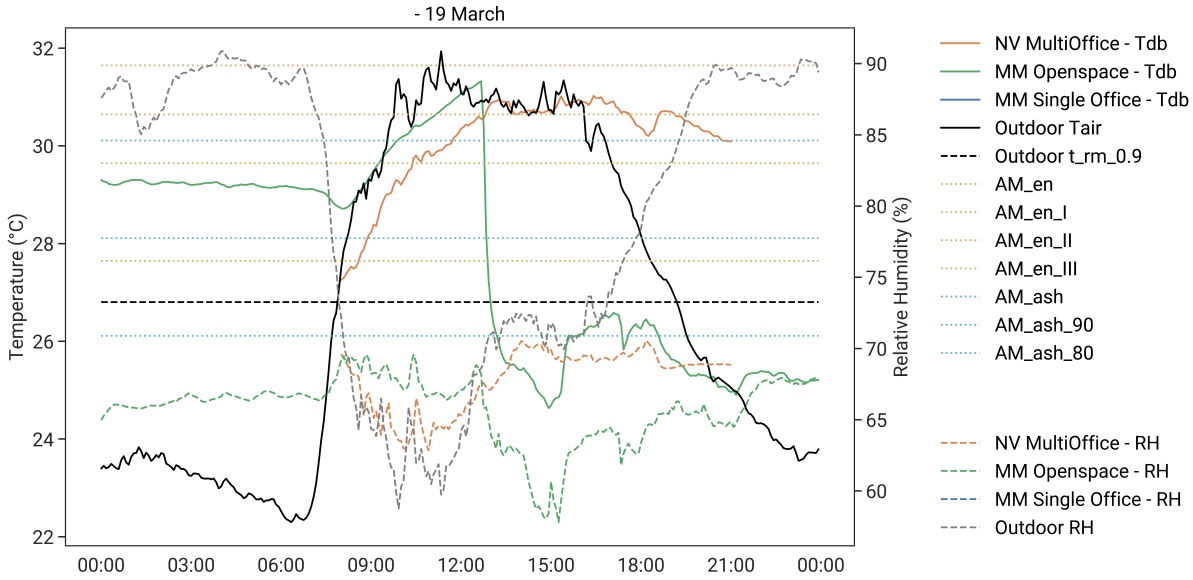

Figure 3.17: *Temperature and relative humidity of Co-architectes spaces against outdoor conditions for day 2024 March, 19 - typical AC usage without ceiling fan.*

3.3.3 Overview of comfort conditions

The aim of this section is to describe the selected **summer period surveys** in terms of comfort. It is based on the more extensive dataset of 2442 votes. It is worth noting that in 2023 occupants had continuous access to fans, whereas in 2024 fan use was disabled only during two

designated test weeks. In all figures, the 2023 and 2024 summer periods are presented on the left and right, respectively. For plotting clarity, they are mentioned as *"2023" or "2024"* only. Each subject is plotted on the x-axis, even if they were not present from one year to another, to maintain consistency in the graphical representation. Seven types of votes are proposed; they are described previously in section 2.1.1. Figure 3.18 shows recorded Thermal Sensation (TS) and Thermal Comfort (TC) vote for both periods. Figure 3.19 shows Thermal Acceptability, Thermal Satisfaction and Air Movement Acceptability. Figure 3.20 shows Thermal Preference and Air Movement Preference. Votes count per subject and year are already presented in a previous section in figures 3.10.

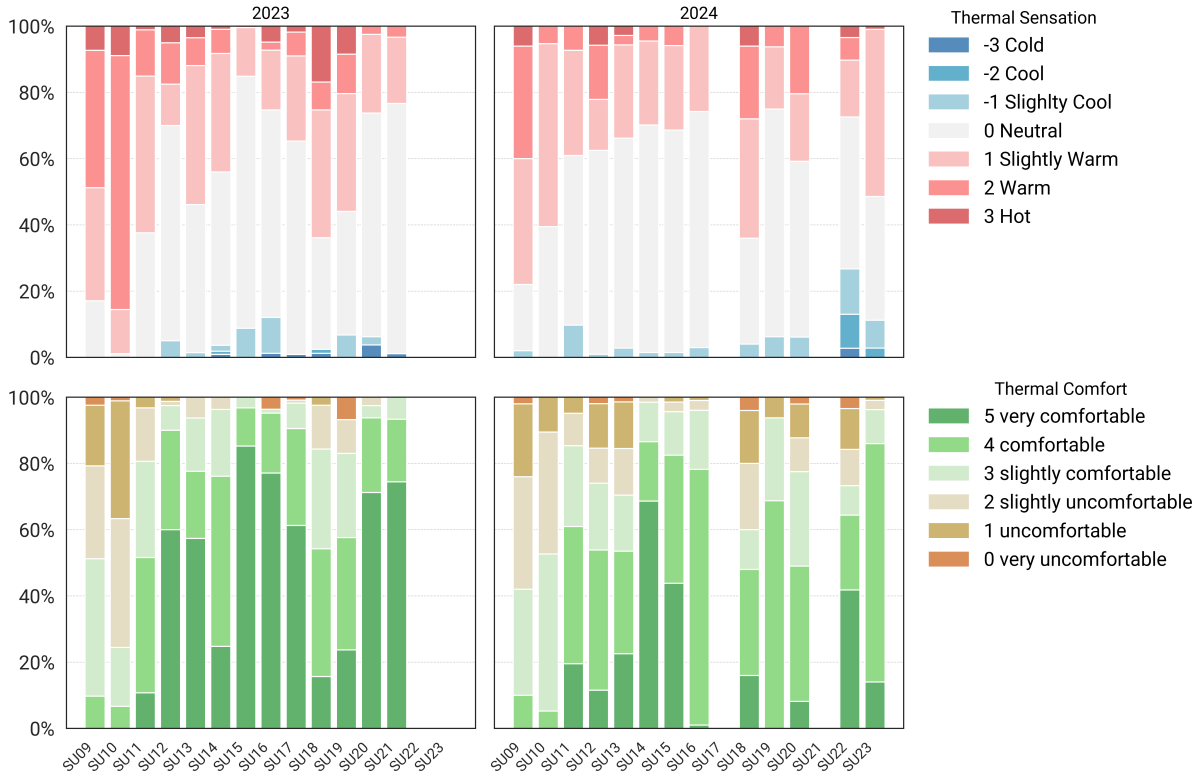

Figure 3.18: *Thermal sensation and comfort votes per subject for 2023 and 2024 periods*

As far as thermal sensation is concerned in 2023, most subjects do not entirely vote *neutral* but skew toward *slightly warm* to *warm* (SU11, SU13, SU14, SU14, SU18, SU19) for more than 50% of the time. More balanced distribution with noticeable *neutral* share over 65 % can be observed for SU12, SU15, SU16, SU17. They are also less prone to *hot* votes to a lesser extent (<10 %). Two subjects (SU09, SU10) show a more pronounced, if not very pronounced, sensitivity to *warm* and *hot* sensations with less than 20 % of *neutral* votes, a bit more for SU18. It will be described in the next section, but those subjects are located in the open space at the total opposite of the AC indoor unit, which might explain part of the sensation deviation. This pattern for people feeling warm-to-hot is reproduced in 2024, while the rest of the population is this time more consistent with a stronger *neutral* presence across all subjects. New 2024 SU22 subject presents a very high proportion of cold votes (25 %) and the same proportion of

warm-to-hot votes. This subject is located in the open space just under the AC indoor unit.

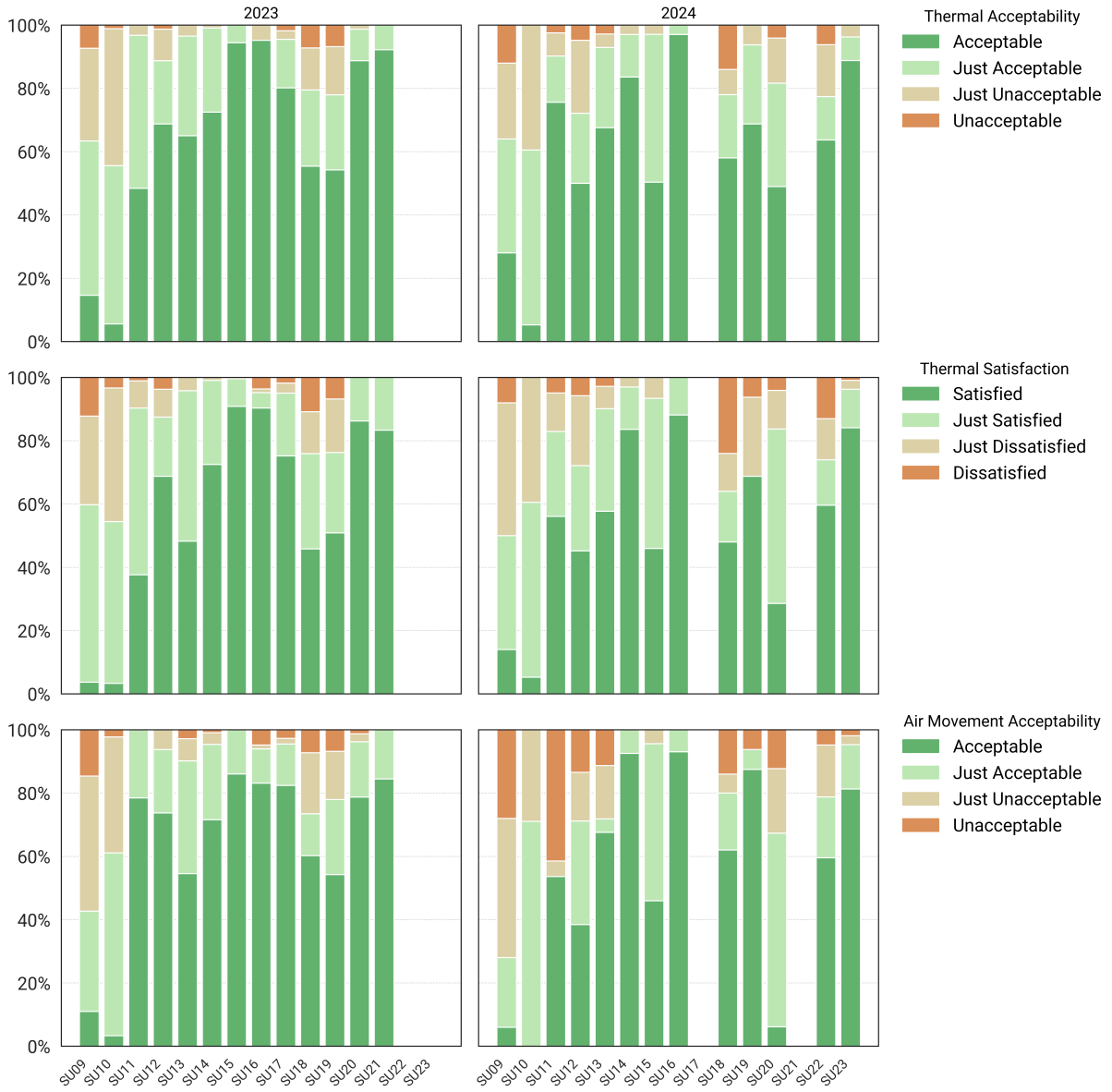

Figure 3.19: *Satisfaction and acceptability votes per subject for 2023 and 2024 periods*

For both 2023 and 2024, thermal comfort follows the same trend as thermal sensation. Overall pattern holds the majority of *comfortable* conditions in green (60-80% for most subjects), with still some notable discomfort fractions (SU14, SU15, SU20). It is essential to note that even when thermal sensation is on the right side of the scale, people can still feel comfortable. This is clearly illustrated by SU09 with more than 50% of comfortable votes. Across both years, most of the subjects surveyed tolerate warm conditions with high comfort, though some still consistently report less comfortable conditions (SU09, SU14, SU15, SU20, SU21)

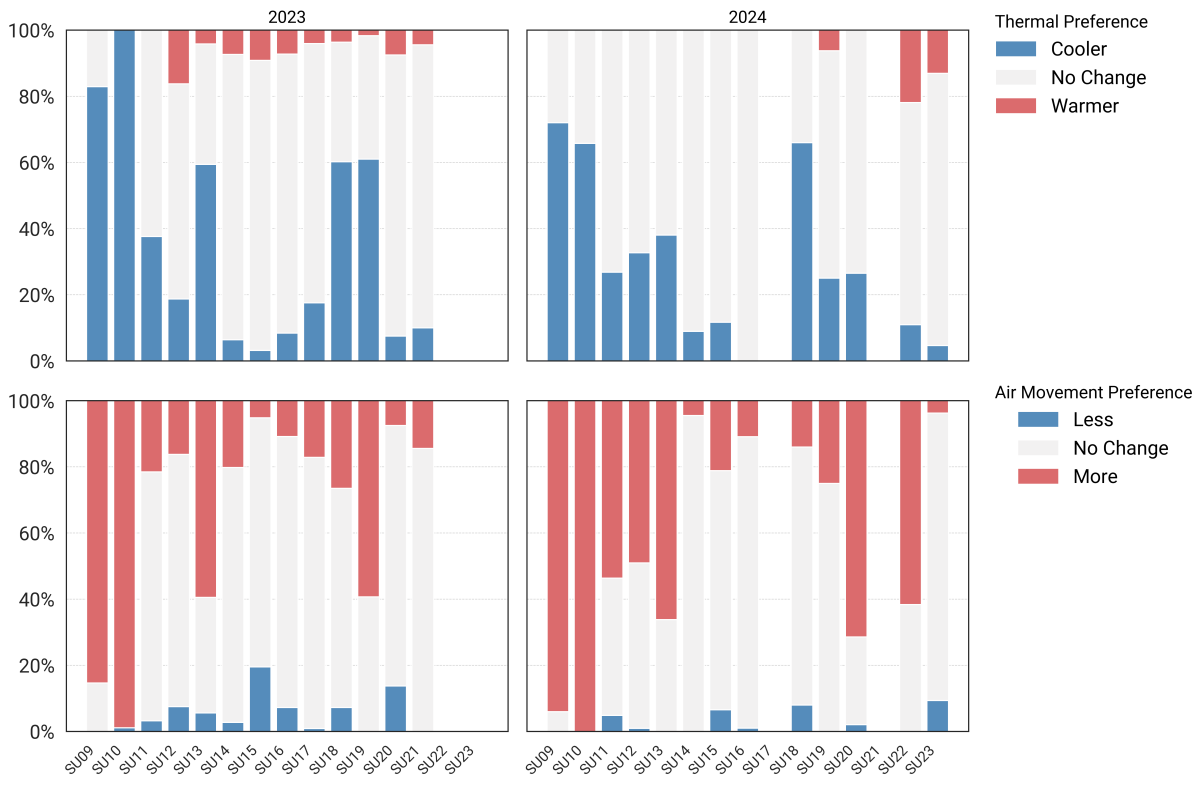

Figure 3.20: *Preference votes per subject for 2023 and 2024 periods*

Both 2023 and 2024 periods are dominated by acceptable and satisfactory conditions as illustrated by figure 3.19. They follow the same trend as thermal sensation, giving around 60 % of overall satisfaction (*Acceptable* + *Just Acceptable*) for two subjects in 2023 (SU09, SU10) and overall 80 to 90 % of satisfaction for the rest of the surveyed population. 2024 seems a bit less acceptable and satisfactory, around half of the population being *Disatisfied* or *Just Disatisfied* 25 to 40 % of the time. This could partially be explained by the lack of air movement in the space, as the Air Movement indicator showed an increase in unacceptable air movement conditions in 2024, with most of the population rating more than 30% unacceptability, while in 2023, only 4 persons were complaining about a lack of air movement with very few *Inacceptable* vote. This can be directly correlated with recorded indoor air velocity being almost half in 2024 than in 2023, certainly due to the lack of natural ventilation as shown previously in figure 3.14.

Overall, subjects, even if they remain comfortable, request for cooler conditions 20 % of time with a strong demand from subject with high thermal sensation votes (SU09, SU10) and to a lesser extent, SU13, SU18 and SU19 as shown in figure 3.20. This demand is directly correlated with air movement as shown in the second plot of the same figure. 2023 shows moderate demand of 20 % average willing more air movement, while it is exacerbated in 2024, with half of the population willing more air movement 50 % of the time. It is rare to find people wanting less air movement.

Overall, most subjects tolerate warm conditions and remain comfortable. There are 5-6 critical subjects, depending on the year, consistently reporting lower acceptability, more discomfort, and stronger preferences for cooling and airflow. Other neutral subjects show consistently high satisfaction, few complaints, and balanced thermal sensations. Although general comfort is high, some individuals demand cooler conditions and more airflow, indicating a systematic warm drift in the environment that raises questions about how the systems are controlled. In large spaces, all cooling system activation is a community decision.

3.3.4 Comfort spatial analysis

We now propose presenting the same dataset from an alternative perspective to evaluate the influence of desk location. This task was not possible by analysing by subject because several employees left the company in 2023, and some got assigned to another desk in 2024.

As in the previous section, figure 3.22 present Thermal Comfort and Thermal Sensation for both 2023 and 2024. Figure 3.23 presents Thermal Acceptability and Satisfaction, as well as Air Movement Acceptability. Finally, Figure 3.24 shows Thermal and Air Movement Preference. All counts are plotted against sub-space location as described in figure 3.21. Apart from the MM Single Office, the layout plan proposes subdividing the space, with each containing two desks. In this regard, the NV Multioffice is divided into two sections: a two-desk facing the wall, with louvres opening on either side and access to one CF, and a double desk in the center of the room, with users facing away from the windows and access to the other CF. One should keep in mind that there is a unique warm-mounted command for both CF. The MM Openspace is divided into four sub-spaces, beginning on the left, where both desks are positioned under a ceiling fan and an AC indoor unit. The centre right space faces away from the AC and the ceiling fan, but is close to the double-pane glazed door. The centre right is approximately 6m from the AC unit, but benefits from a CF and another glazed door. Lastly, the extreme right sub-space benefits from a double-pane full-height opening but is somewhat distant from the CF and 8m from the AC unit. The vote counts for each space, presented in Table 3.5, is significant.

Table 3.5: *Comfort observations breakdown by office space subdivision*

Space	Observations 2023	Observations 2024
multioffice_center_NV	281	83
multioffice_wall_NV	166	151
openspace_center_left_MM	252	178
openspace_center_right_MM	173	145
openspace_left_MM	341	283
openspace_right_MM	172	88
sgloffice_MM	80	49

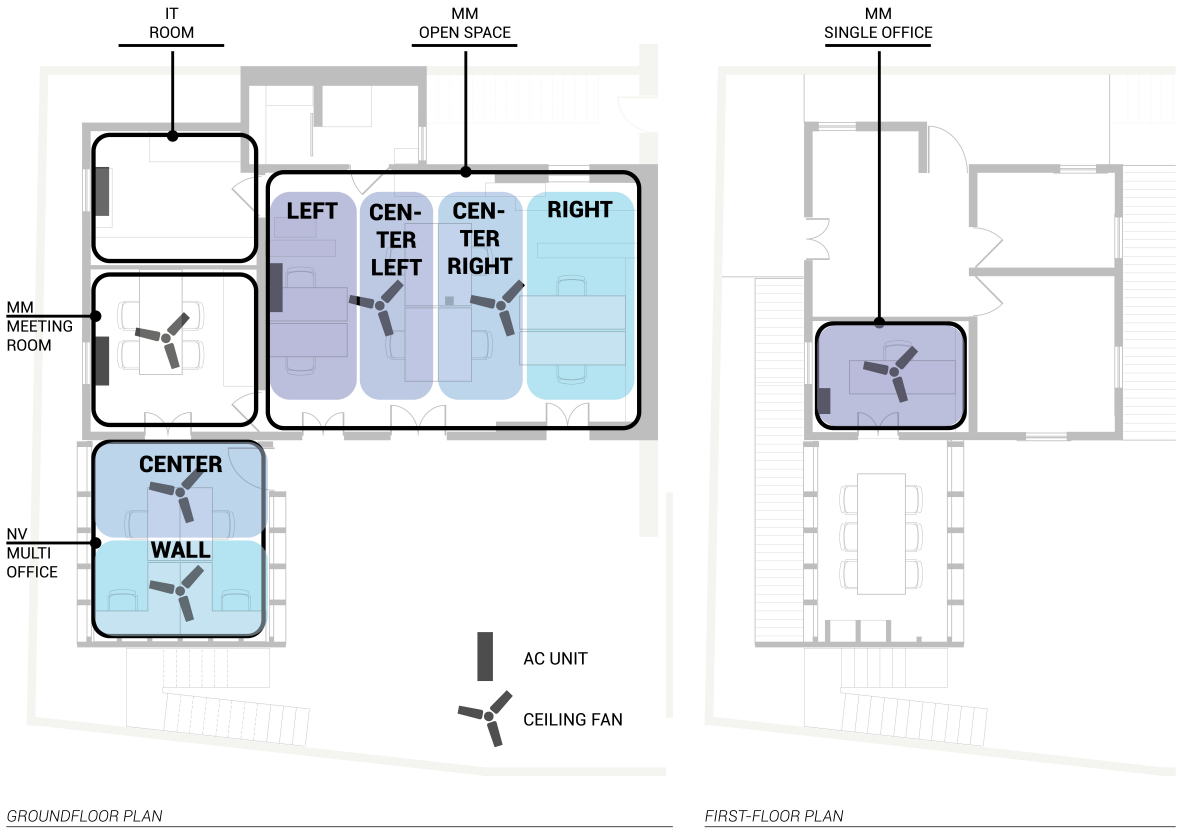

Figure 3.21: *Layout plan of Coarchitectes with spaces subdivisions*

The previous section 3.3.3 has shown that overall, all subjects remain comfortable even if sensations tend to shift to the right side of the scale. Digging into the dataset by space location brings new information on how the building behaves.

Starting from the Naturally Ventilated Multioffice (NV Multioffice), both sub-spaces (wall and centre) are consistent in thermal sensation and thermal comfort in 2023 and 2024. Sensation is rated as *Slightly warm* for 25 % of the time, and between 10-15 % *Warm and Hot*. More than 50 % of votes are rated *Neutral* and very few votes fall on the cold side of the scale. Nevertheless, while the sensation distribution is equivalent for both years, in 2024, voters were less likely to vote *Very Comfortable* than in 2023 and more likely to choose *Comfortable*. As far as acceptability and satisfaction are concerned, only 10-14% were unacceptable votes for 2023 and even less in 2024. Dissatisfaction remains in the same order of value. Air movement in the NV multioffice is also stated as *Acceptable* for more than 70 % in 2023 and 80-85 % in 2024. The combination of full-height louvre-type windows for natural ventilation and ceiling fans seems sufficient to satisfy the four people in the NV part of the building. Nevertheless, they still claim *Cooler* thermal preference of 25/30 % in 2023 (15/20 % in 2024), and would ask for more air movement for a bit less than 20 % of the votes, which is directly correlated to Air Movement Acceptability, thermal satisfaction, and thermal acceptability. Overall, including all indicators, the NV multi office suits the users' needs in summer for 80 to 90 % of the votes.

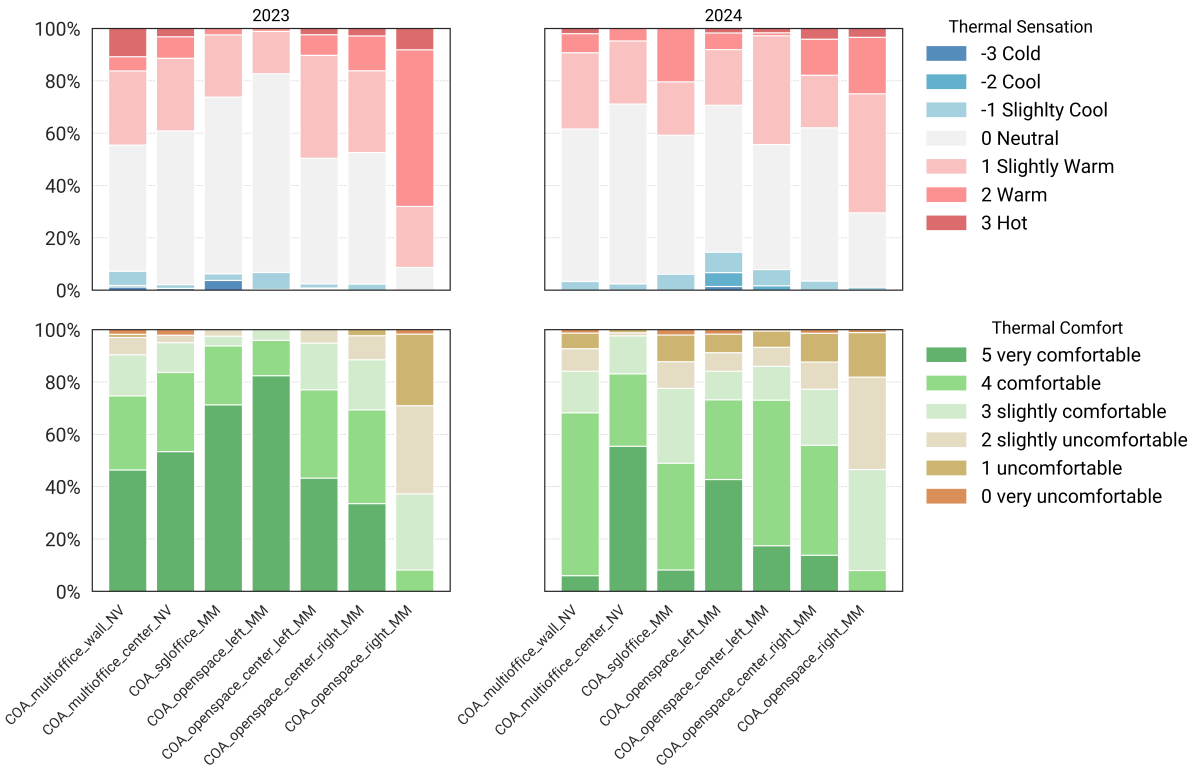

Figure 3.22: *Thermal sensation and comfort votes per space location for 2023 and 2024 periods*

The second space to explore has a totally different pattern. The Single Office is a Mixed-mode operation with cross natural ventilation, a ceiling fan and an AC system to help achieve ultimate comfort in harsh conditions. As named, only one person uses this office, and it has full control over all cooling systems. The only drawbacks of the space are its West orientation, as the façade is well exposed to the sun in the afternoon, and its proximity to a potential acoustic nuisance. In 2023, this office was the second most comfortable space in the whole building. thermal sensation scores at 70 % *Neutral* and 25 % *Slightly Warm* with almost no other vote categories. It is comfortable, with almost 95 % of voters showing up as almost complete satisfaction, acceptability and air movement acceptability. Hence, full control over the system could bring a fully satisfactory environment. Again, it is very sparse to observe *Cooler* or *Warmer* preference vote, as well as *More* or *Less* Air movement preference. In 2024, the space is more in line with other spaces (let's keep in mind that it is the same subject in 2023 and 2024). Thermal sensation drops to 58 % *Neutral* and *Slightly Warm* increases to 20 %, just like *Warm* votes. 80 % of the votes show *Uncomfortable* to *Very uncomfortable* conditions. As the desk is close to the AC unit, the user can sometimes feel *Slightly Cold* to *Cold* around 10 % of the time.

The MM Openspace has eight desks and 4 sub-spaces. The space is not designed for natural cross ventilation as openings are all facing S-E. It has an air conditioning unit and two ceiling fans for 8 people. As mentioned on the spaces layout plan in figure3.21, the AC unit is on the left side of the open space and the right and central zones benefit more from natural ventilation than the left-sided desks. Hence, the first observation is that thermal sensation varies across

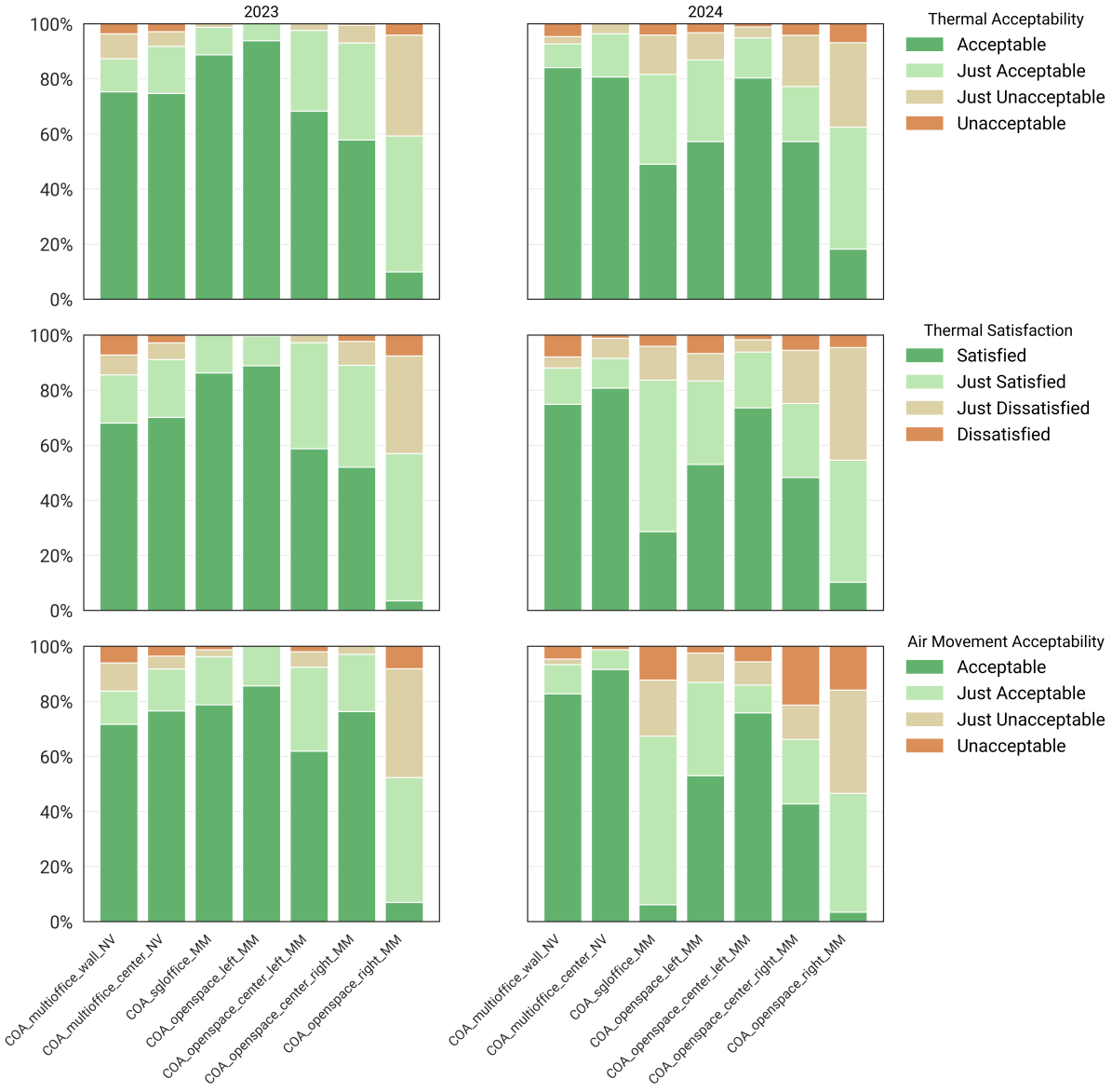

Figure 3.23: *Satisfaction and acceptability votes per space location for 2023 and 2024 periods*

the length of the room. The closer to the AC unit, the more critical the *Neutral* share becomes. In 2023, part of *Neutral* decreased from left (78 %), centre left and right (45 %) and left (10 %). 2024 is less severe but follows the same trend. Comfortable conditions lose 40 % jumping from left to centre and again 40 % jumping from centre to right. Warm to hot thermal sensations are from 20 % under the AC unit to 45 % in the centre to 90 % at the opposite side of the AC unit. Again in 2024, it is less exacerbated, but it reaches 65 % of the vote over *Warm*. Thermal acceptability follows the same pattern, with maximum "full" acceptability under the AC unit, mitigated *Acceptable / Just Acceptable* in the centre of the room, and 50/50 *Unacceptable / Just Acceptable* on the right side of the space. Air movement is another reason why people on the right side vote negatively on the comfort. It is never considered *Acceptable* and only 40 % of the time *Just Acceptable*. When examining the preference vote for both 2023 and 2024, the *Cooler* preference vote increases as the distance from the area where the AC unit is installed increases. Another thing highlights how significant the discrepancy in comfort is in the space, while the extreme right space feels mostly *Warm*, the extreme left under AC can feel *Slightly cold* or *cold*, for a bit less than 10 % of the votes.

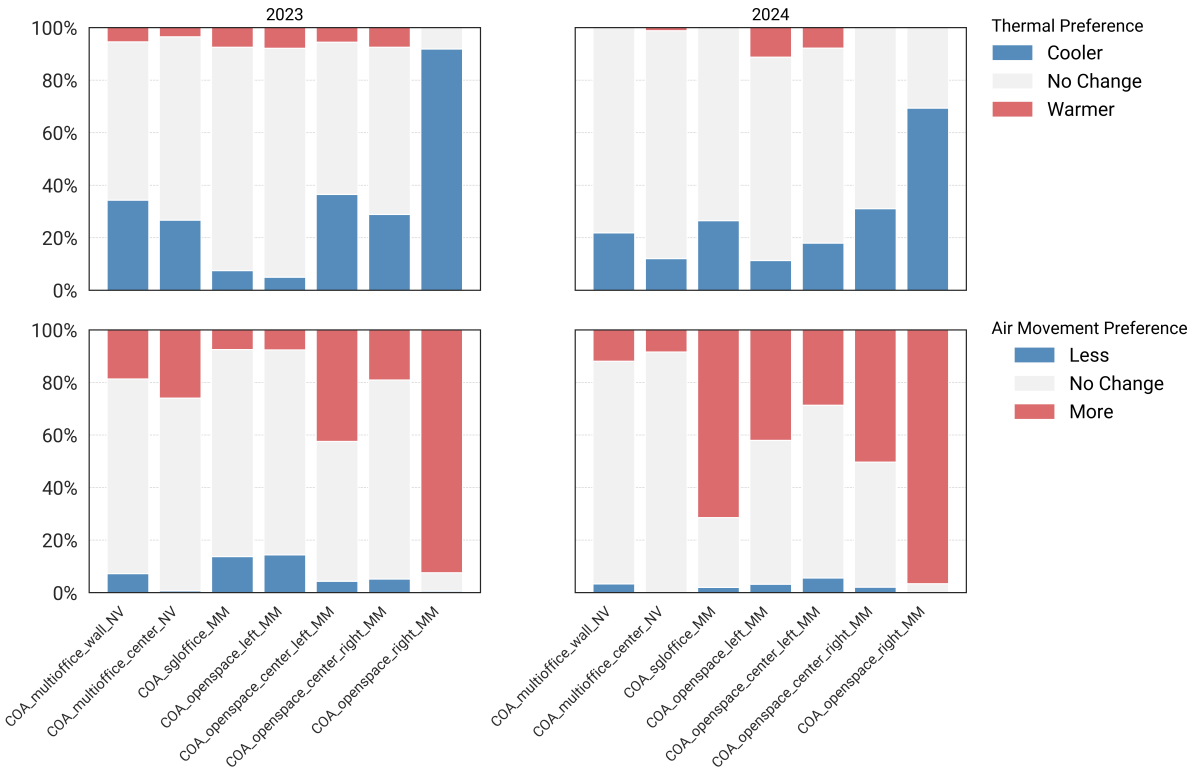

Figure 3.24: *Preference votes per space location for 2023 and 2024 periods*

The *"Zoned"* Mixed mode building, as with Brager et al. definition [69], presents some discrepancies in terms of thermal comfort. The last extension, fully cross naturally ventilated and with very low thermal mass scores, performed pretty well in terms of Neutral sensation, acceptability and satisfaction, even without AC. The single office is probably because only one person can maintain comfort as they wish, and since cross ventilation works the same way, AC certainly plays a significant role in maintaining comfort. This will be described in

the next section. NV offices and single offices are relatively balanced with low change requests.

The open space skew *Warm* leading to lower comfort and presents very strong cooling demand and even stronger air movement demand. This confirms the environmental imbalance between private offices and shared open spaces. Also, there are huge discrepancies across all desks. AC does not seem properly positioned, and it seems to lack ceiling fans (half as many as in the NV room). The space is also not designed for efficient cross-ventilation. Hence, thermal comfort varies greatly. Attention should be paid to equal cooling system availability across the space when designing or retrofitting a space.

3.3.5 Cooling system usage and associated energy use

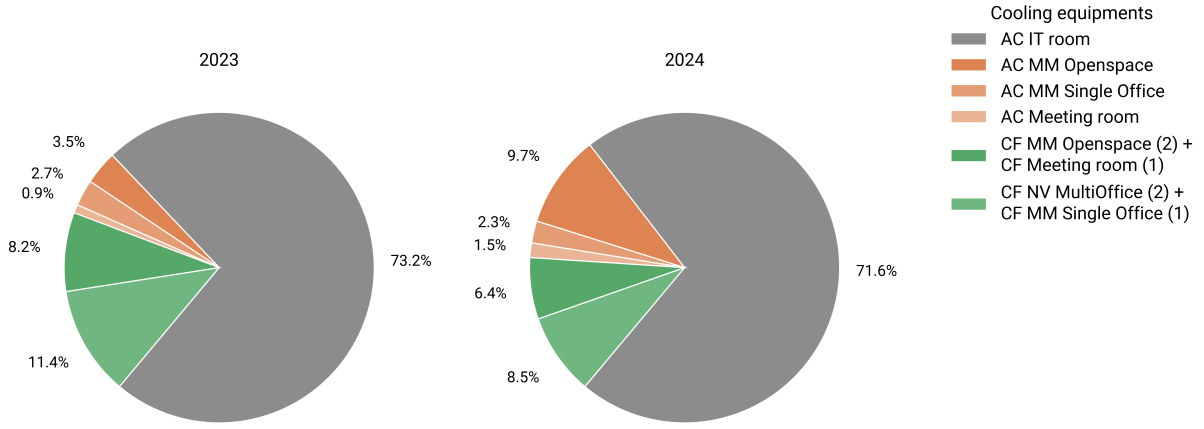

Figure 3.25: *2023 and 2024 Cooling system energy use breakdown for Co-architectes Building, including IT room AC*

The cooling systems (Air-conditioner and ceiling fans) were metered over the course of the year (2023 and 2024). This subsection draws an overview of energy use and usage of active cooling systems. As mentioned in section 3.2, it was impossible to dissociate energy use per ceiling fan because they are wired to the same switch. Hence, the two ceiling fans from the MM Openspace are combined with the MM Meeting room CF, and the 2 CF from the NV multioffice are combined with the MM Single Office CF.

Figure 3.25 shows the overall energy use of cooling systems of all spaces of the studied building. Overall, in this Mixed-mode application, the IT Room AC is by far the most energy-consuming system. The AC is used to cool the IT room with the server 24/24h all year long. Hence, while the setpoint is predefined at 27°C, it almost never stops. It represents more than two-thirds of the AC/CF energy use with 762 kWh (73 %) in 2023 and 833 kWh (71 %) in 2024. The rest of the cooling use is for the Mixed Mode AC+CF and is broken down in Ceiling fans with around a fifth (20 %) in 2023 and (15 %) in 2024, and AC for comfort with around a tenth (7 %) in 2023 and (13.5 %) in 2024. This highlights how low the energy use of AC for

comfort is in this building.

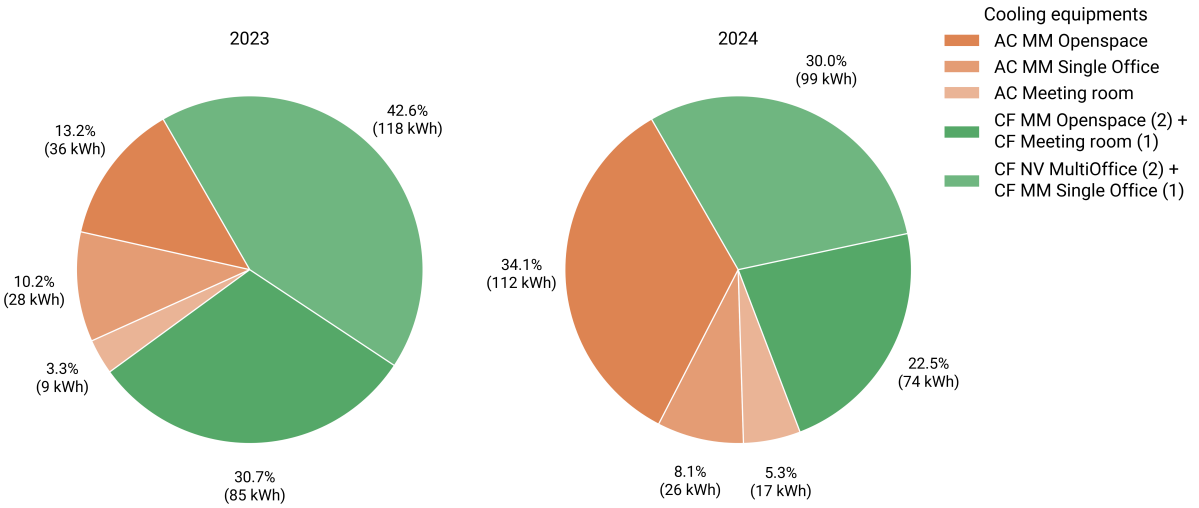

Figure 3.26: *2023 and 2024 Cooling system energy use breakdown for Co-architectes Building without IT room AC*

Figure 3.26 describes the part of energy use per cooling system and per space, specifically for comfort purposes. Overall, when looking at systems for comfort, Ceiling fans consume more than Air-conditioning, which highlights the low use of AC and confirms the Fan-first strategy deployed in the building operation. Yearly energy use difference is also shown in the same Figure 3.26. In 2023, CF accounts for 203 kWh against 73 kWh of AC, while in 2024, CF accounts for 173 kWh against 155 kWh for AC. The more balanced results of 2024 can be explained by the test performed, where, during two weeks (weeks *C04* and *C05*), subjects could not use CF at all in MM spaces (*"NO CF"* test weeks). Hence, they relied only on Natural Ventilation and had to close the windows and turn on the AC when conditions deteriorated. It is interesting to note that in 2023, MM Openspace AC consumed 36 kWh, while it tripled to 112 kWh in 2024 with the two *"NO CF"* test weeks (*C04*, *C05*).

Total energy use was not metered, but we gathered invoices and consumption statements issued by the electricity provider to calculate the part of the overall AC and CF consumption in such an MM building. Reported total energy use in the building is 6690 kWh (2023) and 7965 kWh (2024). The part of energy use for cooling is in line with what was found by Payet et al [195] for a similar type of building i.e., 1AC for IT room, 1 AC for meeting room only, also located in Saint-Pierre, occupant awareness of operation energy use impact. They illustrated that the Mixed-mode operation, with very low AC usage, led to 14 % of AC consumption share of the total energy bill and 4 % for Ceiling fans. Our results are similar in proportion with 12 % of AC energy use and between 2.5-3% of ceiling fan consumption. To illustrate the comparison, a non-MM building's AC energy use under 800 m^2 reaches 51 % of the energy bill according to the latest broad energy metering survey in La Reunion [196]. Nevertheless, this includes the IT Room AC unit. Without considering it, the share for AC dedicated to comfort only falls to 2%. This value reflects the performance of the Fan-First mixed-mode operation,

which reduces the inherent energy use associated with low setpoint temperatures while also delaying or even avoiding the activation of air conditioning.

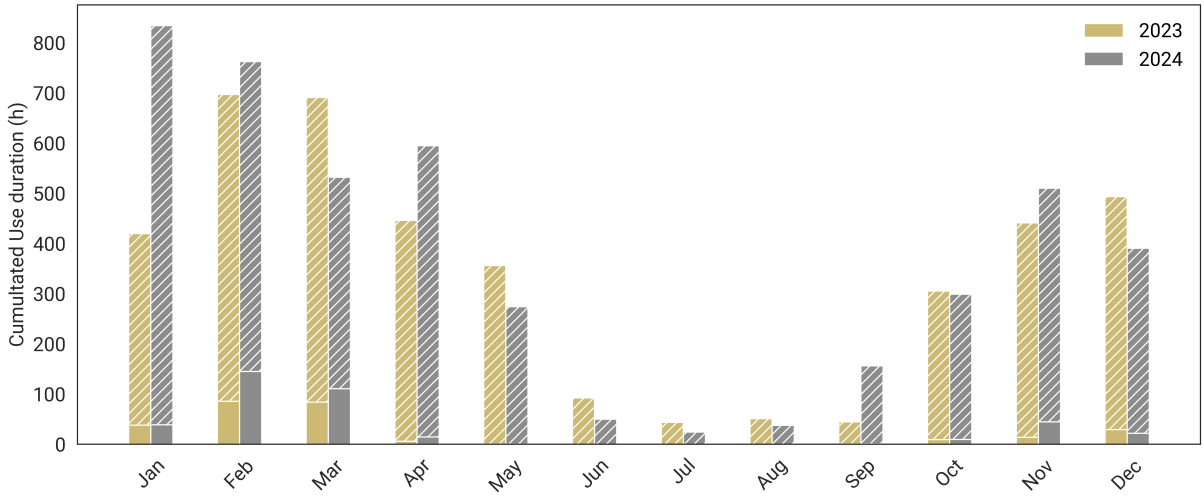

Figure 3.27: *Cooling system usage duration per month for Co-architectes Building without IT room AC. AC is in solid colour, CF in striped colour.*

Cooling systems are used year-round, but with significant seasonal discrepancies in their intensity of use and associated energy consumption can be observed. Figure 3.27 illustrates the cumulative durations of use of AC in solid colour and CF use in striped colour for both 2023 (yellow) and 2024 (grey). Figure 3.27 illustrates the monthly cumulative associated energy use, following the same colour code. As for the analysis of the summer period on those two figures, we should focus on the months of November, February, and March. Indeed, January and December are not full working months due to the annual company closure. So the results are biased. As an illustration, closure dates might vary from one year to another, extending or shortening the working month. Again, discrepancies occur in occupants' presence during annual leave. For example, the consumption values for January are significantly different because one person did not take a break in 2024. All those reasons led us to decide to start the comfort survey in February.

Figure 3.27 shows that less intense usage of the cooling systems is observed during the winter season from June to September, where outdoor median temperatures are below 25°C, and mostly, three-quarters of the temperature distribution is in the [18°C - 26°C] range. Hence, comfortable conditions are met with very minimal ceiling fan use ($<$ 40 hours per month). Not to mention, AC is not used in Winter. It is not used in either the mid-season (April/May and September/October). The recorded data highlights minimal use for a few hours, possibly corresponding to the MM Meeting room when the MM Single Office closes the window due to acoustic disturbance. Nevertheless, CF reached between 290 hours in October 2023 and 439 hours of cumulative use in April 2023 (580 hours in 2024). Assuming a month has an average of 907 fan-working hours (151 working hours/month and 6 CF), ceiling fans are used on average from one-third to two-thirds of the time in mid-season. From

one year to another, and from April to November -hence outside of the summer season- CF is sufficient to keep occupants comfortable. As we approach the summer season, we should focus on the months of November, February, and March. Overall, in summer, CF maintains a high level of usage between 400 hours (November 2023) and 600 hours (Feb/March 2023). AC is activated occasionally at the end of the year, and, from the middle of January, when the company reopened (January cumulative usage is around 40 hours, half of February). AC's most intensive use is in February and March (85 and 83 hours in 2023). Assuming a month has an average of 403 AC-working hours, it represents almost a quarter of the total cumulative duration.

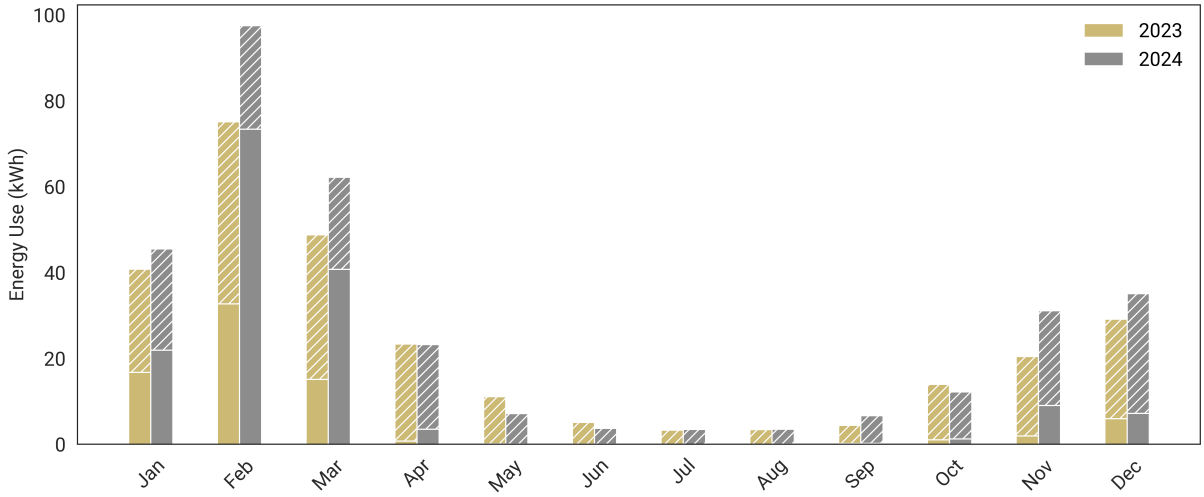

Figure 3.28: *Monthly breakdown of cooling system energy use for the Co-architectes Building, excluding the IT room AC. AC is in solid colour, CF in striped colour.*

3.3.6 Ceiling fan use impact on MM building

When wishing to evaluate the impact of ceiling fan use on energy usage and consumption, it is possible to zoom on the 2024 months during which *'NO CF test weeks* occurred (1 week in February and 1 week in March). Indeed, on Figure 3.27 shows a drift in usage. As an example, February shows a cumulative duration jump to 144 hours and in March to 110 hours, accounting for an increase in use between 32% and 69%. This directly translates into an increase in energy use, as illustrated in Figure 3.28, which clearly shows that AC energy use in March and February is more than twice as high. AC consumption more than doubles in 2024 with only two weeks of 'NO CF' test. Energy demand jumps from 32 to 73 kWh in February and from 15 to 40 kWh in March. Looking more in detail at typical Level 4 survey weeks, Figure 3.29 shows the distribution of cooling systems energy use per equipment (AC in orange, CF in green) and per *Level 4* surveyed week (x-axis). Recalling $C_{01-02-03}$ are the reference weeks of 2023 during which the whole cascade cooling strategy is operated, i.e NV+CF+AC and C_{04-05} weeks are the 'NO CF" test weeks of 2024 during which occupants could only rely on NV and AC to maintain comfortable conditions. First, it is easy to see that the Meeting room AC is nearly OFF during those periods, with a maximum energy demand

of 0.2 kWh.

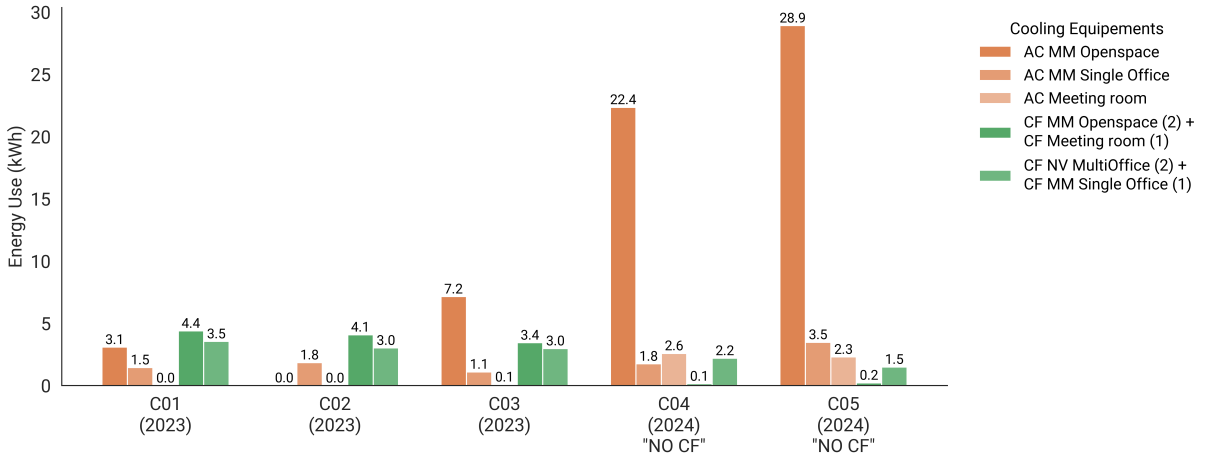

Figure 3.29: *Breakdown of AC and CF energy use per campaign and building spaces*

When CF is allowed (Weeks $C_{01-02-03}$), it consumes between 3.4 and 4.4 kWh per week for the MM Opensapce and between 3.0 and 3.5 kWh per week in the NV Multioffice + MM Single Office. When they are not allowed in MM spaces, the remaining energy use is related to the NV Multioffice, scoring energy use at 1.5-2.2 kWh range weekly. We could deduce from the latter a weekly CF energy consumption of the MM single office of approximately 0.8-1.5 kWh. Focusing now on air conditioning, it can be observed that during normal weeks, when ceiling fans are freely available, AC-related cooling consumption remains relatively contained: ranging from 3.1 kWh (C_{01}) to 7.2 kWh (C_{03}) in the MM open space, for example, and around 1.1–1.8 kWh in the single office. It is worth mentioning that CF themselves managed to avoid the use of AC during C02 week in the MM OpenOffice. When the use of ceiling fans is prohibited, however, cooling consumption rises sharply, exceeding +20 kWh (22.4 and 28.9 kWh for C_{04-05}). The suppression of fan use thus produces a drastic response: air conditioning consumption increases to at least 20 kWh, while stopping the fans in free operation saves only about 3–4 kWh. A similar observation can be made for the single office, where cooling consumption nearly doubles (up to 3.5 kWh against 1.1-1.8 kWh). In the meeting room, while previously only the fan was sufficient, it has now become necessary to turn on the air conditioning, which generates, on average, an additional weekly 2.5 kWh on the energy bill.

It could then be imagined that Air Conditioning by itself, fully controlled by the users according to their expectations, can deliver optimal comfort for the whole team, as it is any other traditionally cooled AC building. Let's recall that predefining the setpoint to 26° should provide comfortable conditions (PMV < 0.5) and 90% Satisfaction (PPD: 10%) at any relative humidity for (clo=0.5; met:1.1; v= 0.1 $m.s^{-1}$). Hence, the overconsumption would be beneficial. It appears to be the exact contrary for our case study.

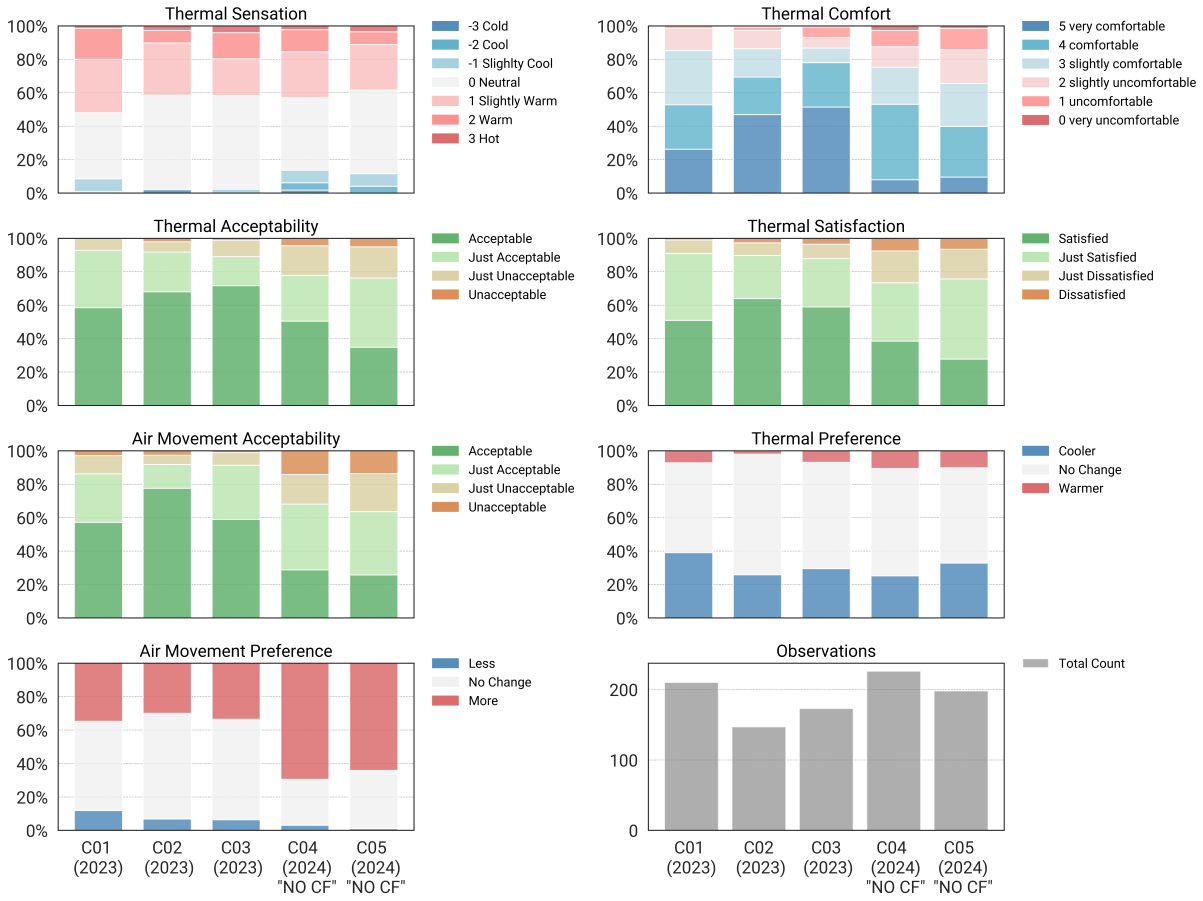

Figure 3.30: *Occupants' votes with Ceiling fan allowed (standard $C_{01-02-03}$ weeks) and without Ceiling fan use ('NO-CF test C_{04-05} weeks) in MM mode spaces only*

Figure 3.30 displays all different votes recorded during standard $C_{01-02-03}$ weeks, allowing ceiling and use and during '*NO-CF test* C_{04-05} weeks without allowed ceiling fan use. This figure is for MM spaces only, e.g, the MM Openspace and the MM Single Office (no votes recorded in the MM Meeting Room). It is build upon a significant number of questionnaire responses (min 148), that is also and consistant over the weeks (mean: 190, sd: 31). For standard $C_{01-02-03}$ weeks with NV and joint CF+AC possible use, results are in line with more global results of 2023 and 2024 already presented in sections 3.3.3 and section 3.3.4. Namely, mean *Neutral* thermal sensation around 40-50%, *Slightly warm* votes over 25% and 15-20% of *Warm to hot* vote. Overall comfort (*Neutral to very comfortable*) is over 80%, and both overall thermal acceptability and satisfaction reach 90%. In terms of preference, occupants claim a cooler space 21 to 38% of the time and for more air movement from 25 to 28% of the time. Even sometimes, 5-10 % would claim less air movement or a bit warmer. When analysing the same thermal sensation votes for "CF" weeks ($C_{01-02-03}$ and "NO CF" weeks (C_{0405}), the first observation is that warm-side votes remain unchanged regardless of whether ceiling fan use is authorised. However, a slight increase in cold-side votes is observed when fans are disabled, indicating the negative impact of relying solely on air conditioning. However, for the other user-voting categories, the difference is striking. *Thermal comfort* loses nearly 10 % in the *Neutral, Comfortable,* and *Very Comfortable* categories, with the largest decrease occurring in the highest votes: *Very Comfortable* responses drop from 22–50 % to only 6–7 %, partly shifting toward *Comfortable* and *Neutral*. The share of *Hot* votes triples. A similar trend is observed for acceptability and satisfaction: *Acceptable* and *Satisfied* responses decrease by 30–50 %, with only a partial shift to *Just Acceptable* and *Just Satisfied*. Finally, the strongest effect concerns air movement: Acceptable responses are reduced by a factor of two to three, while preference for air movement doubles to reach 65 % of the votes, whereas thermal comfort preference remains stable across all weeks. This clearly shows that occupants help to avoid AC use or low setpoint temperatures, but their main expectation is increased air movement rather than reduced temperature.

Furthermore, Figures 3.31 and 3.32 add information about the indoor conditions during which the AC is used, during standard weeks and "*NO CF*" weeks. Both figures present each hour in 2024 when the cooling equipment was on or off on the psychrometric chart, overlaid with still air and NV Givoni zones. Blue dots are for both CF and AC OFF, Green dots are for CF only ON and orange dots are for both CF and AC ON. Figures 3.31 represent all the hours of 2024 without NO CF weeks and 3.32 represent all hours of the NO CF test weeks (C_{04-05}). Figure 3.31 shows that CF is used on a wide range of temperatures (24-34°C) and relative humidity range (50-98%) while AC is used on the same temperature range but only for higher relative humidity conditions (68-98 %). Haese et al. demonstrated in [86] that *"A threshold value for relative humidity (68%) in this range of air temperatures seems to condition the panel's dissatisfaction index*. Hence, satisfaction would be an indication of AC use. When switching the "NO-CF" test weeks represented by Figure 3.32. AC alone is used in the same range of temperature (24-34°C) but this on a broader range of relative humidity (55-98%). When the ceiling fan or any kind of air movement is not available to the occupants, AC is activated at

a lower relative humidity threshold than when the ceiling fan is allowed. Hence, Ceiling Fan could have both a positive impact on temperature by 2-4°C on average, as described by numerous studies in 1.2.3, and also gain around 10-15% of relative humidity.

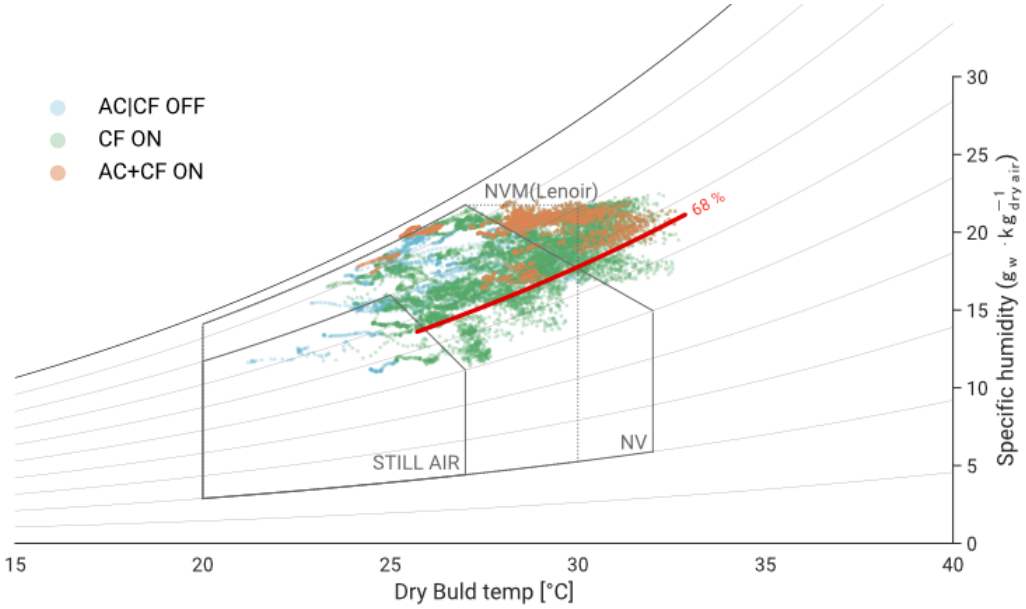

Figure 3.31: *Recorded Indoor conditions when AC and CF are in use for 2024 periods, without weeks C_{04-05}during which CF use was not allowed*

To confirm that these results have nothing to do with exceptional outdoor conditions occurring during C_{04-05}, we can evaluate the NV multioffice space as a reference. Figure 3.33 presents the same vote categories as MM spaces figure 3.30. It is directly visible that conditions are steady for thermal sensation and in line with those of MM building. Satisfaction, acceptability and air movement acceptability are also steady across all weeks, scoring respectively at 95%, 90% and 95%. Thermal comfort remains overall comfortable (Neutral + Comfortable + Very comfortable) at 89% on average. Thermal Preference, like for MM building, is between 20 and 40% cooler oriented, and people claim more air movement for less than 20%, which is quite a huge difference, with far less negative results than MM spaces' results described above. This suggests that a well-designed, naturally cross-ventilated envelope can be as efficient as a poorly designed envelope with mixed-mode cooling, but also that not providing air movement while operating AC in a tropical climate abruptly increases both discomfort and energy use.

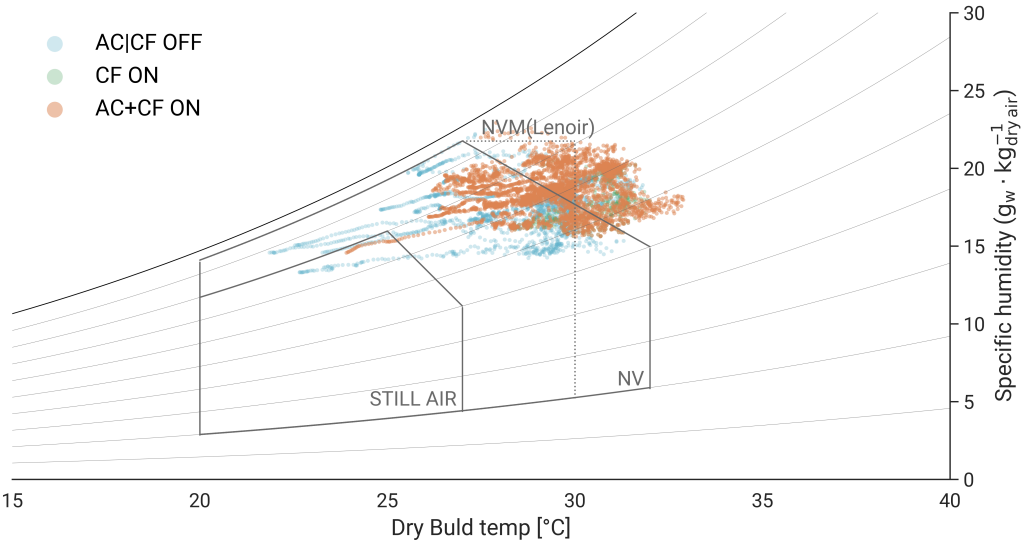

Figure 3.32: *Recorded Indoor conditions when exclusively AC is in use for 2024 periods (i.e. weeks C_{04-05} during which CF use was not allowed - NO CF test weeks)*

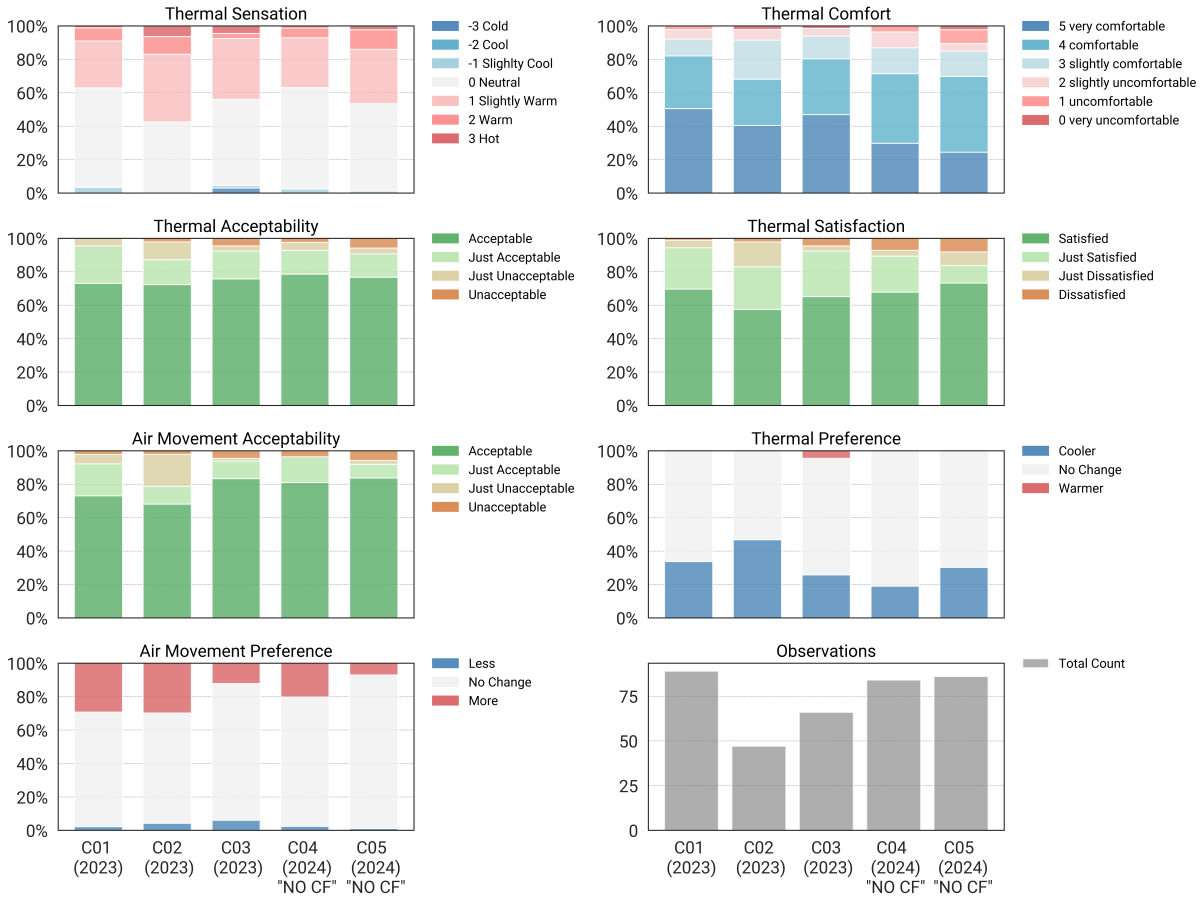

Figure 3.33: *Occupants' votes during $C_{01-02-03-04-05}$ weeks in NV spaces only*

3.4 Conclusive remarks

This chapter addressed two research questions through an experimental setup. The first section describes the experimental aspect of this study in terms of context, building, surveyed population and adaptive opportunities. The Coarchitects case study was primarily selected because of its envelop characteristics and ceiling fan-based mixed-mode operation, providing an excellent case to investigate the stakes and impacts of mixed-mode adaptive operation in a tropical climate. A second section details the monitoring of indoor environmental conditions, occupant feedback, and energy use of the in-operation cascade cooling system. From this field survey, two consolidated datasets were obtained in summer conditions: a 2442-votes dataset and a subgroup of the latter, comprising 1911 votes with IEQ data. Also, two years of energy use data for cooling systems were recorded. The first dataset served as the basis for the comfort analysis of tropical summer conditions in the case of mixed-mode operation. The second dataset will be used in the next chapter for model prediction / actual vote comparison.

This experimental work contributes to a better understanding of the extent to which a ceiling fan-based mixed-mode cooling operation can maintain comfort throughout the summer period in a tropical climate at a lower energy cost. It indeed highlights several valuable findings that extend beyond current literature:

Even with thermal sensation slightly drifting to the right of the scale, building thermal comfort remains acceptable and satisfactory for around 90% of the respondents. Meanwhile, air conditioning use and energy consumption remain very moderate , even low. It has also been shown that a very good natural cross-ventilation design can be almost as efficient in terms of overall comfort while using minimal energy (only CF). In contrast, in MM space, specific "test weeks " during which Ceiling Fan use was forbidden reveal the crucial role of air movement for comfortable environments in hot and humid climates. Indeed, when ceiling fans were not allowed, the recorded warm thermal sensations remained consistent with those in the reference weeks, whereas all other votes dropped sharply, indicating lower acceptability and satisfaction with the thermal environment and air movement. This observation coincided with increased AC use — up to four times that of a conventional AC-cooled building in La Reunion — yet it failed to deliver comfort. This also raises questions about the relevance of predicting a comfortable environment based solely on thermal sensation. Lastly, plotting cooling system energy use against environmental variables demonstrated that the use of a ceiling fan can not only save a few degrees of temperature but also save a tenth of a point of relative humidity.

Lastly, the richer dataset, containing IEQ data against votes, obtained from the experimental setup, will serve as the basis for the next chapter, which proposes the selection of an off-the-shelf comfort model for mixed-mode control applications.

4

Comfort model selection for Mixed-mode control modelling

This chapter proposes a methodology for selecting the most suitable off-the-shelf comfort model for mixed-mode cooling applications in presence of air movement. The methodology is graphically summarised in Figure 4.1. The aim is to choose a model that (1) reflects key human adaptation mechanisms, (2) remains valid under hot and humid indoor conditions with significant air movement, and (3) is practical for real-time control action in building energy models.

The proposed scheme focuses on a single case study of ceiling-fan-assisted mixed-mode operation in a tropical climate, but can be applied to any type of mixed-mode operation and climate, as well as to wider data samples. The following is based on previous results from chapters 2 and 3.

The models from literature are screened through a 3-step process:

Qualitative screening: This section argues that the comfort model should have key aspects for applicability to mixed-mode cooling, hence model selection criteria are defined. A qualitative preselection is made based on those criteria, relying on the extensive literature review presented in Chapter 2, which will help identify models with potential applicability to our study.

Quantitative screening: Model Prediction - Actual recorded votes comparison is the heart of this section. The second step will rely on the second dataset obtained from the experimental aspect (chapter 3) to confront model predictions with observations. This step will refine the selection by focusing on thermal sensation for system control. The final selection will represent as closely as possible the recorded mean vote of the occupants.

Model sensitivity to controllable parameters: Lastly, an extra step will detail how to ensure that the selected model handles control parameters correctly, i.e., that acting on the cooling system has a significant impact on the model output. This final step examines two sensitivity analysis techniques and addresses the interdependence of model inputs.

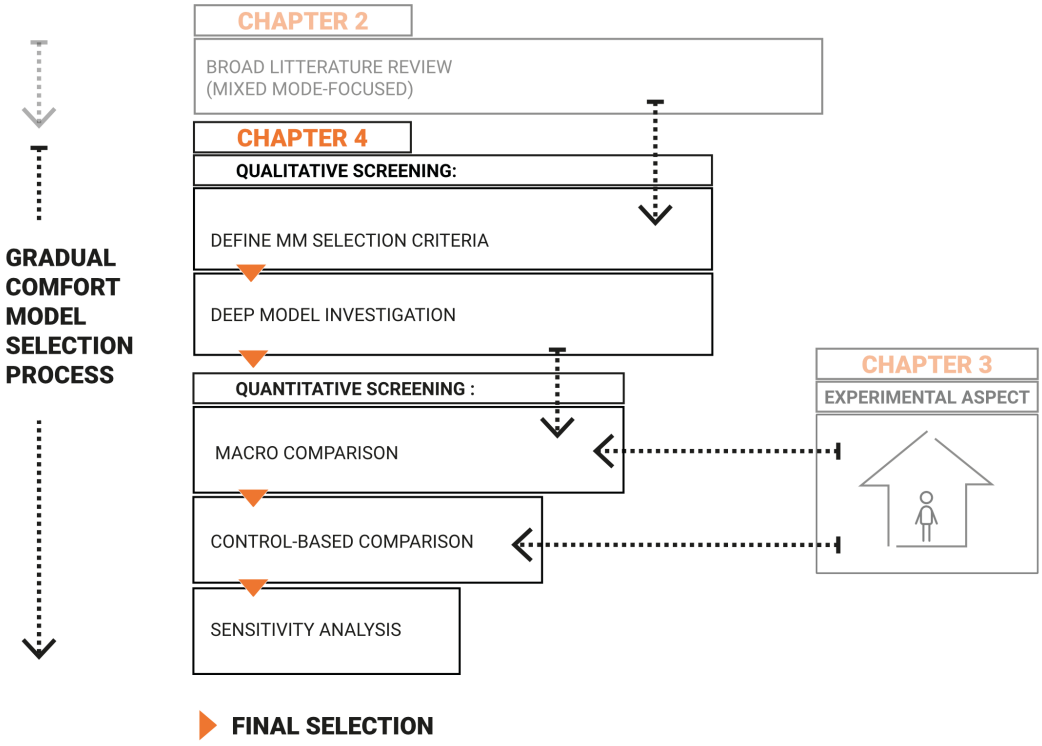

Figure 4.1: *Gradual comfort model selection methodology*

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4.1 Qualitative screening

4.1.1 Selection criteria

MM control in the literature

The exclusive use of compressor-based mechanical cooling is responsible for a significant portion of global energy demand worldwide. Mixed-mode buildings are gaining interest in the Architecture, Engineering and Construction (AEC) industry and in the research community as an efficient way to keep people comfortable while reducing the energy drift. However, very little guidance is provided for modelling, simulating, and optimising the cascade cooling system described in this work [77], [78], [197]. Several researchers took an interest in controlling the indoor environment in tropical conditions; most of them use static or predefined setpoints. Others consider numerous adaptive opportunities and sometimes include mixed-mode operation with fans. However, it remains unclear how they selected the comfort model for that purpose.

Mui et al. [198] simulated an adaptive HVAC temperature setpoint in the hot and humid climate of Hong Kong based on the assumption that a fixed setpoint was not adapted to the local culture and habits. They developed an algorithm which defines the AC setpoint based on outdoor temperature to control the cooling production. There are no other cooling systems involved in this study, and no readily available comfort models were considered.

Babich et al. [197] are interested in mixed-mode operation in the indian residential sector, combining Air-Conditioning (AC) and Natural Ventilation (NV). They highlighted a 70% reduction of AC energy use with the use of an air motion device. They used the ASHRAE 55-2013 adaptive model to account for neutral temperature calculation and extra air velocity (1.2°C for $v = 0.6\ m.s^{-1}$, 1.8°C for $v = 0.9\ m.s^{-1}$, 2.2°C for $v = 1.2\ m.s^{-1}$), while in essence the model is strictly applicable to NV (*"thermal environment only for occupant-controlled naturally conditioned spaces where no mechanical cooling system is in operation"*) [104]. They mention that the IMAC adaptive model is not appropriate because it already considers elevated air velocity within its comfort range.

Schiavon et al. [23] highlighted the AC energy reduction potential of 17-48% in the presence of a fan. They simulated 54 case studies located in Europe using Energy Plus, considering the EN 15251:2007 standard upper limit of summer categories to account for the influence of air velocity on operative temperature. Specifically, when air temperature equals radiant temperature, the operative temperature is reduced by 1.7°C for a wind speed of $v = 0.5\ m/s^{-1}$,

2.5°C for $v = 0.8\ m.s^{-1}$. These remain predefined CF and AC setpoints, with no consideration given to clothing flexibility and thermal physiology.

Zhang et al.[199] proposed an adaptive control based on indoor and outdoor temperature. No comfort model is involved in controlling windows, ceiling fans, and air conditioners. The presented control flowchart shows that CF and AC activation is based solely on indoor temperature limits, and the difference between indoor and outdoor temperatures determines their intensity of use. The control algorithm was not implemented in a Building Energy Models.

Shuo et al. [45] proposed a PMV and a SET-based control, but only dedicated to fan intensity use. It was neither aimed at building energy simulation nor MM control but for in-room multiple fan control.

In 2023, Sánchez-García et al. [76], [200] developed a Python-based *Adaptive Comfort Control Implementation Script* (*ACCIS*) in the vein of Babich et al. [197], i.e., extending the use of an adaptive model to air-conditioned spaces. The authors explicitly mention that according to American and European standards, *adaptive models are only appropriate for naturally ventilated spaces"* but argue that several studies demonstrated the adaptability of occupants in any kind of building cooling, particularly citing Parkinson et al. [78]. They add that mixed-mode specific adaptive models should be developed based on new recorded data; however, they did not take the opportunity to implement the Parkinson's SET-based adaptive model that is dedicated to MM. To address the overgeneralization of standard regression, the proposed tool implements adaptive models from worldwide standards, including ASHRAE, EN16798, GB/T50785, and ISSO74. Adaptive setpoint temperatures are implemented in two ways: first, by pre-computing the monthly setpoint, and second, by dynamically calculating the setpoint based on outdoor conditions.

In 2024, Rugani et al. [49] conducted energy simulations using both HVAC systems and personal comfort devices for heating and cooling in four regions. They aimed to define a new methodology for evaluating the Personal Comfort Device (PCD) sizing (in terms of numbers and usage) to maintain comfortable conditions in conjunction with other primary cooling systems, such as HVAC ones. Hence, a ceiling fan complements a temperature drift from the set point. Thermal comfort was not modelled, and relaxed setpoints were assumed from other studies.

Another study by Hoyt et al. [49], [201] demonstrated, through simulation, that a more even air distribution maintained satisfaction levels in a traditional Variable Air Volume (VAV) cooling system, even when the setpoint was rescheduled to 25°C instead of 22.2°C. PMV is used as a comfort model to assess comfort in post calculation, but no PMV-based control was implemented in the simulation.

Definition of selection criteria

As described in one of the publications related to this thesis work [80], Building Energy Models BEM should integrate a more flexible approach to cooling strategy [200]. The case of mixed-mode cooling adds an extra degree of complexity to the model selection process.

Whereas air conditioning is available in such buildings, they are designed with an adaptive concept in mind. Indeed, as a Mixed-Mode (MM) building is proven to be closer in essence to an NV building [78] it should offer total flexibility to occupants to be active in their comfort, mainly through solar shading, ventilation openings, the use of ceiling fans, and a flexible dress code. Hence, occupants *"favour a certain indoor environmental variation"* [202]. For designers to accurately estimate energy use and comfort performance, Mixed-mode cooling presents challenges for comfort models to encompass the full range of controllable parameters of the MM cascade cooling operation. Mechanical, Electrical, Plumbing (MEP) engineers should be able to simulate AC temperature setpoints and air velocities (from NV or CF) within a broader adaptive framework that emphasises occupants' behavioural adaptation, such as clothing flexibility. As an example, incorporating flexible clothing policy into BEM can enhance comfort and energy efficiency, e.g. reducing clothing insulation by 0.1 clo (20%) of a summer average of 0.5 clo per ASHRAE 55:2023) equates to a 0.6°C decrease in operative temperature.[105]. Furthermore, our problem must be solved in a critical, hot and humid environment. The selected model should be the most reliable for those climatic conditions.

To select the most appropriate comfort model for simulating MM Fan-First coupled system operation in BEM, we defined the criteria of selection as follows, given by importance:

- **Controllable parameters**: The comfort model chosen should consider at least variables such as the clothing (clothing flexibility), the airspeed (ceiling fans, ventilation openings), and the setpoint temperature of air conditioners. Relative humidity is considered a consequence of mechanical space cooling, and for energy reasons, it is not intended to control indoor RH.
- **Validity domain**: Its ambience validity domain should contain hot summer tropical indoor conditions, especially for Temperature and Air velocity on the high end. ($24 > T_{db} > 34$°C, $0 > v > 2.5\ m.s^{-1}$). Wherever possible, it shouldn't be restricted to steady-state and uniform conditions.
- **Hot-humid conditions**: It should be the most reliable in warm, hot and humid conditions for office applications and should have been proven so.
- **Generalizable adaptive concept**: It should consider somehow adaptive opportunities (through inputs or through the model itself) while remaining generalisable, i.e. not dependent on very regional or building or population-dependent survey dataset.
- **Air movement system flexibility**: It should give the most flexibility to control different kinds of air movement systems, i.e. Ceiling Fan with any number of rotation positions

The above-mentioned selection criteria have been proposed explicitly for Fan-assisted Mixed mode cascade cooling of this thesis work and should not be generalised to other kinds of cooling systems. Indeed, it is worth noting that for other types of mixed-mode cooling systems, additional criteria should be considered. For example, implementing radiant cooling in the simulation would necessitate the controllable parameter to integrate the mean radiant

temperature. Implementing evoporative cooling will necessitate the controllable parameter to integrate relative humidity.

Please note that all models described in Chapter 2 and investigated in this chapter are designed for the built environment, as they provide a comprehensive overview of comfort conditions and are mostly computationally cost-effective. Hence, they have been proven consistent with thermal modelling at the zone level (nodal modelling) for Building Energy Simulation. If the methodology is to be applied to a broader range of models, such as multi-node and multi-segment models for more refined simulation (i.e computational fluid dynamics), the balance between computational cost and prediction performance must be considered.

In the following proposed comparative tables, icons are defined as follows:

- ✓: The model fully accounts for the criteria;
- (✓): The model partially accounts for the criteria, or it accounts for it with some limitations;
- ✗: The model does not account for the criteria;
- ?: To our knowledge, it is not mentioned in the literature whether the model accounts for the criteria.

4.1.2 Questioning Adaptive models for MM application

Adaptive thermal comfort emerged in the late 1990s and has revolutionised, for numerous reasons, the way indoor environmental comfort is considered. It was the first approach that highlighted the discrepancy between active (AC) and passive (NV) buildings through their occupants' expectations and implication in maintaining their own comfort. Hence, it was the first approach to consider behavioural, psychological, and physiological adaptation, and to underline the influence of the outdoor climate's short-term history. It has been validated through numerous field surveys and has shown great flexibility, along with a simple calculation procedure [202]. In this regard, it has been widely adopted in international and national building standards [202].

Being statistical analysis-based models, AM fall into the black-box group of models, which necessitates understanding their foundation. Adaptive models were explicitly designed for NV buildings, whether in its ASHRAE or European versions [18]. However, the European AM grounded on the SCAT database only includes two buildings in Athens that present warm conditions over 25°C [76], which questions its applicability in tropical conditions. Its American counterpart, based on the RP-884 database, presents a broader range of applicability with 24% of its records (4962 over 20693) coming from buildings in 5 tropical locations, including three subclimat groups A_w, A_m and A_f [10]. Neverthless, in the original dataset, there was insufficient data for Mixed-Mode building to provide recommandation on their operation [115]. The original model from De Dear and Brager [115] which has still not been updated to date, has some limitations, as stated in the 1998 RP 884 report [186] and literally reproduced hereafter :

- *"naturally conditioned spaces where the thermal conditions of the space are regulated primarily by the occupants through opening and closing of windows. It is specifically noted that the windows must be easily accessible and operable."*
- *"spaces can have a heating system, but the method doesn't apply when it is in operation. "*
- *"spaces cannot have a mechanical cooling system (e.g., refrigerated air-conditioning, radiant cooling, or desiccant cooling)."*
- *"spaces can have mechanical ventilation with unconditioned air, but opening and closing of windows must be the primary means of regulating thermal conditions."*
- *"occupants of spaces must be engaged in near sedentary activity (1-1.3 met), and must be able to freely adapt their clothing to the indoor and/or outdoor thermal conditions."*

More recent research has shown that occupants adapt similarly in naturally ventilated and MM-cooled buildings, supporting the use of the adaptive model in both [70], [78], while the original dataset contained only one MM case. The proven concept is presented by Bachich et al. [197] and Sanchez et al. [76], who both propose an AM-based control strategy for HVAC flexible setpoint management. Recent guidance has been provided by IEA task 69 : *Annex B2 Guidelines for low energy building design based on the adaptive thermal comfort concept* [203]. Nevertheless, Mixed-mode in those studies is mostly understood as the bridge between natural ventilation and mechanical cooling. Personal comfort devices, such as fans, are referenced as comfort-enhancing elements, but no explicit treatment of their control is provided. Table 4.1 summarise all selection criteria for AM screening for mixed-mode applications with fans. Most of the time, as mentioned in the comment of Table 4.1, AM are proposed only for the naturally ventilated or free-running building, even when hybrid or mixed model operation is described. Hence, the question arises when ceiling fans are introduced into the control strategy, in conjunction with first natural ventilation and then with air conditioning [80].

The Adaptive regression-based approach lacks the flexibility to control air velocity. To a broader extent, environmental and personal variables are hidden in a black-box model, which, by affecting thermal perception, can hinder its application to building and engineering system design [102]. Both European [42] and American [104] standards include a stepped comfort temperature upper acceptability limit increase based on air speed categories. This cooling effect is integrated as an "extra layer" of the original European models through the formula 2.52, as the SCAT database records present a very low mean air velocity [123] and only two buildings in warm conditions. ASHRAE 55:2023 has a similar procedure based on SET values as illustrated in section 5.2.3.2 of the standard [104]. While the RP-884 also presents a low mean air velocity, closer examination of warm conditions (over 26°C, which the SCAT does not cover) shows the recorded air velocity in summer ranged from 0.1 to 0.95 m/s (Figure 3.16 of the report [186]). This is also confirmed when plotted against outdoor mean running temperature (Figure 3.16 of the report [186]), showing that comfortable conditions over 25°C are in the presence of high air velocities (mean around 0.4 $m.s^{-1}$. In essence, flexible airspeed seemed to be already included in $AM_{Ashrae,\,55:2023}$ acceptability range [186], [204] as mentioned above. At the same time, recorded clothing values are on the higher

end of the summer clothing scale, with an almost 0.7clo mean, whereas our case study is at 0.48 clo. In terms of applicability, EN 16798 standard states that AM is valid only for users with full access to windows and fans. This applies only to near-sedentary activity when the indoor temperature reaches 25°C. It is assumed that the radiant temperature equals the air temperature [23], and the occupant wears light clothing.

In terms of air movement control, the three predefined cooling effects limit the Adaptive Model to a ceiling fan with three speeds that perfectly match the stepped cooling effect speed of the standard. Furthermore, 0.8 $m.s^{-1}$ is advised as the upper velocity limit for office work for reducing the risk of paper-blowing [205] when research [55], [62], [80], [134], [195], and the case study of this thesis, underline the benefit of higher air velocity. Other European national building codes, such as ISSO74, CIBSE or RE2020, stick to the EN16798 as a reference for air velocity control.

Regarding the consideration of moist air. There is a lack of studies on thermal comfort in the humid tropics [10]. The Vellei [176] model integrates the relative humidity with three categories based on a Random Forest classifiers. Nevertheless, the authors exclude air velocity for building categories, while airspeed is shown to be almost as influential as relative humidity in terms of the relative importance of features, as given by the RF classifier. Vellei study is also based on RP-884 database. The author mentions a significant drawback in [206] which is the non-consideration of other outdoor influential parameters like outdoor relative humidity and wind air speed. It is noteworthy that this was initially addressed by De Dear and Brager's original model, which regressed neutral indoor temperature against Effective temperature. For simplification reasons, the ASHRAE committee did not select this formulation for the 55:2004 standard [144].

Finally, Parkinson et al.[78] benefited from the release of the Global Comfort Database II of ASHRAE to review the Adaptive Model (AM) for the three building categories on the most extensive database to date. Strong discrepancies were confirmed between AC and NV buildings as well as similar behaviour and expectancy between MM and NV ones, assuming that MM are NV-designed buildings with Air-conditioning capabilities and not the contrary. Considering that the heat-balance accounts for at least a third of occupant thermal comfort, they propose integrating all environmental and personal parameters by using the Standard Effective Temperature (instead of a neutral temperature) as a comfort condition to be regressed against outdoor temperature. This index, based on the two-node model, has proven reliable in warm conditions. The other part of the sensation is accounted for by adaptive opportunities, the influence of past climate and the expectation of occupants. Hence, parkinson's model can account for heat balance and the full range of adaptive opportunities. While they provide little guidance on how to integrate their model to reduce HVAC load and energy consumption, it definitely lacks an acceptability deadband, which could be used for control. The authors state : *"Defining the conditions which justify switching mixed-mode buildings between cooling strategies remains a fruitful area of research, and will depend on many contextual factors for each building*

considering this."

From the above analysis of Adaptive Model based on our selection criteria, only the Parkinson model will be selected for mixed-mode control. Because it cannot provide an acceptable range of comfortable conditions, the concept won't be challenged against actual recorded vote and will only be used on the simulation of MM control to understand the perspective it offers.

Table 4.1: *Adaptive model qualitative screening*

Model index	Temperature control	Air speed control	Clothing flexibility	Validity domain	Hot/Humid conditions	Generalizable adaptive concept	Air movement syst. Flexibility	Comments	Selected
$AM_{EN16798}$ AM_{CIBSE}	✓	(✓)	✗	✓	✗	✓	✗	NV specific model. The European model is built upon a cold and temperate climates SCAT database only (25–26 office buildings in 5 European countries (UK, France, Sweden, Greece, Portugal)) representing all building types. Three predefined stepped air movement speed controls (cooling effect) are available over 25°C for fully adaptable occupants (no control).	✗
$AM_{Ashrae,55:2023}$	✓	(✓)	(✓)	✓	✓	✓	✗	NV specific model. De Dear and Brager model is built on the legacy worldwide RP-884 database, which includes tropical climates but very few MM buildings.Mainly office buildings. Poor air movement flexibility with 3 predefined stepped air movement speed control (cooling effect) based on the SET heat-balance calculation. It could be used as is if clothing is not an issue and if the fan's mean speed matches the predefined stepped cooling effects.	(✓)
$AM_{RH,Vellei}$	✓	✗	(✓)	✓	✓	✓	✗	Vellei model considers 3 humidity ranges by means of Random Forest classifier ($< 40\%, 40\% < RH < 60\%, > 60\%$), but air velocity and clothing are not usable parameters for control. For tropical conditions, only the high RH category could be used. It is built on older worldwide RP-884, including tropical conditions with very few Mixed-mode buildings	✗
AM_{IMAC}	✓	✗	(✓)	✓	✓	✓	✗	The three Indian models for NV, AC and MM are specific to the indian building stock over 5 climates. The IMAC-MM model is validated for buildings that switch between NV and AC across the year. Do not consider clothing or airspeed for control [197]	✗
AM_{ISSO74}	✓	✗	(✓)	✓	✗	✗	✗	ISSO74 model is built from the RP-884 database, but the latest iteration (2024) on the more restrictive SCAT. Guidance given for hybrid operation but for free-running building (windows/occupant control, HVAC off) in summer (Alpha type) and fully centralised Air-conditioned building (beta-type)	✗
$AM_{GB/T\,50785}$	✓	✗	(✓)	✓	✓	✗	✗	The Chinese model is specific to the Chinese building stock. Only valid for Buildings without mechanical heating or cooling (free-running: windows/occupant control, HVAC off). Air velocity can be accounted for only by using the $aPMV$ adaptive heat-balance model, so MM is oustide the scope of $AM_{GB/T\,50785}$	✗
$PMV_{n,Orosa}$	✓	✗	(✓)	(✓)	✗	✗	✗	The model has nothing to do with Fanger original model. Closer in essence to an adaptive model regressed on temperature and vapour pressure. While promising, the author's limit is applicability to the young population and hot/dry climates. Furthermore, there is no consideration for air velocity.	✗
$AM_{SET,Parkinson}$	✓	✓	✓	✓	✓	✓	✓	Parkison AM is specifically built on MM building dataset from the most up-to-date ASHRAE Global Comfort database II. It included tropical climates but remains generic. It fully accounts for environmental, personal and adaptive variables because the SET index is calculated through the Gagge two-node Heat Balance model. Parkinson's proposal fills the gap between NV and AC. It lacks the definition of an acceptable range to compare to comfort survey recorded vote.	✓

4.1.3 Questioning original Thermal Heat-balance Models and related sensation models

Fanger's single-node and Gagge's two-node models are the most widely studied and used models in the built environment. They are proposed with several options for thermal sensation formulation. The last twenty years of research have brought to the scene combinatory approaches, also known as the explanatory adaptive approach try to bridge the gap between both worlds of NV (Adaptive Model) and Air-Conditioning (AC) (Thermal Heat-balance Models) [79]. This section presents the pros and cons of traditional Thermal Heat-balance Models and adaptive (explanatory) THM. It follows the same comparison schemes as the previous section and is summarised in the following tables:

- PMV-based models (Table 4.2) include original and normative PMV models as well as models with core equation modifications.
- Gagge two-node based models (table 4.3) and its Thermal Sensation Model formulations
- Adaptive-THM (Table 4.4 (part 1) and 4.5 (part 2)) presents adjusted Thermal Heat-balance Models outputs using either a field-calibrated corrective factor or by adapting the behavioural (personal) inputs such as MET and CLO

Some authors argue that the use of adaptive models in the built environment pushes the comfort limit to its extreme, yielding to a rebound effect, and thus pushing people to use energy-intensive AC in buildings designed for NV operation. [10]. With the oversimplification of AM, Heat-balance work and findings are underestimated, although they provide a good starting point for further enhancement. In their 1998 RP-884 report proposing the new AM a that time, De Dear and Brager stated that both theories of AM and THM should not be opposed and that there is a misunderstanding in the way Thermal Heat-balance Models, such as Fanger's and Gagge's two-node models *"prescribe a single, constant temperature"* [186]. They can provide some sort of adaptation through flexibility, possibly including metabolic and clothing adjustments, as well as enhanced air movement by adjusting a window or using a fan. As stated *"the static model of comfort is in reality an 'adaptive' model in its own right"* [186], the only difference is how the temperature drift is addressed. The adaptive approach accounts for psychological and acclimatization processes, whereas heat-balance models describe adaptation through quantifiable behavioural adjustments, including changes in clothing insulation, metabolic activity, and air movement. To the same authors, the controversy between the two theories is unjustified, as they offer complementary approaches. While many debate on the (low) accuracy of Thermal Heat-balance Models in a broad range of conditions and climates [117], [178], especially the Fanger models, it is necessary to recenter the debate on Mixed-Mode (MM) control application.

The first aspect questioning the relevance of the PMV model (Table 4.2) for mixed-mode control in tropical conditions is its validity domain [80], [149], which does not fully comply with tropical conditions. Indoor ambient tropical conditions often reach temperatures over 30°C, high relative humidity rate ($RH > 60$ %), and air velocity on the higher end to enhance thermal comfort in NV and MM building ($0\ m.s^{-1} < \mathrm{V} < 2.5\ m.s^{-1}$). This go beyond the

validity domain of Fanger's original $PMV_{ISO,EN16798}$ with a maximum input temperature of 30°C and maximum air velocity of 1 $m.s^{-1}$ [42], [95]. This domain is extended by the American Standard 55:2023 [73] at a temperature up to 40°C and an air velocity in the $[0 : 2\ m.s^{-1}]$ extended range. It has been permitted by the introduction of the *"cooling effect"*, which is determined from the Gagge two-node model (SET index). The original $PMV_{ISO,EN16798}$ has proven to have low performance in warm conditions, systematically overestimating sensation on the right side of the scale. Recent research by Tartarini et al. [149] has highlighted that neither PMV model ($PMV_{ISO,EN16798}$ or AHSRAE 55:2023 PMV_{CE}) could accurately predict thermal sensations on the warm side. They should only be used in neutral conditions, i.e. $|\text{PMV}| \leq 1$, which in the presence of air velocity can still increase the comfortable temperature over 27°C, leading to AC usage and energy use reduction. They also recommend revising the validity domain of both standards to an indoor temperature in the $[17 : 30°\text{C}]$ range and maximum relative humidity to 80%, confirming again the limitation in tropical conditions. It is worth noting that the model is also only applicable to a uniform environment and steady state conditions [140]. Rugani et al. [49] note that the PMV is not well-suited for unsteady conditions and cannot model Personal Comfort Device such as ceiling fans. Huang et al. [207] demonstrated that, under warm steady-state conditions, the PMV model fails to account for the cooling effect of airflow when the skin wettedness exceeds the 'dry' threshold of 0.06.

All those drawbacks to its applicability in hot, humid, and high air movement conditions can be explained by a cursory consideration of evapotranspiration. Indeed, Fanger's equation considers heat loss through perspiration solely through the metabolic activity [119]. The evaporative sweating heat loss equation 2.15 clearly shows that at around 1 MET, the term remains constant. Hence, evaporative sweating occurs only during higher activity than office work. Any other influence, from relative humidity or air velocity, on evaporative cooling will be negligible, which sounds counterintuitive in tropical conditions.

Aside from Fanger's model, the Gagge model (Table 4.3) has undergone multiple refinements since its development in 1971 [80], [142], [208]. Vellei et al. [16] mention the most up-to-date versions and reference several studies on its performance, noting a good accuracy for neutral and warm or hot conditions. Parsons mentions another advantage of Gagge's model over Fanger's steady-state equation : thanks to its calculation procedure based on a time step of one minute, it is possible to conveniently determine the physiological constants over the chosen duration, making the model more dynamic and appropriate to unsteady conditions [107].

Evapotranspiration is one of the primary driving forces that regulate the human body in tropical conditions. Gagge's model proposed a more refined approach than Fanger's model. Sweating heat loss depends on the skin's wettedness and the difference in partial vapour pressure between the skin and the environment. It further demonstrates that skin wettedness, defined as the ratio of evaporation on the surface to the maximum evaporation capacity in the environment, is a good indicator of discomfort and thermal stress well beyond the sweating rate proposed by Fanger [114]. Furthermore, a recent study shows that physiological variables

such as skin temperature are well predicted by the model [151], [168].

Gagge himself, at the time the latest article regarding SET was published in 1986 proposed alternatives directly comparable to the PMV, namely the $PMV_{Gagge,1986}$ and the $PMV_{SET,1986}$. Gagge's extensions to the PMV framework take two forms. In PMV_{Gagge}, the Gagge two-node model is used to replace PMV's heat-loss/heat-gain equations. Alternatively, PMV_{SET} replaces the operative-temperature input with SET under low air-speed conditions. Designed for humid environments, this latter approach extends the usable temperature range of PMV from 30 to 40 °C. More recently, Zhang proposed two modifications of the PMV, the first one ($PMV_{SkinT,Zhang}$) substituting the original equation for skin temperature by Gagge's one, the second ($PMV_{SkinW,Zhang}$) by implementing the notion of skin wettedness from Gagge two-node model. While these approaches tend to enhance the Fanger model, it is questionable to do so when the two-node model could be used on its own.

Regarding the Gagge Two-node model, there are several options for its application in building control. SET index can be used as is, defining the sensation range based on the SET-Sensation and SET-acceptability correspondence table. This table 2.4, reproduced in section 2.2.3, is sourced originally from Gagge's books [142] and referenced in more commonly available McIntyre or Parsons books today [107], [114]. It should be close in essence to the Gagge T_{sens}, which we will confirm later. Gao et al. [156] mention the Predicted Thermal Sensation model based on SET. They reference McIntyre's book [114] even if the formulation is not clearly stated. One could assume that they regressed the model based on the correspondence table 2.4, accounting for minor rounding that we were unable to replicate in the present work. Based on skin wetness, the DISC index is dedicated to warm and humid environments; it should provide the best accuracy in our case study conditions. Alternative models developed by other researchers include those of Ji et al. [172], which are climate-specific regressions based on the ASHRAE Global Comfort Database II, featuring, for example, more than 10,000 observations in the tropics.

The Vellei Dynamic Mean Vote (DMV) is promising because, instead of using the two-node model outputs as a steady-state input to its sensation model, it utilises the time derivative of skin temperature to account for the dynamics of fluctuations in ambient conditions. The model captures the transient effects of changing environmental conditions. The DMV (Dynamic Mean Vote) is validated under stepped-change conditions in a lab experiment but has not been tested in real-building observations [147]. Unfortunately, it will not be possible to compare it to our data type, as it is not a right-here, right-now metric according to Carlucci et al. [209] definition (*"indices [...] developed to assess localised and instantaneous hygrothermal conditions inside a built space*). The Static Mean Vote (SMV) alternative will be better suited to our case study recorded data.

Above all, Gagge's two-node model and SET are known for being consistent in warm conditions [21], [173]; however, apart from the SET, the literature remains sparse in performance assessment of the aforementioned thermal sensation models.

Table 4.2: *PMV-based model quantitative screening*

Model index	Temperature control	Air speed control	Clothing flexibility	Validity domain	Hot/Humid conditions	Generalizable adaptive concept	Air movement syst. Flexibility	**Comments**	Selected
$PMV_{ISO,EN16798}$ *Fanger*, 1972	✓	✓	✓	(✓)	✗	(✓)	✓	Well established (ISO7730 and numerous standards) with useful satisfaction model (PPD). Air velocity limited to 1 $m.s^{-1}$ and dry bulb temperature to 30°C. The perspiration model is very simplified and only MET-dependent. I have proven to overestimate warm conditions. Valid for uniform and steady state conditions. Because of its popularity, we will use the Fanger model as a benchmark for model comparison.	✓
PMV_{CE} $PMV_{Adjusted}$ *ASHRAE* 55:2023	✓	✓	✓	(✓)	✗	(✓)	✓	Same core model as the Fanger $PMV_{ISO,EN16798}$ but extending the air velocity range to 2 $m.s^{-1}$ and dry buld temperature to 40°C by using the Gagge model to account for cooling effect. The PPD model's link to the PMV is questionable, as the equation has not been adapted to extend to different conditions.	✓
$PMV_{Gagge,1986}$ $PMV_{SET,1986}$	✓	✓	✓	✓	✓	(✓)	?	Extension of the PMV model by Gagge, using both the Gagge model to either replace heat loss/gain equations in PMV_{Gagge} or use SET has input to replace the operative temperature at low air speed. The latter $PMV_{SET}$is dedicated to humid environment and extend the PMV temperature range from 30 to 40°C	(✓)
$PMV_{SkinT,Zhang}$ $PMV_{SkinW,Zhang}$	✓	✓	✓	✓	✓	(✓)	?	Same core model as the Fanger $PMV_{ISO,EN16798}$ but extending with either modified equation for skin temperature or skin wettedness calculated by means of Gagge two-node model. The PPD model link to the PMV is questionable as the equation has not been adapted to extend conditions. Both model have been validated with latest Ashrae Global Comfort Database. Nevertheless, it is not mentionned whether is advised to use the standard equation or the PMV_CE equation to account for air velocity higher than 1 $m.s^{-1}$	(✓)

Table 4.3: *Gagge-based indices qualitative screening*

Model index	Temperature control	Air speed control	Clothing flexibility	Validity domain	Hot/Humid conditions	Generalizable adaptive concept	Air movement syst. Flexibility	Comments	Selected
$SET_{Gagge,1976}$	✓	✓	✓	✓	✓	(✓)	✓	Original Gagge two-node Standard Effective Temperature providing a normalised image of the environment, whatever the environmental and personal variables. While no continuous sensation model is provided, a sensation and acceptability scale is proposed for each SET range (see Table 2.4). Proven good in warm and hot conditions. Good skin temperature and wettedness prediction with refined evapotranspiration model. Valid for transient and non-uniform conditions.	✓
$T_{sens,Gagge,1976}$	✓	✓	✓	✓	✓	(✓)	✓	Gagge's original Sensation model linked to the two-node heat balance equation. Valid for a wide range of conditions. For very humid conditions, Gagge recommends the DISC index. Not widely used in scientific studies.	✓
$DISC_{Gagge,1976}$	✓	✓	✓	✓	✓	(✓)	✓	Gagge alternative sensation model for hot and humid conditions, calculated from skin wettedness or SET. Not widely used in scientific studies.	✓
$PTS_{McIntyre,1980}$	✓	✓	✓	✓	✓	(✓)	✓	Sensation model based referenced by Gao et al.[156] and proposed by McIntyre [114]. Simple linear regression from SET.	✓
$PTS_{Ji,2024}$	✓	✓	✓	✓	✓	(✓)	✓	New sensation models built from Gagge two-node and climate sub-datasets from ASHRAE Global Comfort Database II. Three linear regressions for hot and humid conditions. Simple linear regression from SET in the vein $PTS_{McIntyre,1980}$.	✓
$DMV_{Vellei,2024}$ $SMV_{Vellei,2024}$	✓	✓	✓	✓	✓	(✓)	✓	Sensation model to evaluate transient condition. DMV is proposed with a new satisfaction model (DPD). The updated version of 2024 outperforms the PMV outside the neutral range. DMV cannot be compared to actual data because votes are not recorded only with past corresponding IEQ data. Nevertheless, DMV could be used in MM control. SMV will be selected for further investigation	(✓)

Lastly, it is challenging to analyse the latest developments, attempting to convert a "black box" model into an explanatory one [79], or to incorporate an adaptive dimension into physics-based heat-balance models. From table 4.4 and 4.5, three groups of those models can be identified.

- **Fanger expectancy consideration:** this group include original $ePMV_{Fanger,2002}$ and subsequant addition by Gao et al. $eSET_{Gao,2015}$, $ePMV_{Gao,2015}$ and Zhang et al.

- **Yao adaptive feedback loop:** This group include original Yao et al. original $aPMV_{Yao,2009}$ and subsequant addition by Gao et al and Zhang et al.
- **Schweiker Adaptive Framework:** this group includes the variants of the ATHB framework for PMV and PTS ($ATHB_{PMV}$ $ATHB_{PTS}$) from both 2015 and 2020 study as well as Zhang et al. $PMV_{MET,Zhang}$ following the same philosophy of personal variable adaptation.

The first group is the Fanger "expectancy" consideration [167] $ePMV_{Fanger,2002}$ and later $ePMV/eSET$ variants by Gao et al. [156] and Zhang et al.[177], [180], [181]). The key concept behind the corrective factor is to retain the PMV core formulation and apply an expectancy factor e (and sometimes a reduction of MET per unit TSV) to better align predictions with field sensations for NV buildings. However, the value of e is difficult to estimate, as it is strongly linked to the AC penetration rate of the location where the building is investigated [79]. Therefore, a fixed e looks fragile. The thermal domain is also stretched (high T_{db}, high RH, elevated air speed v with fans), while it is not clear if one should rely on PMV_{ISO} or on PMV_{CE} with extended limits; the classical linked equation $PMV - PPD$ is not recalibrated either, which makes satisfaction evaluation uncertain. In short, these corrections behave like a statistical patch rather than addressing the physical mechanisms (evaporation, convective transfer with air movement) which are key in the tropics. Gao et al.[156] ($ePMV/eSET$) contribution to the generic coefficient is only based on cold and temperate weather in China for both the case of low air velocity and high air velocity, out of the scope of the original Fanger and Toftum study. Zhang et al. added several improvements for the "e" factor determination and even proposed an indoor temperature regression-based approach to match the Adaptive Model theory [177], [180], [199].

The second family is the Yao "adaptive feedback" approach $aPMV_{Yao,2009}$ and its extensions, including $aSET$. Here, a coefficient a is regressed from large questionnaire datasets (often with TSV and T_{db}) and then used to correct PMV. This looks attractive but is very dataset-dependent; outside the training context (different culture, building stock, or operation). It hence lacks generalisability. There is also a risk of circular logic (calibrating on TSV to predict TSV back), so explanatory power remains limited. Several generic coefficients based on the Chinese building stock and later on a larger dataset should be investigated. Still, the same drawbacks from the PMV model remain. Gao et al. [156] and Zhang et al.[177], [180], [181]) transposed exactly the same concepts they proposed for the $ePMV$ to the $aPMV$.

The third family is the Schweiker et al. [183], [184] adaptive heat-balance framework, $ATHB_{PMV}$ and $ATHB_{PTS}$, which appears the most promising because it is more transparent in its attempt to consider the effects of individual adaptive processes [115]. The method maintains a physics-based balance while modifying inputs, such as MET and CLO, using regressions from RP-884 or the ASHRAE Global Comfort Database. This is more mechanistic, but practical issues remain: lower bounds on clothing (e.g., $CLO_{\min} \approx 0.46$) are not consistent with actual dress code in tropical settings (at least for our case study with 0.29 lower bound and

0.48 mean), which can bias predictions. Guidance on air speed as an adaptive opportunity is not always explicit (PMV_{ISO} vs. PMV_{CE}), while high v (over 1 $m.s^{-1}$) is available and beneficial in the tropics. Nevertheless, the Gagge-based version of the model could be more interesting for our study. Furthermore, the coverage of truly tropical cases is limited in the validation of the 2015 model [183] and the latest iteration [184], where the tropical group A is not investigated. Finally, dependence on site-specific or hard-to-measure variables (e.g., $PSYCH$) reduces the portability of the concept. We also place $PMV_{MET,Zhang}$ in this group because it follows a similar idea of adapting personal variables. $PMV_{MET,Zhang}$ has been developed for a specific population (students) and application (classroom and aircraft cabin), which places it outside the scope of this study's selection.

Overall, while each family tries to "open" the black box or to infuse adaptive concepts into heat-balance, their applicability to tropical humid climates and to MM operation stays questionable because the extensions are either statistical and context-bound, or they remain underspecified when T_{db} is high, RH is high, and v is large. Further investigation based on this thesis's experimental aspect will be valuable in better catching the value of these attempts to bridge the best of both worlds. These investigations will refer to the generic coefficient proposed by the numerous literature and enumerated in section 2.3.5. Creating a new coefficient based on our data is outside the scope of this thesis because it would be contrary to the criteria of generalisability above defined. The aim is not to create the best-fitted model to our case study but to propose a transferable solution for similar building designs.

Table 4.4: *Adaptive THM model qualitative screening (part 1)*

Model index	Temperature control	Air speed control	Clothing flexibility	Validity domain	Hot/Humid conditions	Generalizable adaptive concept	Air movement syst. Flexibility	Comments	Selected
$ePMV_{Fanger,2002}$	✓	✓	✓	✓	✓	(✓)	✓	Corrected model by Fanger, specifically designed for NV building. Twofold correction of the original PMV value to account for adaptation. MET is reduced by 6.7% for each TSV over 1, and an expectancy factor "e" is applied to the final calculation. Difficult to estimate the "e" and unclear how it has been estimated. MET correction justification lacks evidence based justification.	✓
$nPMV_{Humphrey}$ 2002	✓	✓	✓	(✓)	✗	✗	✓	The nPMV uses a correcting factor regressed from a large dataset, but only with NV and AC buildings. It is dependent on outside temperature, operative temperature, relative humidity, clothing, and metabolism. The model is a cooling system independent so could be used for either NV or AC operation	✓
$aPMV_{Yao,2009}$	✓	✓	✓	✓	✓	✓	✓	Proposed adaptive coefficient regressed from TSV and T_{db}, built on Chinese building stock dataset including tropical climate. Adaptive coefficient a is based on adaptive feedback theory with a "circular logic" to correct the PMV. The authors propose a generic coefficient set for AC and NV building based on various Chinese climates. The conception is included in GB/T 50785 as a complementary approach to $AM_{GB/T\,50785}$ The concept appears very impractical due to its strong dependence on large on-site questionnaires if the generic coefficients are not used.	(✓)
$ePMV_{Gao,2015}$ $aPMV_{Gao,2015}$ $eSET_{Gao,2015}$ $aSET_{Gao,2015}$	✓	✓	✓	✓	✓	✓	✓	Propose a new formulation to determine expectancy e and reproduce Yao's formulation for adaptive coefficient λ based on data for three chinese educational NV buildings (dorms, teaching classes, offices). Propose extension of $ePMV$ and $aPMV$ concepts to SET and PTS because SET is proven to represent reliably the effect of air movement through both convective and evaporative sweating [115]. The authors provide generic coefficients. Very dependent on the dataset if the generic coefficient is not used. The distinctive impact of this study is the proposition of a coefficient for low air velocity and high air velocity. The concept, identical to Yao's $aPMV_{Yao,2009}$ suffers from the same drawbacks	(✓)

Table 4.5: *Adaptive THM model qualitative screening (part 2)*

Model index	Temperature control	Air speed control	Clothing flexibility	Validity domain	Hot/Humid conditions	Generalizable adaptive concept	Air movement syst. Flexibility	Comments	Selected
$ATHB_{PMV}$ $ATHB_{PTS}$ *Schweiker* 2015 – 2020	✓	✓	(✓)	?	(✓)	(✓)	✓	Adaptive concepts are considered through MET and CLO adjustment (no expectancy considered). For the 2015 model, regression models for adapted personal variables are built using RP-884. 2022 models enhance the initial proposition by integrating model type and building types to adapt to personal variables, based on the latest ASHRAE Global Comfort Database II. The CLO values have a minimum threshold of 0.46, which makes the model inconsistent with our MM case study comfort survey. Furthermore, it is not specified whether one should consider the original PMV_{ISO} equation for air velocity or if PMV_{CE} is also valid with extended upper limits for T_{db} and v. In the authors' papers, performance is evaluated for numerous climates, but not tropical ones. The model is dependent on an on-site recorded variable named PSYCH, making it highly data-dependent.	(✓)
$aPMV_{Zhang,2019}$	✓	✓	✓	✓	✓	✓	✓	Modification of the original $aPMV$ adaptive coefficient λ calculation procedure to enhance final prediction. Very dependent on the "training" dataset if the generic coefficient is not used.	✓
$PMV_{MET,Zhang}$ 2020	✓	✓	✓	✓	✓	✓	✓	MET adjustment correction based on temperature and air velocity. The correlation between MET and temperature is well established, but there is a lack of evidence-based correlation with air velocity. The regression is validated on the RP-884 database. Designed for both the student classroom and the aircraft cabin. The PMV original equations are abandoned in favour of simple quadratic regression of environmental variables.	✗
$ePMV_{p,Zhang}$ $arPMV_{p,Zhang}$ *and equivalent SET / PTS methods* 2020	✓	✓	✓	✓	✓	✓	✓	Modification of the original $aPMV$ adaptive coefficient and $ePMV$ calculation procedure to enhance final prediction. Both "e" and "λ" coefficients are from a linear regression of temperature ($a.T + b$). Very dependent on a large questionnaire database when the generic coefficients are not used.	✓

4.2 Quantitative screening

This first round of qualitative screening did not allow determination of the best-suited model, but it did help narrow the selection for quantitative screening. Above all, PMV variants will remain in scope for benchmarking purposes. The SET index, calculated from the Gagge two-node model, appears most promising—particularly via the Parkinson adaptive SET

regression model, which is directly applicable to MM control (but can not be compared to our data). All other Gagge-based indices require further investigation, as their performance is not well documented. Finally, adaptive thermal heat-balance models also lack performance assessment and should be further investigated in their original formulation, i.e., with the generic corrective coefficients provided by their authors.

These thermal sensation models (e.g., PMV) are defined as predicting "the average thermal sensation of a large group of occupants" [149]. Because neither the definitions nor the standards specify a minimum required number of occupants, we will analyze the full Co-architecte population as a single group. One-by-one (individual) vote comparisons are not recommended.

4.2.1 Models and computation

For performance evaluation, all required models were computed with open-source scripts whenever they were referenced in the literature. Pythermalcomfort is a Python library supported by the Centre for the Built Environment and developed by Tartarini et al.[128]; version 2.10 was used in this work. Rcomf is an open-source `R` library created and maintained by Schweiker et al.[210]. *SMV* model is provided by Vellei et al. in their article [174], which includes a modified Gagge-model procedure adapted from `Pythermalcomfort 2.09`. Some custom development was undertaken when open-source options were unavailable, particularly for adaptive THM and alternative sensation models. Please also note that the relative air velocity and the resultant clothing insulation were calculated using the equations provided in Section 2.1.3 when applicable.

The following Tables 4.6 and 4.7 list all variants of the selected indices compared with the recorded votes from the demonstrator used in this thesis. The column fields provide the following information about the investigated models

- **Base model :** This is the foundation of the model, i.e Fanger equation or Gagge equation, followed, if applicable, by the author who proposed the modified model
- **Variant:** If applicable, the base model is declined in several variants
- **Reference:** Main source(s) from the literature
- **Source code:** Most indices were computed using open-source scripts. The tables include a *Code* column with icons that correspond to the following :
  - PTC is given for PythermalComfort Library;
  - RC is given for Rcomf Library;
  - V is given for Vellei source code ;
  - CS is given for Custom-developped script.
- **Details:** Further details relative to the model variant are given, such as the coefficients and applicability of the model.
- **Figure (Fig.):** Figures number where the performance of the model can be observed.

Overall, the original Fanger $PMV_{ISO,EN16798}$ and the ASHRAE version of the model are represented on all the figures for reference. They are detailed in Table 4.6 with Gagge PMVs, Gagge indices, Vellei Gagge-based static mean vote, and all Schweiker's $ATHBversion$. Table 4.7 describe the Fanger $ePMV$, for which we tested only three cases from 0.5 to 0.9, Yao et al. [102] original work and its Chinese GB/T building code version and all variations of Gao et al. that give different expectancy and adaptive coefficient for low air speed and high air speed. The complete set of Zhang PMV and PTS variants is also listed in this table. For more details on the models' concepts, we refer to their original paper and Chapter 2 of the present manuscript.

Table 4.6: *Evaluated models' details for quantitative screening*

Base Model	Variant	Ref.	Script	Details	Fig.
Fanger	$PMV_{ISO,EN16798}$	[99], [119]	PTC	Original PMV	*all*
Fanger	$PMV_{CE,ASHRAE\,55:2013}$	[73], [149]	PTC	ASHRAE version with Gagge elevated airspeed	*all*
Fanger - Humphreys	$nPMV$	[178]	CS	DMV correction of PMV	4.2,4.4
Fanger - Gagge	PMV_{SET}	[121]	PTC	PMV with SET	4.2,4.5
Fanger - Gagge	PMV_{Gagge}	[121]	PTC	PMV with SET	4.2,4.5
Gagge	$PTS_{McIntyre}$	[114], [156]	PTC CS	Gao regression based on McIntyre book	4.2,4.5,4.6
Gagge	T_{Sens}	[121], [153]	PTC	Original Gagge Sensation model	4.2, 4.5, 4.6
Gagge	$DISC$	[121]	PTC	Original Gagge Discomfort model	4.2, 4.5
Gagge	$PTS_{Ji,TropicalSavanna}$	[172]	PTC CS	TropicalSavanna regression	4.2, 4.3
Gagge - Ji	$PTS_{Ji,HumidSubtropical}$	[172]	PTC CS	HumidSubtropical regression	4.2, 4.4
Gagge - Ji	$PTS_{Ji,WetEquatorial}$	[172]	PTC CS	WetEquatorial regression	4.2, 4.3
Gagge - Vellei	SMV_{Vellei}	[174]	V	Static Mean Vote	4.2, 4.4
Fanger - Schweiker	$ATHB_{PMV,original}$	[183]	RC CS	Original ATHB model (RP884)	4.2, 4.4
Gagge - Schweiker	$ATHB_{PTS,original}$	[183]	RC CS	Original ATHB model(RP884)	4.2, 4.5
Fanger - Schweiker	$ATHB_{PMV,standard}$	[184]	RC CS	Standard method with updated ASHRAE Global comfort database II	4.2, 4.5, 4.6
Fanger - Schweiker	$ATHB_{PMV,extended}$	[184]	RC CS	Extended method MM regression	4.2, 4.3

Table 4.7: *Evaluated models' details for quantitative screening*

Base Model	Variant	Ref.	Script	Details	Fig.
Fanger	$ePMV_{0.5}$	[167]	PTC	e = 0.5 low : region with few AC	4.2, 4.4
Fanger	$ePMV_{0.7}$	[167]	PTC	e = 0.7 moderate : region with some AC	4.2, 4.4
Fanger	$ePMV_{0.9}$	[167]	PTC	e = 0.9 high : region where AC is commun	4.2, 4.4
Fanger - Yao	$aPMV_{Yao,original}$	[102], [179]	PTC CS	λ = 0.293	4.2, 4.4
Fanger - Yao	$aPMV_{Yao,GB/T}$	[102], [179]	PTC CS	λ = 0.21 Chinese code recommanded coefficient	4.2
Fanger - Gao	$ePMV_{Gao}$	[156]	PTC	e = 0.770 for velocity over 0.2 $m.s^{-1}$ e = 0.974 for velocity under 0.2 $m.s^{-1}$	4.2, 4.5
Fanger - Gao	$aPMV_{Gao}$	[156]	PTC	λ = 0.167 for velocity over 0.2 $m.s^{-1}$ λ = 0.029 for velocity under 0.2 $m.s^{-1}$	4.2, 4.3
Gagge - Gao	$ePTS_{Gao}$	[156]	PTC	e = 1.330 for velocity over 0.2 $m.s^{-1}$ e = 1.363 for velocity under 0.2 $m.s^{-1}$	4.2, 4.3
Gagge - Gao	$aPTS_{Gao}$	[156]	PTC	λ = −0.195 for velocity over 0.2 $m.s^{-1}$ λ − 0.213 for velocity under 0.2 $m.s^{-1}$	4.2, 4.3
Fanger - Zhang	$ePMV_{Zhang,AC}$	[181]	PTC	$e = -0.0570\,T_{db} + 1.4557$ for AC buildings	4.2, 4.3
Fanger - Zhang	$ePMV_{Zhang,NV}$	[181]	PTC	$e = 0.0058\,T_{db} + 0.3132$ for NV buildings	4.2, 4.4
Gagge - Zhang	$ePTS_{Zhang,AC}$	[181]	PTC	$e = 0.0256\,T_{db} + 0.1905$ for AC buildings	4.2, 4.3
Gagge - Zhang	$ePTS_{Zhang,NV}$	[181]	PTC	$e = 0.0500\,T_{db} + 0.7403$ for NV buildings	4.2, 4.3
Fanger - Zhang	$arPMV_{Zhang,AC}$	[181]	PTC	$\lambda = 0.240\,T_{db} - 5.326$ for AC buildings	4.2, 4.3
Fanger - Zhang	$arPMV_{Zhang,NV}$	[181]	PTC	$\lambda = 0.034\,T_{db} - 0.646$ for NV buildings	??
Gagge - Zhang	$aPTS_{Zhang,AC}$	[181]	PTC	$\lambda = -0.0197\,T_{db} + 1.1281$ for AC buildings	4.2, 4.3
Gagge - Zhang	$aPTS_{Zhang,NV}$	[181]	PTC	$\lambda = -0.1946\,T_{db} + 5.88232$ for NV buildings	4.2, 4.3

4.2.2 Overall model prediction comparison to recorded votes

The following figure explores the prediction of the 34 selected models against the actual recorded votes from the Coarchitects field survey. Recalling that the survey aggregates all subjects and all spaces for the two selection summer periods of 2023 and 2024, as described and analysed in Chapter 3. The dataset contains 1911 records with matching Indoor Environmental Quality measurements used as input for each model. For all field survey records, models are calculated with above-mentioned details in tables 4.6 and 4.7 to provide a continuous thermal

sensation which is then "categorised" to match the seven-point ASHRAE Thermal Sensation Scale.

Figure 4.2 aims to provide an overview of model predictions against the observed vote. Each row of bar charts illustrates the model-predicted thermal sensation distributions on the same scale as the recorded vote, ranging from -3 (Very cold) to +3 (Very Warm/Hot), in a blue-to-red colour gradient. Grey represents the neutral votes. The panel is expressed in both the number of observations (bottom x-axis) and the percentage of observations (top x-axis). The Y-axis presents the predicted sensation for each model, based on the warm votes (sum of "+3", "+2", and "+1") in ascending order (top to bottom).

The actual vote distribution is separately plotted at the bottom of the bars as a reference. Actual vote reference bars are also reproduced at their ranked position within the model predictions. It is highlighted with a thick dark frame. The reference actual vote is dominated by Neutral vote (60-65%), then slightly warm votes (25-30 %) and warm to hot votes at around 15%. Cold votes are minimal, with less than 10% of the observations.

Some models are far away from the prediction on the cold side: as an example, $arPMV_{Zhang,AC}$ predicts 65 % of cold votes, which is obviously totally inconsistent. This might be due to the very data-dependent adaptive coefficient proposed in their study and the fact that the corrective factors are defined for AC operation. This is confirmed by the other variant $ePMV_{Zhang,AC}$, which predicts only neutral votes. All other variants proposed by Zhang et al. [180], [199], which are based on PMV or PTS, fail to correctly predict the vote. The closest to the actual vote would be $arPMV_{Zhang,NV}$, which predicts well warm or neutral conditions, but with no increment in sensation on the warm side. Ji et al's Predicted Thermal sensation model for three tropical climates is also far from actual records on both the cold (2 times more) and the warm (two times less) good prediction for tropical Savana $PST_{Ji,HumidTropicalSavanna}$ and Wet equatorial $PST_{Ji,WetEquatorial}$ climates. Surprisingly, the Humid Subtropical regression $PST_{Ji,HumidSubtropical}$ is very close to the actual recorded vote, despite its foundation being data from essentially colder and drier climates than classical tropical ones. This questions the reliability of such regressions or suggests that the experimental survey in this work behaves differently from a classical tropical population. $ePMV$ with 0.5 expectancy factor and the adjusted PMV_{ce} are getting closer to predicting overall sensation with a very close overall warm vote prediction (25-30%), still underestimating warm votes. On the other side, when choosing 0.7 as an expectancy factor for the $ePMV$, we get very close (+/- 3-5%) to the actual overall vote distribution, may it be for cold, neutral or warm sensation. $ATHB_{PTS}$ follows the same trend with the warm vote being very close, but it slightly overestimates on the cold side compared to the PTS proposed by Gao based on McIntyre's work ($PTS_{McInytre}$). This introduces complexity for relatively modest improvements in prediction. Finally, the original Yao's adaptive concept and Fanger expectancy concept, adapted by Gao with a new formulation to PTS ($aPTS_{Gao}$) and PMV ($ePMV_{Gao}$), still provide accurate overall predictions, maybe thanks to the concept of two coefficient, one for high air velocity and one for low air velocity.

Gagge-based original indices, such a T_{sens}, modified PMV (PMV_{Gagge} and PMV_{SET}) or even $DISC$, do not score very high in individual prediction with 12% to 23% more warm votes, thus yielding to more AC usage if used for a control algorithm. On the contrary, Vellei SMV excels at predicting the total count on the warm side but fails to predict details in warm and hot votes. It also overestimates cold votes.

It is noteworthy that most models, while performing well in predicting warm conditions, struggle to distinguish between slightly warm and warm or hot conditions. The only two models that can do so are the $PTS_{McIntyre}$ and $aPTS_{Gao}$, which come at the cost of slight overestimation on the warm side. They are also quite cold on the side. This would make them good candidates for control if the target of acceptability or satisfaction drifts on the right side of the thermal scale.

On average, several models predict outcomes similar to those recorded by the comfort survey, with some models getting very close. Nevertheless, this graphical representation has two drawbacks. Firstly, while giving a rich overview of model behaviour, this approach may not accurately represent factual discrepancies between predictions and observations. For example, the model can predict 'neutral' when the observation is slightly warm and then predict 'slightly warm' when an observation is neutral, which cancels out the error. Secondly, it is also essential to focus on the primary question, which is to use the model to control the cooling system. Indeed, the graphical representation compares the overall distribution of votes in a population. Each record represents a unique vote, and for each record, we calculate a mean vote of a large group of people [149]. To achieve greater consistency, it would be necessary to average the population votes. It makes complete sense from a control perspective. Indeed, investigating the comparison at a macro scale does not appear to be sufficient. In real building control, actions are taken based on real-time measurements. Therefore, the actual recorded votes should be averaged after having binned them on an easily measurable physical variable and then compared to the mean vote predicted by the models. It is easy to measure dry bulb temperature and relative humidity, but relying on air velocity or globe temperature measurement is more challenging due to cost and intrusiveness. For the sake of the demonstration, we will depend on the example of dry buld temperature.

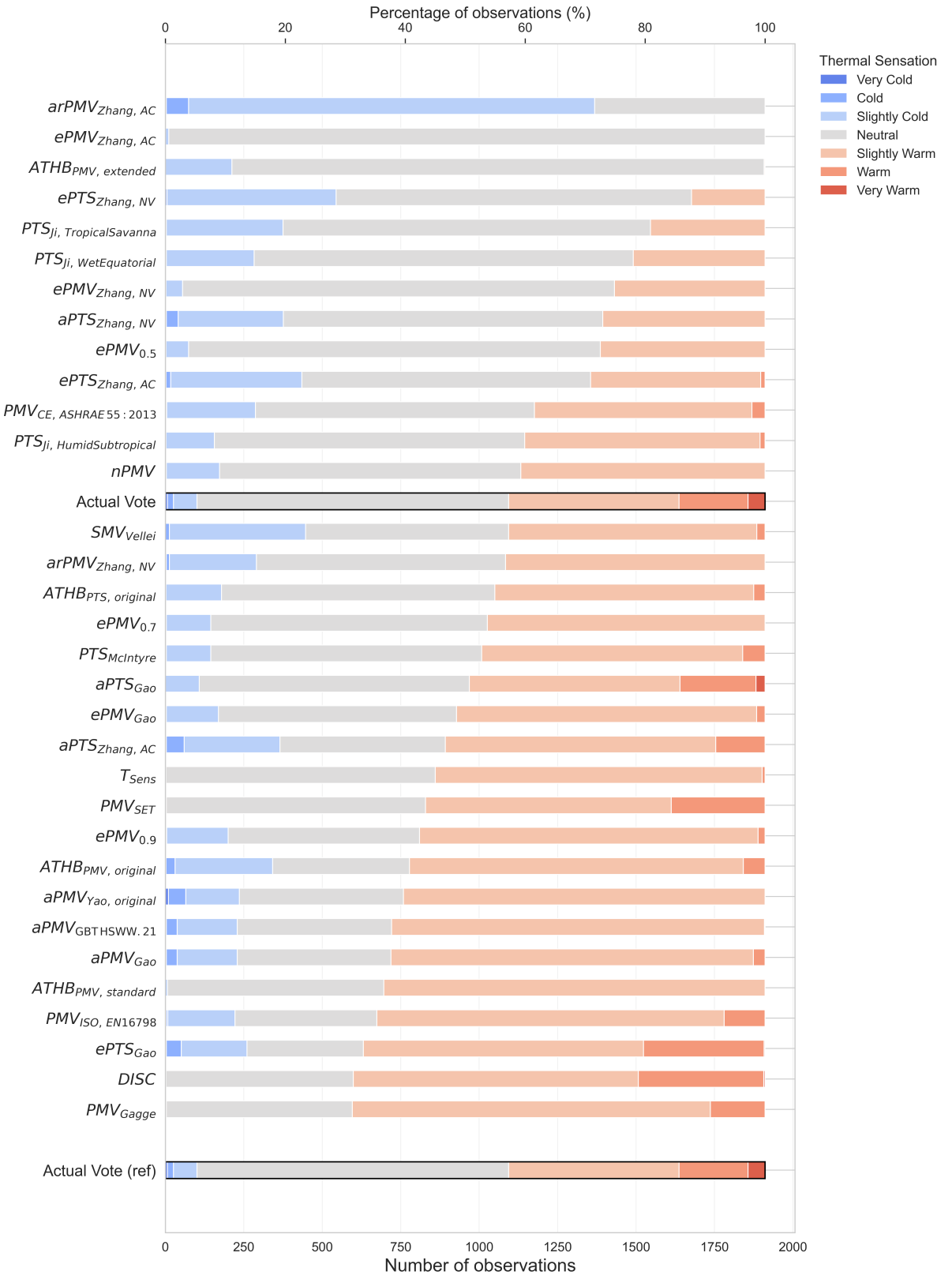

Figure 4.2: *Comparison of Model Predication against recorded vote (1911 records) of Coarchitectes field survey summer conditions*

4.2.3 Control-based comparison

Based on a previous macro-level exploration of the prediction performance of the models, the following figures examine their performance from a control perspective. Figures 4.3, 4.4, 4.5, and 4.6 show four groups of models, ranked based on their performance in predicting a mean thermal sensation against a mean recorded sensation for the whole population of the coarchitect building. We primarily bin recorded votes in 0.5 °C temperature ranges. This chart shows bins from 24 to 31 °C on the horizontal axis. Beyond those limits, the number of observations varied significantly in terms of the number of voters and fell outside the selected summer periods (see Chap. 3). The vertical axis represents the predicted mean thermal sensation with a 0.25 increment, and the range is zoomed in on [-1.5: 1.5]. Orange dots represent actual mean votes, circled by a light grey disk whose size corresponds to the number of observations in the temperature bin. As can be easily observed in each figure, the bins contain at least 50 observations between 25°C and 27.5°C. Between 28 and 29 °C, bins count a hundred votes. The range between 29 and 31 °C contains the most votes, with more than 200 observations per bin. The over 31°C bin remains sparse in votes, with around 60 votes for the last bin. To facilitate reading, we made a graphical distinction between PMV-based, PTS-based, and the two reference PMV models. A solid line with a cross for the bin mean represents PMV-based models. PTS-based models and other alternatives are plotted in dashed lines with a triangle indicating the bin average vote. On each plot, we plotted both standard-compliant PMV models for reference. $PMV_{ISO,EN16798}$ in a thicker solid dark line presents a strong drift in predicting accurately the Coarchitects building mean actual vote. On the cold side of the scale, it underestimates sensation by 0.5-1 point, and on the warm side of the scale, it presents a systematic overestimation of 0.5 points. $PMV_{CE,Ashrae\ 55:2023}$ in a thicker solid grey line, does not render better on the cold side of the scale, but the "cooling effect" adjustment of the 55:2023 index makes warm predictions rather good from temperatures over 28°C.

Figure 4.3 shows the lowest-ranked indices. Overall, all models presented in this figure exhibit very low prediction accuracy below 29°C and generally low accuracy under 29°C, rendering them largely irrelevant for sensation prediction in our case study. Indices dedicated to AC, i.e with a generic coefficient built on an AC-operated building and coupled to the PMV equations, such as $ePMV_{Zhang,AC}$ in brown and $arPMV_{Zhang,AC}$ in purple, are totally out of prediction. It highlights the substantial discrepancy between AC and other types of cooling operations. Furthermore, they present negative slopes which could indicate that over 25 °C or 26°C, they are out of the validity range of the data-regressed coefficient, resulting in very inconsistent predictions. Gao's updated $aPMV$ (green) and $aPMV$ with the Chinese GB/T HSWW coefficient (red) are closer in prediction to the actual vote on the warm side, following the same trend but vastly overestimating the mean thermal sensation vote by 0.3. Furthermore, Fanger ePMV is not mentioned on the figure, demonstrating that Zhang's and Gao's updated versions are less accurate than the original concept of Fanger and Toftum. Again, the original $aPMV$ by Yao is not present on this figure, demonstrating that the updated

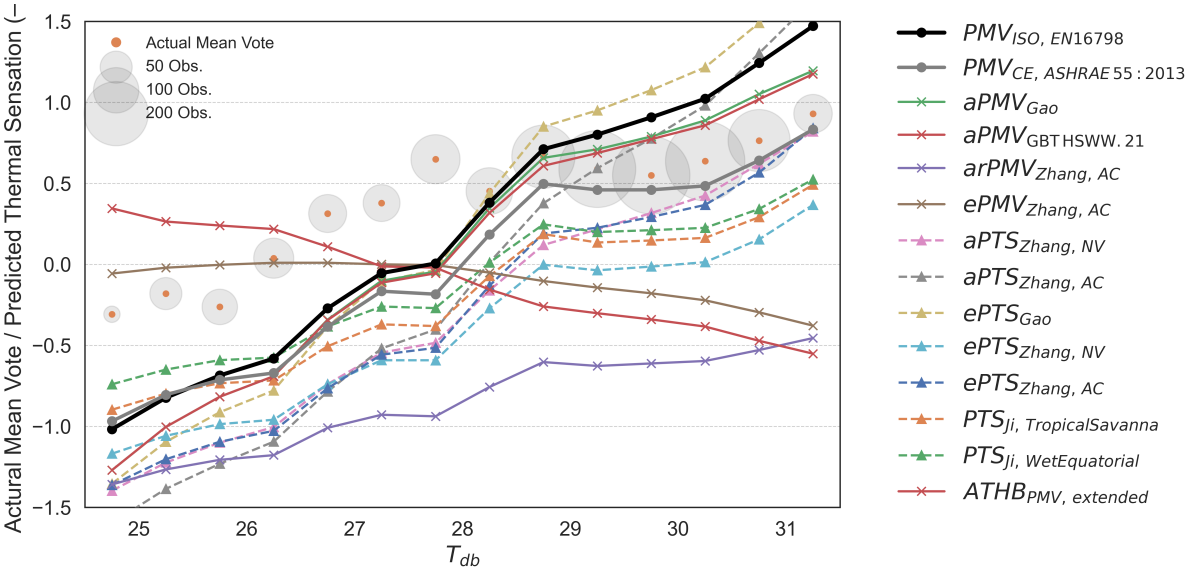

Figure 4.3: *Quantitative screening: Lowest-ranked thermal sensation indices*

versions of $aPMV$ by Gao and Zhang are less accurate in our case. Regarding PTS-based versions, they are all better predictors of warm sensations but still fall significantly short in predicting actual votes, with considerable underestimation (greater than 0.4 TSV units), and also remain far from PMV_{CE} predictions.

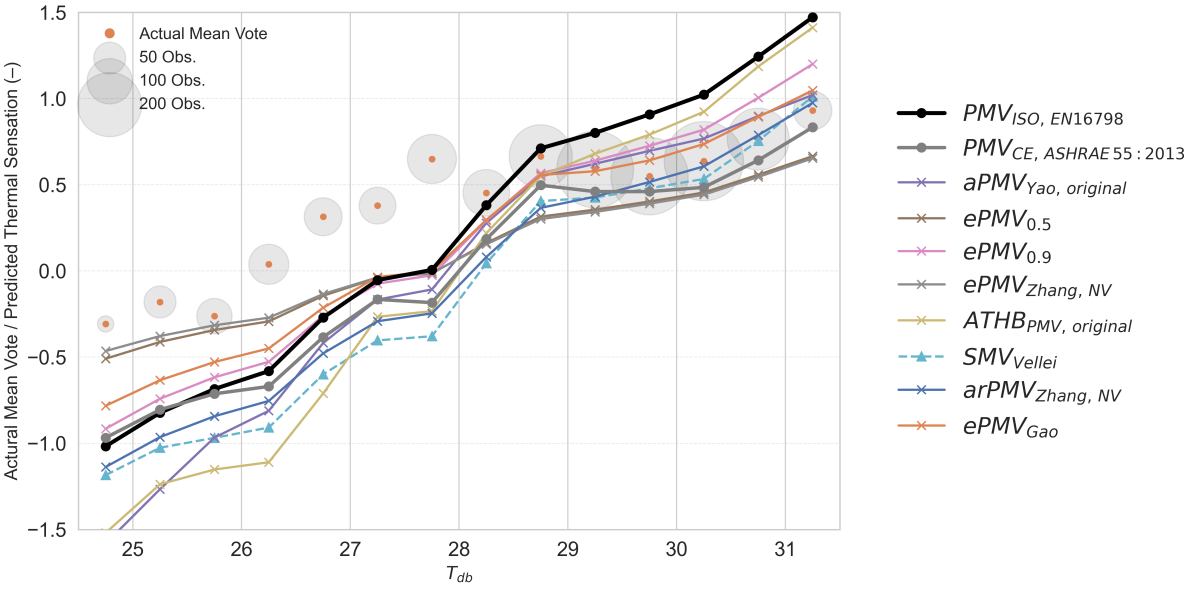

Figure 4.4: *Quantitative screening: Third-ranked thermal sensation indices*

Figure 4.4 shows a few better predictors. Unless $ePMV_{0.5}$ (brown) and $ePMV_{Zhang,NV}$ (grey), which are best in predicting sensation on the coldest side of the scale (under 26°C), all other models are better predictors only on the warm-to-hot side of the scale (over 28°C). They all fall in between reference $PMV's$ ($PMV_{ISO,EN16798}$ and $PMV_{CE,Ashrae\ 55:2023}$), making them more relevant in this situation for our case study. $ATHB_{PMV,Original}$ (yellow) is quite close to $PMV_{ISO,EN16798}$ on the warm side. But, it significantly underestimates the sensation

on the neutral-to-cold side by 0.7-2.0 units. On the warm overestimation side, Fanger $ePMV_{0.9}$ (pink), original Yao's $aPMV_{Yao,original}$ (purple) and $ePMV_{Gao}$ are correct performers, slightly overestimating by a few tenth of a unit. Vellei SMV is also very good on this warm side, and $arPMV_{Zhang,NV}$ is excellent. Nevertheless, they all fall significantly short of the actual recorded sensation when temperatures drop below 28.5°C, thereby solving only part of the control problem.

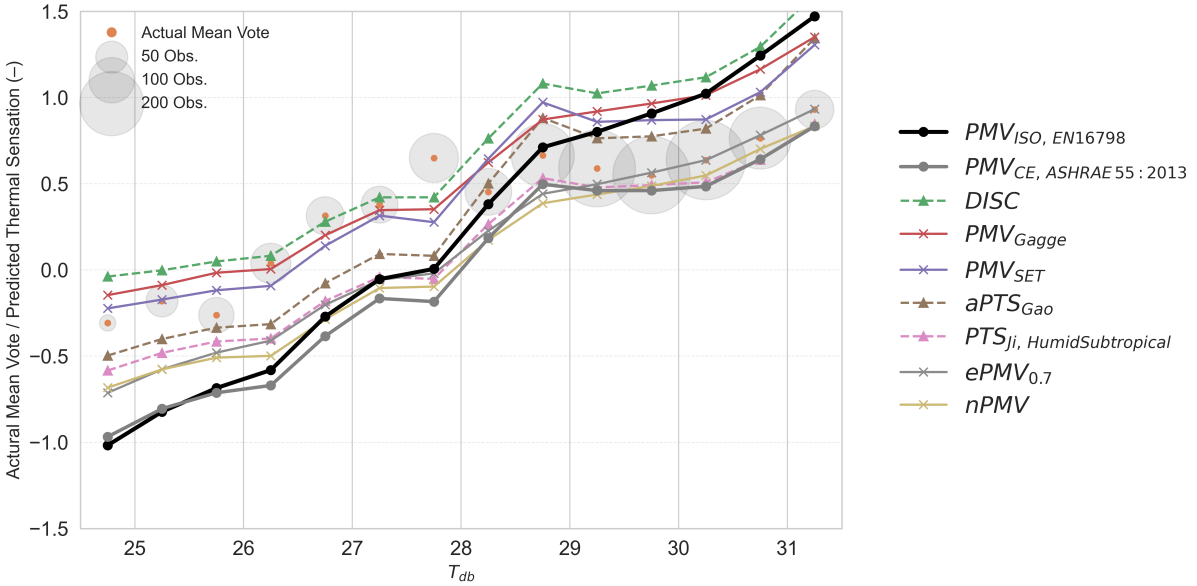

Figure 4.5: *Quantitative screening: Second-ranked thermal sensation indices*

Figure 4.5 also shows better predictors, but mainly on the neutral to cold side. Indeed, Gagge-based indices such as $DISC$ (green), PMV_{Gagge} (red), and PMV_{SET} (purple) appear as promising candidates for prediction under 28°C but deviate significantly from the mean recorded vote when the temperature exceeds 29°C which was already the case in figure 4.2. SET-based $aPTS_{Gao}$ makes the prediction more realistic, following better the distribution of recorded votes. The previous comparison in Figure 4.2 ensured consistency in reproducing the distribution of votes, with a slight overestimation in the "slightly-warm" category. Furthermore, on the warm side, they surprisingly predict higher sensation than the ISO PMV (black) itself. Humphrey's indoor ambience-corrected $nPMV$ (yellow) predicts better overall than all others across the entire range, but not better than the more straightforward and easily calculable implementation of Fanger's $ePMV_{0.7}$ (grey). Again, SET-based regression from Ji ($PTS_{Ji,HumidSubtropical}$) shows good predictions and follows the distribution of mean recorded votes, slightly underestimating neutral to cold votes. It does not predict better than the PMV_{CE}, though, on the warm side. Overall, all indices shown in this figure predict a neutral to cold vote under 28°C with higher accuracy than the reference ISO and ASHRAE $PMVs$.

The last figure 4.6 presents the most consistent indices in reproducing the case study distribution of mean recorded vote per temperature bin. All presented indices predict better overall than the reference $PMV's$. Schweiker $ATHB_{PTS}$ 2015 (No updated version of PTS was proposed in 2022), built from the former RP-884 database, shows very similar results to the

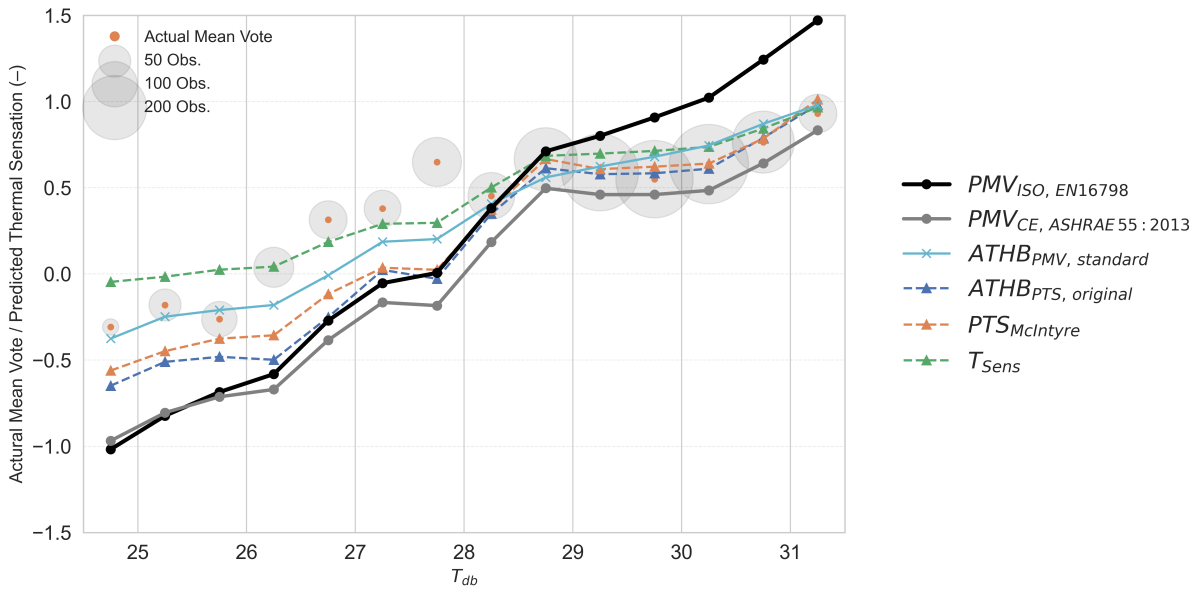

Figure 4.6: *Quantitative screening: Best-ranked thermal sensation indices*

Gao/McIntyre SET-based $PTS_{McIntyre}$. They are excellent at reproducing the distribution mean vote of the population when the temperature exceeds 28°C, but underestimate sensation by 0.15-0.2 TSV units at temperatures below 28°C. $PTS_{McIntyre}$ remains a little better under 28°C and is more straighforward to calculate (no need to input the mean outdoor temperature). Schweiker ATHB framework $ATHB_{PMV,standard}$ (light blue), built in 2022 on ASHRAE Global Comfort Database II with 2015 original method, is rather very good when temperatures are over 29°C, and is far better than the $ATHB_{PMV,Original}$ built on RP 884 (see $ATHB_{PMV,Original}$ on figure 4.3). The results are similar to those of the former method, the PTS version of ATHB. Hence, updating the $ATHB_{PTS}$ of 2015 with the more recent ASHRAE Global Comfort Database II could be an opportunity to again improve the SET-based $ATHB_{PTS}$ model. It is noteworthy that when looking at an overall comparison in figure 4.2 $ATHB_{PTS}$ was well ranked, but $ATHB_{PMV,standard}$ was very far from actual reference votes. We found the same difference with T_{sens}, which is closely related to SET, when it was averaged and ranked in Figure 4.2. Nevertheless, in conjunction with$ATHB_{PMV,standard}$, T_{sens} are the best performers in reproducing the whole distribution of actual recorded mean vote when performing a temperature-binned comparison, but at the cost of a very slight warm vote overestimation. The 28-31°C range is where the most records occur, making the comparison more reliable and favoring SET-based PTS indices.

Comparing model predictions to actual votes can be done in different ways, but it should target a clearly defined objective. Both types of comparison we proposed provide helpful information for selecting the most consistent index. While some models can provide an overall close-to-actual, consistent distribution of votes, it is not apparent that they can reproduce the same structure when a binned comparison is conducted. The binned comparison is closer to reality in terms of what a building simulation might encounter in terms of building control. The last four binned comparisons permitted the exclusion from the study of many indices that over- or underestimated the mean vote of a population on the cold or warm side. The

last figure 4.6 highlights two categories of indices that could be used in an MM control simulation. The ATHB framework indices, while excellent at reproducing the mean vote distribution, raise questions about their applicability due to the systematic adaptation of met and clo which fall outside of simulation control. Furthermore, they do not provide much more performance than the original Gagge-based model, such as T_{sens} or PTS regression. These are only minor shortcomings, and the underlying concepts of Schweiker appear to be highly robust. Nevertheless, the well-established performance of the Gagge model under hot and humid conditions, together with the confirmation that the simple indices that can be derived from it are accurate for the studied condition range, leads us to favour SET-based solutions as the study progresses.

4.3 Model sensitivity to controllable parameters

4.3.1 Problematic

Having processed a quantitative and a qualitative screening of various comfort models from the literature, the selection is narrowed down to a few options. Namely, the Gagge two-node SET index is regarded as a good candidate for several reasons. (1) It can be used as is, utilising the averaged correspondence table proposed by Gagge, which can be found in [107], [114], [142]. The T_{sens} regression model serves as the foundation of this table, and therefore, it is closely related to SET-based control. Lately, Gao et al. [156] proposed the PTS regression based on SET. Again, Parkinson et al.[78] propose an MM-specific Adaptive Model to determine the SET neutral temperature from outdoor conditions.

The quantitative analysis has shown that the predicted sensation, for the average population, converges toward the mean of recorded votes. The final step of the selection is a verification step. Indeed, as for control, the occupant (or the Building management system) must take action. These actions must have a significant impact on the mean comfort of the population. This section aims at answering to the research question 3: **Is the comfort model relevant enough to control mixed-mode adaptive opportunities (use of ceiling fan, clothing flexibility) in front of controlling AC setpoint temperature in tropical conditions?** The studied output of the two-node model study in the section is the SET for the reasons mentioned above. Because all other indices are linearly regressed from SET, the results of this sensitivity study will apply to all SET-based indices. The conditions of the study are those of a tropical summer in Reunion.

The following methodology and results are reproduced and adapted from the Journal article part of this thesis work with the authorisation of co-authors Jean-Castaing Lasvignottes and Aurélie Foucquier:

[80]**Maxime Boulinguez**, Aurélie Foucquier, Jean Castaing-Lasvignottes. Sensitivity analysis of Gagge's Standard Effective Temperature for fan-first cooling control strategy in tropical mixed-mode buildings. *Building and Environment, 2025, 272, pp.112667.* ⟨10.1016/j.buildenv.2025.112667⟩. ⟨hal-04958917⟩

The paper can be found in the annexe of the present manuscript.

The characteristics of Gagge's SET (Standard Effective Temperature) index mentioned earlier present a promising opportunity for a Fan-First control application. However, the variability of tropical conditions raises questions about the applicability of this index to the MM Fan-First strategy. The primary inquiry is how Gagge's SET index responds in hot and humid indoor conditions. When using the SET for cooling control, are air velocity and clothing good alternatives to AC temperature setpoint? i.e. how can we quantify the variation in input variables to the model's output in hot and humid conditions? Futhermore, it is crucial to understand how relative humidity, particularly at higher levels, affects evapotranspiration heat loss and consequently influences the selection of one control action over another. Conducting a Sensitivity Analysis (SA) of the SET can help to address these important questions.

Sensitivity Analyses assess the relative contribution of input variables to a model output. It has been widely used in the building industry for several decades, utilising BEM simulation programs (Trnsys, EnergyPlus, DOE2) or ISO 13790:2008 simplified models, especially for studying the influence of building design components or climates on energy consumption, space conditioning loads, and thermal comfort objectives [211]. De Wit et al. [212] investigated the impact of material uncertainty on HVAC sizing and energy use, aiming to enhance the decision-making process. Bomptemps et al. [213] employed an association of SA techniques to investigate the reliability of dynamic simulation models and proposed a framework for parameter selection in high-CPU-demanding models. Breesch et al. [214], [215] employed SA techniques to investigate various natural ventilation designs with the goal of achieving thermal comfort in buildings. Tian et al. [211] presented a tenth of other application examples of sensitivity analysis in building energy simulation in their review.

However, research on Thermal Heat Balance comfort models' sensitivity for coupled systems control has been limited, even more so in hot and humid conditions. Moutela et al. [216] demonstrated that metabolism and radiant temperature parameters significantly influence Fanger's model over the entire PMV validity range. At the same time, relative humidity and air speed only played a secondary role in the PMV deviation. Hasan et al.

[217] concentrated solely on the sensitivity of PMV to variation in metabolism within the same domain as Moutela et al.[216]. Finally, Ji et al. [208] explored Gagge's model and its sensitivity to various thermoregulation sub-models. They compared them to measured physiological temperature to propose an updated two-node model. Still, they did not investigate the Gagge's SET sensitivity to its inputs and even less in tropical conditions.

For this study, two approaches can be developed by the researcher or the designer willing to evaluate the behaviour of the model in specific conditions:

- The first option is to consider that all the variables are independent of each other. Hence, it permits evaluating the model behaviour on the whole range of possible variation, considering the equiprobability of combinations. This could be defined as the *Physically possible"*. It does not necessitate knowing a priori the distribution of variables; just the range extremum has to be chosen. For example, one can evaluate the behaviour of the SET between 20 and 26 °C, 40 and 80%RH and 0-0.5 $m.s^{-1}$. In the following sections it is described as the *"Independent-variable framework"*
- The second option is to evaluate the model based on real data measurements. This implies an a priori consideration of the interdependence of variables, necessitating the use of other techniques. This could be defined as the *"Physically probable"* option because we add the knowledge of measurement-specific distribution. It permits a more realistic investigation, especially when data present a strong dependency. In the following sections it is described as the *"Dependent-variable framework"*

The following sections describe an example of how we conducted the sensitivity analysis of the SET using various techniques. This includes comparing the latest Shapley Effect technique with the traditional Sobol indices and quantifying the contribution of simulating air velocity control (via ceiling fans or openings) and clothing (occupant adaptive behaviour) against controlling the AC setpoint temperature solely.

4.3.2 Global sensitivity Analysis for independent-variable framework : Morris and Sobol methods

Various SA methods exist for independent variables. Their choice depends on the objectives set and the constraints of the models [218]. Screening techniques used for fast exploration are commonly based on OAT (One-factor-at-A-Time) discretisation of the inputs in levels. Although they are straightforward to implement and require minimal simulation/model evaluation, they have the main drawback of not offering a study of parameter interaction and being limited to a qualitative approach. The Morris method, among the most popular in engineering, can be applied to complex models. It measures the perturbation of the output while changing only one parameter. The disadvantage is that Morris's OAT-type matrix might not fully cover the possible space of inputs and can also exaggerate trends if extreme values are often selected. It also provides a qualitative response and is frequently used when testing many parameters [218], [219]. It has the advantage of quickly evaluating if specific parameters

can be excluded from the study or if they present a combined influence. Another use of the Morris method is simplifying a model before conducting other, more time-consuming SA techniques. Also, it is often used if the input parameter variability is close to its nominal value [220]. This is not the case in our study. Furthermore, only five parameters are being tested, and running the two-node model costs very little on a desktop computer. Hence, the Morris method appeared irrelevant to our case. Nevertheless, for further details on the technique, the reader should refer to Machard et al.[219], [221], and Ioss and Lemaitre [218] and Tian et al.[211].

Global Sensitivity Analysis (GSA) based on the decomposition of the output variance, also called ANOVA (ANalysis Of VAriance), is more resource-intensive than the screening method. Still, they provide quantitative and valuable information. For example, Sobol's method can decompose all the output variance due to corresponding inputs and consider all interactions. The first-order Sobol indices Si can be used to assess the variability of the output (Y) of a function (f), given the variability of the input parameters (X_i), as shown in equation 4.1, which represents the main effect. The second-order indices S_{ij} can be used to assess the variability of the output (Y) of a function (f), knowing the variability of the input parameters (X_i) and (X_j), as shown in equation 4.2, representing the combined effects due to interactions. Finally, the sum of both represents the total effect, as denoted by the total indices S_{Ti} (eq. 4.3). It includes the first-order effect. It fully accounts for the higher-order effects due to interactions between inputs. With Sobol's indices, it is then possible to measure the relative importance of the contribution of all input variables in terms of the main effect and interactions of inputs [222]. The main property of Sobol S_i is its positiveness, and the sum of S_i is equal to 1 when there are no interactions, which makes Sobol indices very easy to interpret.

$$S_i = \frac{\mathrm{Var}\left[\mathbb{E}[Y \mid X_i]\right]}{\mathrm{Var}[Y]} \tag{4.1}$$

$$S_{ij} = \frac{\mathrm{Var}\left[\mathbb{E}[Y \mid X_i, X_j]\right]}{\mathrm{Var}[Y]} \tag{4.2}$$

$$S_{T_j} = S_j + \sum_{i<j} S_{ij} + \sum_{\substack{j \neq i \\ k \neq i, j<k}} S_{ijk} + \cdots \tag{4.3}$$

Several methods exist to estimate these indices, such as Sobol and the Fourier Amplitude Sensitivity Test (FAST). They all consider evaluating the model numerous times with different combinations of inputs; it becomes rapidly very computationally intensive. Typically, it could be counted on tens of thousands of evaluations. Monte Carlo sequences are well known but remain costly compared to their adaptation by Saltelli [218]. Multi-Fourier and coupled multi-Fourier transforms with Random Balance Design (RBD) have been provided to lower the number of model evaluations [223]. These methods are adapted to our case study with a rapid model evaluation call and few inputs (5). Otherwise, they remain unstable and biased [223]. We use the GSA Random Balanced Design (RBD) FAST method (Random Balance Design Fourier Amplitude Sensitivity Test [219], [223]) associated with the method of generating

samples by LHS permutation (Latin Hypercube Sampling) to determine the first-order Sobol indices. This method is as calculation time-efficient as an OAT and has the advantage of quasi-random sampling across the entire range of variations. It is directly available in the SAlib Python library [224]. The Latin Hypercube sampling ensures a more homogeneous exploration of the parameter variation domain than traditional random sampling. The variation range is divided into N non-overlapping subranges with a probability of 1/N and is used for a random pickup process of values [214].

For the independent-variable framework, the variation range is based on actual building data, and the screening of the whole domain is bounded by the field study extrema reproduced in Table 4.8. The choice of the uniform distribution for all variables ensures that they are independent of each other. Chapter 3 describe the detailed comfort field study. It reveals, like in [86], a strong correlation between relative humidity and thermal sensations, as well as user satisfaction. Haese et al. [86] mention a shift in user satisfaction at 68 % relative humidity, independent of the other ambient conditions of the austral summer noted in the demonstrator building. Five series (i from 1 to 5) of sampling are executed using each time a different range of 10 relative humidity points, from 45% to 95%, called RH series (i) (see Table 3, note (1)). The LHS sampling technique mentioned above is used, and SET values are evaluated for all possible combinations. The five series of humidity ranges are plotted and compared. In this section, the metabolism value is constant and equal to 1.1, the normative value of an office typing activity according to ISO7730. The clothing distribution is uniform between recorded extrema. Table 3 summarises all field measurements and distribution for the independent framework.

Table 4.8: *Variation ranges and distributions for independent-variable framework, reproduced from* [*80*]

Statistic	**Relative Humidity (%)**[1]	**Dry-bulb Temperature (°C)**	**Mean Radiant Temperature (°C)**	**Air Velocity ($m\,s^{-1}$)**	**Metabolism (met)**	**Clothing (clo)**
Min	49	25.4	23.1	0.01	1.1[2]	0.29
Max	88	32.1	31.2	2.20	—	0.79
Distribution (for Sobol indices)	Uniform	Uniform	Uniform	Uniform	Fixed	Uniform

[1] Field measurements define humidity range series for Sobol's method: [45%–55%], [55%–65%], [65%–75%], [75%–85%], [85%–95%].
[2] Typical fixed value for office activity (sitting and typing) per ISO 7730.

Sensitivity analyses are carried out over the entire variation domain for independent inputs and uniform distributions. After preliminary tests, it appeared that 10,000 draws were sufficient for converging the Sobol indices. SET is calculated using the two-node model available in the Pythermalcomfort library [128] for each draw of the five RH series. Runtime is on the order of minutes on a desktop computer. For each series, the vertical extent of a violin

diagram (Figures 4.7 and 4.8) makes it possible to assess the dispersion of the output Y (SET index). The horizontal extent represents its probability density. The comfort and acceptability ranges of the SET are represented in colours from "slightly cold, slightly unacceptable" in blue to "hot, very unacceptable" in red, according to Parsons' correspondence (Table 2.4) for SET [107]. The black bar corresponds to the interquartile range, representing 50% of the data, centered on the median (white dot). Figure 4.7 corresponds to our reference case study in still air conditions, whereas Figure 4.8 represents our case study with actual measured air velocities up to 2.2 $m.s^{-1}$. The extrema, as well as the median value of the series (represented by the white dot), are also shown. Median lines are plotted in blue (actual case with wind) or red (actual case but with still air conditions). The full-coloured line corresponds to the median of the plotted violin plots; the dotted-coloured line corresponds to the median of the other case.

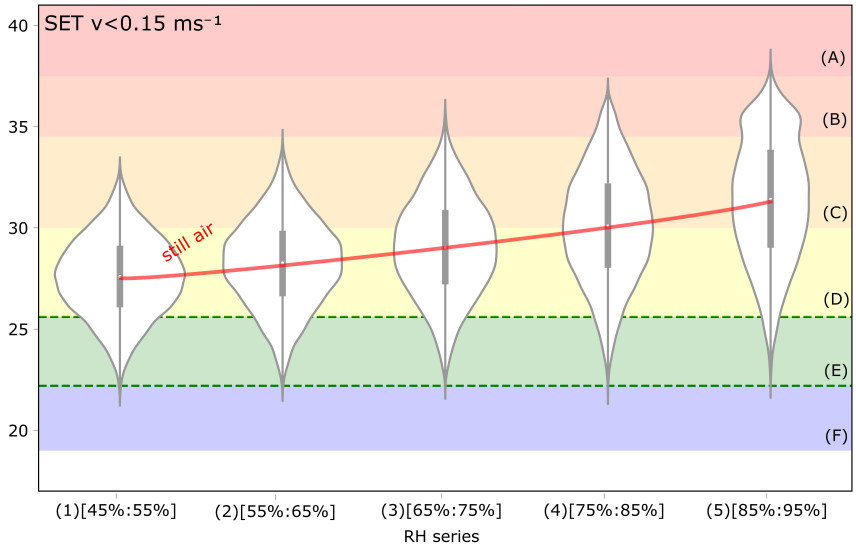

Figure 4.7: *Range of variability of the SET (Standard Effective Temperature) index as a function of relative humidity ranges with hypothetical low air speeds (still air) 0.01 to 0.15 $m.s^{-1}$, reproduced from [80]*

Unsurprisingly, the probability of discomfort increases with relative humidity, as shown in 4.7 and 4.8. When in still air conditions, as shown in Figure 4.7 for air velocities under 0.15 $m.s^{-1}$, the median of the SET increases by 1° to 2° SET for each series and by 5°SET from the RH series (1) to the RH series (5) as shown by the red line. The dispersion of the SET also doubles. More than 75% of the points are in the hot zones for each RH series. It is exacerbated at high RH, where having more than 10% of points in the comfortable zone (green) is difficult. With high air velocities (Figure 4.8), it is possible to lower the overall dispersion of the SET for each RH series with an average median of 5°SET under the one for still air conditions (blue line). Below 70% RH, it is possible to have at least 50% of the output in the comfortable and acceptable (green) to cool (blue) categories. The remaining 50% are mainly in the slightly warm zone (yellow). Only from the RH series (3) with high air velocities (Figure 4.7) can one observe more than 25% of the points in an unacceptable situation (orange gradient) when all RH series with still air (Figure 4.8) showed a significant amount of uncomfortable SET.

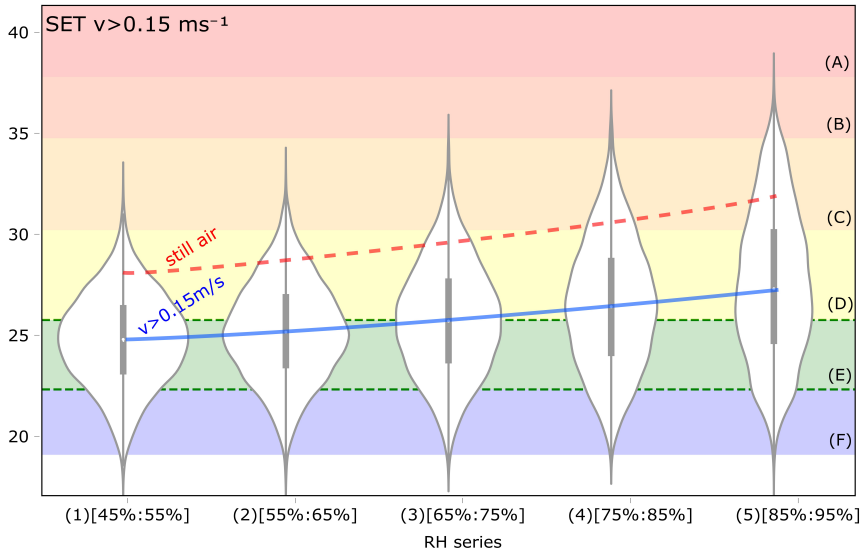

Figure 4.8: *Range of variability of the SET (Standard Effective Temperature) index as a function of relative humidity ranges with air speeds representative of the case study from 0.01 to 2.2 $m.s^{-1}$, reproduced from [80]*

The partial variances (Table 4.9) represent the absolute contribution of the parameters X_i on the output Y. They are expressed as a square of Y, i.e. SET². When comparing several sensitivity analyses, i.e. for several relative humidity ranges, it is necessary to validate that variance is not null, which could lead to a meaningless interpretation of first-order Sobol indices. All RH series show a total variance ranging from 4.8 to 13.4 SET². Figure 4.9 presents the first-order sensitivity indices Si for each input parameter of each series. The Sobol indice is the partial variance of Y knowing X_i, normalised by the total variance of Y (eq. 4.1). These Sobol indices represent the relative contribution of a parameter to the variability of the output. Within each series, we ensure that the sum of the Sobol indices is close to 1 and that the error bars are less than 5% (figure 4.9). Then, we can confirm that there are no interactions of the input variables in the model evaluation. A parameter whose index is less than 0.1 can be considered to have a negligible influence on the output. Figure 4.9 shows that the relative contributions of the airspeed v and the clothing clo are of the same order of magnitude, whatever the relative humidity ranges. They are relatively constant at 0.25 from 45% to 75% RH and decrease slightly from 75% RH. Their actual contribution (Table 4.9) increases with relative humidity to approximately double from the RH serie (1) range to the RH serie (5). In other words, the effect of a user action on one of these two parameters will have twice as much impact on the SET in conditions of high relative humidity than in dry conditions. At low relative humidity, the relative contribution (Figure 4.9) of the two parameters v and clo is slightly below (0.25) the contribution of temperature T_{db} (0.35). The more the relative humidity increases, the wider the gap becomes. It goes from 0.1-point difference in the RH serie (1) to 0.15-point difference in the RH serie (3) to finally reach 0.35-point difference for the series RH serie (5). Thus, a user's action on the clothing and the airspeed will have the same impact as acting on the temperature setpoint at low relative humidity. However, the effect will be at least twice as low from 75% relative humidity. This is explained by the higher the relative

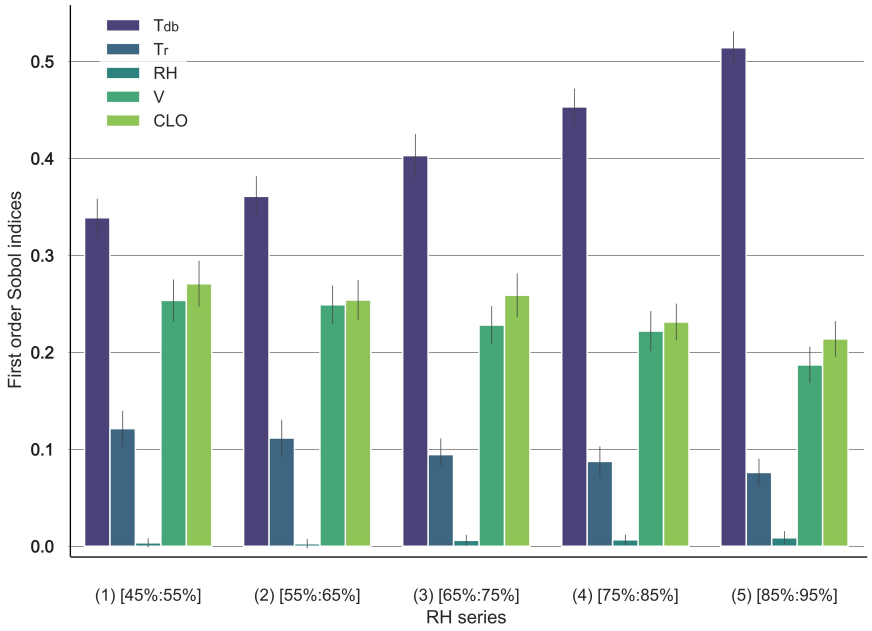

Figure 4.9: *Influence of control parameters on the SET (Gagge two-node model). Representation of the first-order Sobol sensitivity indices of the input parameters for a uniform distribution of independent inputs. Representation as a function of different relative humidity ranges for the tropical climate study case, reproduced from* [80]

humidity in the environment; the more difficult it is for evaporative exchanges to restore body temperature. At this stage, it becomes necessary to act on the setpoint temperature T_{db} of an air conditioner to complete the effects of air velocity v and clothing clo. Finally, the contribution of the average radiant temperature of the walls remains marginal in our case study, as the building is well protected from solar stress, with a slight variation (10 % maximum) in relative humidity.

Table 4.9: *Partial variance of the input parameters for a uniform distribution of independent inputs. Representation as a function of different relative humidity ranges for the tropical climate study case, reproduced from* [80]

Variables	**[45%-55%]**	**[55%-65%]**	**[65%-75%]**	**[75%-85%]**	**[85%-95%]**
T_{db}	1.77	2.37	3.10	4.37	6.86
T_r	0.20	0.70	0.75	0.80	1.03
RH	0.01	0.02	0.02	0.06	0.10
V	1.33	1.54	1.89	2.10	2.65
CLO	1.46	1.60	1.96	2.23	2.73
Total	4.77	6.23	7.72	9.56	13.37

4.3.3 Sensitivity analysis for the dependent-variable framework: the Shapley effects

All the methods mentioned in the previous section are well-suited for independent variables but cannot handle correlated inputs. Nevertheless, in the field of building

engineering, Tian et al. [211] mentioned that it is common to work on building stock data that can have some form of correlation. Hence, the input space of parameter variation is not rectangular. For example, building age can be correlated to the building area of a city, or building geometry can be linked to a specific construction period or building stock [211]. As mentioned by Ioss and Prieur [225], "When the inputs are described by an empirical distribution on observational data, the variables are rarely statistically independent". In those cases, Sobol's indices lose their interpretability in the presence of correlated inputs [225], they can become negative, and their sum does not necessarily equal 1. The relative importance of correlated inputs can be assessed by different methods like LMG (Lindeman Merand and Gold), PMVD (Proportional Marginal Variance Decomposition) or conditional variable importance from random forest, which are recommended and described in Tian's review of sensitivity analysis techniques for building energy analysis[211]. Those methods remain computationally intensive.

To overcome this issue, Shapley values φ_i were introduced by Owen in 2014 [226] and are based on the coalitional game theory proposed by mathematician and economist Lloyd Shapley in his 1951 thesis. It is recommended for dependent input variables. This concept aims to attribute the overall profit among players (or variables), given that they cooperate in a team (set of input variables). The marginal contribution of a player across all possible coalitions of players (also called permutations) defines the Shapley value. Shapley's value has four axioms:

- (1) Efficiency – The sum of all effects represents 100% of the gain,
- (2) Symmetry – If two players contribute the same way, they get the same gain,
- (3) Dummy – if a coalition has the same gain with and without player Xi, then Xi gain should be zero,
- (4) Additivity - When two models described by the prediction functions f and f' are combined, the prediction should correspond to the sum of the contributions derived from f and the contributions derived from f'.

It stands right in between Sobol' S_i and S_{Ti}, and their sums remain equal to 1 ($0 < S_i < \varphi_i < S_{Ti} < 1$). Contrary to Sobol's total indice S_{Ti}, which fully accounts for higher-order interaction (interaction of S_{ij} is fully accounted in both S_{Ti} and S_{Tj}), Shapley value φ_i accounts for the main effect and only the part of higher order contribution X_{ij} of X_i interacting with X_j (with $j>i$). In other words, the interaction contribution is not counted twice like in the Sobol method. As mentioned by Ioss and Prieur [225], the first algorithms to calculate Shapley values were proposed in 2016 by Song et al. [227] (Monte Carlo) and then in 2019 by Benoumechiara et al.[228] (block bootstrap procedure). They are computationally intensive and impose an a priori knowledge of the conditional distribution. Broto et al. [229], [230], introduced a subset aggregation method based on KNN metamodel (K-Nearest-Neighbours) that can solve this issue and be used for any dataset when a sample of the inputs is available and their distribution is unknown, which is our case in this study. This method is available in

R sensitivity package 1.30.0 under the shapleySubsetMc function [231].

Table 4.10: *Summary statistics of environmental and personal parameters for Summer 2023 and Summer 2024 datasets*

Dataset	RH (%)	Dry Bulb T (°C)	Mean Radiant T (°C)	Air Velocity ($m\,s^{-1}$)
Summer 2023				
Min	49.0	25.4	23.1	0.01
Max	88.0	32.1	31.2	2.20
Mean	68.9	29.2	27.7	0.83
Std. dev.	5.9	1.1	1.5	0.54
Summer 2024				
Min	51.7	23.2	21.1	0.01
Max	87.0	31.8	31.5	0.96
Mean	70.3	29.2	27.9	0.38
Std. dev.	6.2	1.6	1.6	0.20
Distribution-dependent framework				
Distribution	Normal	Normal	Normal	Normal (truncated)

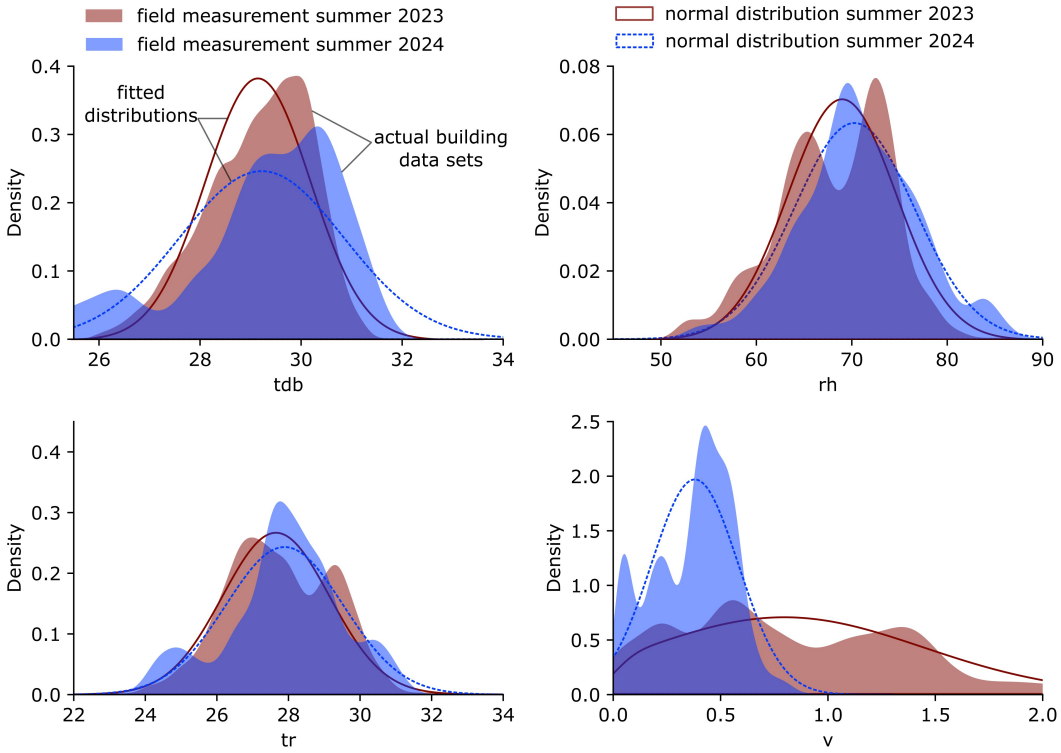

Figure 4.10: *Field measured environmental variables and their fitted normal distribution LHS sampling based on mean and standard deviation for summers 2023 and 2024, reproduced from* [80]

The parameter variation ranges are based on the actual building data distributions recorded during the summer working hours of the MM office in 2023 and 2024. Figure 4.10 shows the distribution of actual data in solid colours, red and blue. Based on the mean and standard

deviation of these two datasets (4.10), a normal distribution is fitted to better represent the actual distributions on site. As mentioned above, distributions are non-rectangular and lose their independent feature. At this stage, it is impossible to subdivide by humidity ranges as in the previous section because fitted distributions are dependent on one another. As in the last section, the metabolism value will remain constant and equal to 1.1, the normative value of an office typing activity according to ISO 7730 [95]. Clothing distribution will remain uniform between recorded extrema. Table 4.10 summarises all field measurements and distribution for the independent framework.

The distributions of variables are constructed by fitting normal distributions from experimental datasets for summer 2023 and 2024. It is first noted that the measured indoor conditions (Figure 4.10) are similar in 2023 and 2024 for relative humidity and mean radiant temperature. Nevertheless, air temperature presents a more flattened normal due to a concentration measurement between 26 and 27°C, resulting from more intensive use of the AC unit in 2024. Recorded air velocities are very different from the two datasets, with a mean of 0.83+/-0.5 $m.s^{-1}$ in 2023, divided by 2 in 2024 (0.38+/-0.2 $m.s^{-1}$). Recorded meteorological data from the closest station (Pierrefond Airport, 5 km from the building site) can partially explain this discrepancy; it presents an almost identical outdoor wind intensity distribution, with a mean of around 3 $m.s^{-1}$ at 10 m high, but the wind directions differ. The southern façade of the building was far more exposed to strong winds (between 3-6 $m.s^{-1}$ and over 6 $m.s^{-1}$) in the summer of 2023 than in the summer of 2024. (30% of S-facing winds in 2023 compared to 20% in 2024, 24% of W-SW winds in 2023 compared to 21% in 2024). 2024's strong winds exclusively come from the E-SE direction, and a construction mask highly protects the building's opened façade. Hence, it provides less wind access for the S-SW single-oriented opening spaces.

Figure 4.11 presents the result of the Shapley values for both the dependent and independent frameworks. The dotted barplot is the uniform distribution shown as a reference case from the independent framework section 4.8 In solid color, the result of the Shapley method (Figure 4.11) is similar to Sobol indices, when compared with the average RH series (3) of [65 %: 75 %] (Figure 5) because onsite measurement shows a normal distribution of RH centred on 70% +/- 6%. Shapley effects are relevant to managing the independent framework. In the case of random draws in a rectangular space, the influence of temperature remains predominant (40 %), while airspeed and clothing make an equivalent contribution, each at +/- 5%, for a total of 45%. Those results align with Sobol's technique regarding trends, but one should remember that the absolute values of Sobol indices and Shapley values cannot be compared side by side. Shapley values (Figure 4.11) show different results according to the distribution ranges. First, it is noted that, such as in the independent framework, one can reproduce the same trend concerning the influence of air velocity and clothing as for the independent framework. Their contribution to the SET remains equivalent at +/- 5%. It has been possible to reproduce the result sketched in section 3.2 for the independent framework on two experimental datasets. Secondly, according to the average air velocity in the building, the influence of air temperature changes on clothing and air velocity is also significant. When air velocity is provided with a narrow range [0 : 1 $m.s^{-1}$], just like in 2024 campaign, the influence

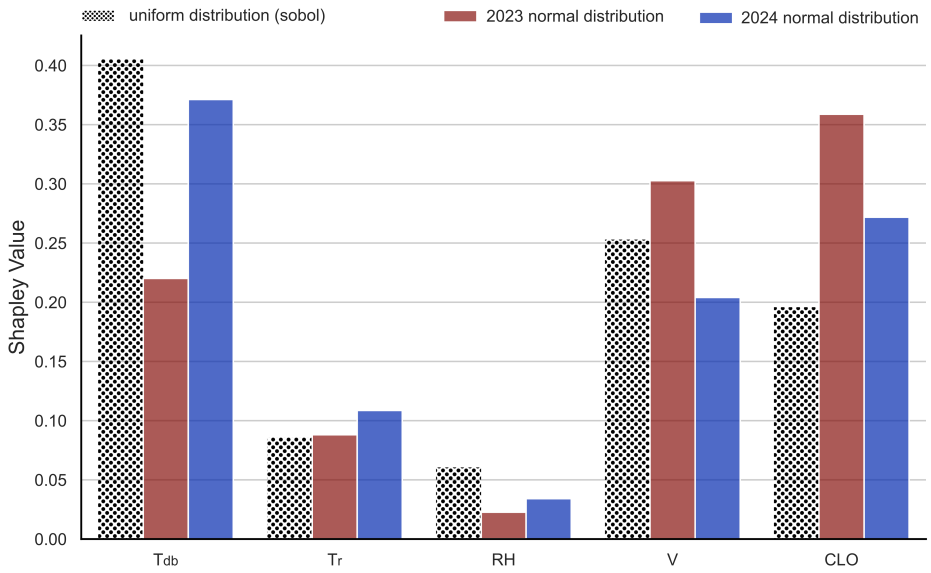

Figure 4.11: *Influence of control parameters on the SET (Gagge two-node model). Representation of the Shapley values of the input parameters for a normal distribution of dependent inputs with uniform independent distribution as reference, reproduced from* [80]

of air temperature is almost double that when air velocity is available for an extended range $[0 : 2\ m.s^{-1}]$ (2023). It is worth noting that with this latest extended range of airspeed, air temperature has become less influential than both airspeed and clothing (0.22 vs 0.36). Those two parameters of the mixed-mode control are operated at a very low cost (ceiling fan) or no cost (clothing flexibility), offering a new perspective in reducing energy use and system sizing in MM buildings. It should be noted that the traditional ceiling fan's power use is around 50 W, while the minor AC unit's power is over 1500 W. Radiant temperature's contribution remains marginal in our two cases, where it is close to air temperature, which is typical of NV buildings or conditioned buildings with high setpoints. Relative humidity, centred for both datasets around 70 +/-5%, does not influence the SET. More significant variations are needed to assess its influence, just as in Section 3.2, between RH series (1) and RH series (5).

4.3.4 Conclusion

To better understand the behavior of the SET index based on the Gagge model in tropical conditions, a sensitivity analysis is contextualized in a case study in La Réunion. It highlights the relative and actual contributions of an input parameter to the SET, resulting from the two-node model. This study validates that temperature is not the only action that restores a comfort situation, and, it provides quantitative elements for the SET index. Although acting on temperature always has a significant impact, acting on airspeed and clothing in these tropical conditions is a viable alternative solution with a substantial, if not equal to temperature, effect on SET. Both clothing and air velocity are equivalent. It has been shown in a reference case and validated on two datasets of actual indoor building conditions. These two actions are

energy-conservative compared to traditional AC unit setpoint control. Let us keep in mind that the modulation of clothing and the use of openings is done at zero energy costs, the use of ceiling fans has very low energy consumption, while the modulation of air conditioning generates a significant electricity demand. This energy approach remains to be integrated into building management, especially in BEM. Finally, this study provided insight into how the two-node model behaves in such tropical summer conditions and how the range of available air velocity provided by the systems (louvres, fans) can impact the contribution of the AC setpoint to maintaining a comfortable SET. More specifically, it highlights that special care should be given to our building case study's distribution, construction, and variable dependence. Such a context imposes the use of specific sensitivity analysis techniques, such as the Shapley value. As an illustration, results again show the equivalence of influence for air velocity and clothing but rank them differently in front of air temperature depending on the indoor air speed conditions of the two datasets of field measurement.

4.4 Conclusive remarks

In this chapter, the second contribution of this thesis work is presented. A gradual selection methodology is proposed to address the comfort modelling choice intended for mixed-mode cooling control in tropical conditions. It contributes to addresses two research questions (RQ 2, RQ3) relying on (i) the system control-focused comfort modelling literature review presented in chapter 2, (ii) the experimental aspect detailed in chapter 3 to compare actual vote and model prediction, and (iii) a sensitivity analysis study example to confirm the relevance of the chosen model for control application. Let us recall that Chapter 2 shows that the literature is abundant in comfort modelling options, but does not directly address the application of mixed-mode cooling strategies. It has been highlighted that the SET-based adaptive comfort model of Parkison et al. [78] is, to our knowledge, the only dedicated MM building-specific model.

To evaluate all other alternative options, a qualitative screening of the off-the-shelf comfort models and indices is proposed initially. It narrows the model selection by defining specific criteria for selection and thoroughly investigating the literature regarding the latter. This provides a guide to analyse the foundations and limits of available models in the literature. It broaches conventional Thermal Heat Balance approaches, highlighting the poor applicability potential of Fanger-based indices, in contrast to Gagge's two-node ones. Still, it highlights the lack of studies that confront non-PMV models with comfort surveys. Adaptive models, built for naturally ventilated buildings, would be good candidates if their mean output were not temperature-specific, diverting them from the MM control-focused selection. Many of the latest attempts to bridge the best of both worlds for AC and NV lack evidence-based studies that confront them in operational mixed-mode applications or tropical conditions. This step is summarized in easy-to-screen tables.

A quantitative screening, conducted in five steps and based on Coarchitects' building comfort survey, complements the qualitative one. It is first shown that comparing overall model predictions on an entire vote database may not accurately reflect the on-site reality. A temperature-binned approach is proposed to better match the controlling context of a mixed-mode operation. Four gradually ranked performance figures illustrate the performance of various thermal sensation indices. This highlights the reliability of certain Gagge SET-based indices and of the recent adaptive framework proposed by Schweiker et al. [184], which best suits our control requirements. Nevertheless defining the conditions that allow switching from one cooling mode to another remains an entire question. Indeed, as mentioned by Parkinson et al. [78] this *"remains a fertile area of research and will depend on many contextual factors for each building"* [80].

As a final step to ensure the most suitable model is used for controlling mixed-mode cooling operations, a sensitivity analysis methodology is established. It aims to answer research question 3: *How would the comfort model respond to a change in air velocity and clothing in front of the AC setpoint temperature shift?* SET index is chosen for the demonstration. This study demonstrates that SOBOL's method is suitable for exploring the behavior of the model under specific tropical conditions, assuming independence of the variables. This part of the methodology could be defined as the *"range of physically possible"*. It confirms that air velocity and clothing significantly influence temperature when using SET in extended tropical conditions. It also shows that relative humidity influences the output variability by modifying the impact of input 'controllable' parameters, but that air velocity and clothing remain significantly more influential. To confirm this result in a real case study, the dependence of the experimental dataset of the Coarchitects building suggests using another method suitable for correlated data. The Shapley effects confirmed the initial findings regarding the influence of air velocity and clothing. It also emphasized the importance of actual distribution in considering control perspectives. Both methods can be applied in different contexts. The SOBOL index can be used when prior knowledge of the data distribution is unavailable, while the SHAPLEY effect is relevant for addressing the sensitivity of a model when the prior distributions of variables are known.

The next chapter describes the co-simulation framework proposed as a methodological example of this thesis work. It implements a flexible comfort-based multi-scenario controller to evaluate the impact of a chosen comfort model and cooling strategy on comfort evaluation and energy use.

5

Mixed-mode Control simulation framework proposition

In the previous chapter, we proposed a methodology for selecting the most appropriate comfort models to simulate mixed-mode scenarios in tropical conditions, including natural ventilation, ceiling fans, and air conditioning.

The present chapter aims to propose a flexible simulation framework capable of assessing energy and comfort performance of the full range of cooling system combinations to define the best possible scenario, and envision Mixed-mode cascade cooling system sizing and control testing. We propose coupling the `EnergyPlus` Building Energy Models with a comprehensive `Python` Environment for comfort and cooling systems using a co-simulation framework known as the Functional MockUp Interface. In this chapter, we describe the numerical models and control scenarios, and evaluate the added value of Mixed-mode solutions against traditional predefined cooling scenarios using a simple case study. We also investigate the impact of several comfort indices on the predicted total energy use of the whole cooling system.

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5.1 Co-simulation framework

5.1.1 Building Energy Simulation tool

Building Energy Simulation (BES) provides a robust and flexible platform for conducting detailed heat and mass transfer calculations over time, taking into account interactions with outdoor conditions. They are commonly used in the AEC industry by engineers to size HVAC systems based on the peak demand for conservatory heating and cooling. They are based on a simplistic representation of the envelope and systems. Indeed, all calculated variables are nodal, meaning that environmental variables used as inputs for comfort models are single values for the thermal zone [232]. This approach is well established and valid for most cases of the built environment [232]. When using this approach, it is essential to recognize that temperature gradients and significant variations in the air velocity field cannot be directly accounted for. Hence, those Building Energy Simulation codes remain limited to low-ceiling and moderately glazed spaces, such as those found in office or residential sectors.

As mentioned by [195], [233], several dynamic simulation tools exist, such as `DOE-2`, `TRNSYS`, `PLEIADE`, `IES-VE`, and `EPS-r` or `EnergyPlus`. Most of them can process sub-hourly simulations. Others, such as `DOE-2` or `BLAST`, are limited to a 1-hour stepped simulation. Some are open-source, while others are commercial codes. While several studies are interested in comparing tools, there is a good agreement on their equal performance [233]–[235]. `EnergyPlus` remains one of the most used tools today [147], [189]. It has been a Department of Energy project in the USA since 1996. Lawrence Berkeley National Laboratory and DOE have been developing it since then, combining features from previous system modeling with DOE-2 and the heat balance of BLAST [235]. The first version officially launched in 2001. Over heat-balance capabilities, `EnergyPlus` has several interesting features making it interesting to our case study, including the airflow network module, detailed window modelling, control possibilities, a built-in Energy Management System, and built-in co-simulation interoperability, such as the Python Plugin and Functional MockUp Interface [189], [235]. Furthermore, `EnergyPlus` is commonly used by consulting firms based in La Réunion and

Mayotte [63], [195], which envision a better transferability of the methodology to the local construction industry.

5.1.2 Co-simulation of Mixed-mode strategies

While direct simulation in `EnergyPlus` is highly parametrizable to the user requirements, it sometimes does not offer the complete flexibility required by researchers for testing new sub-models. When focusing on mixed-mode application, for example, `EnergyPlus` provides the possibility to:

- Size HVAC system by using an IdealAirLoad component or by using the design-day method and thermostat set-points,
- Report comfortable conditions, using comfort models such as PMV, Gagge model indices, or Adaptive Models,
- Control HVAC system based on built-in comfort models, accounting for a dead-band of comfortable conditions.
- Apply a predefined air velocity planning to be accounted for in comfort model reporting
- Control window opening based on temperature or enthalpy difference

All of these features would be sufficient for a Mixed-mode application if we stick to switching between NV and AC modes and adhere to the built-in comfort models included in the EU and US building standards. However, `EnergyPlus` does not have direct modelling features to :

- Implement a dynamic set-point schedule based on both a comfort model and outdoor conditions.
- Implement dynamic airspeed from ceiling fan based on comfort model calculation (or implement a ceiling fan model)
- Implement a comfort-based control of window openings
- Uses a different comfort model and index than the native ones.
- and, overall, implement optimisation control for cascade cooling strategy

There are workarounds to deal with these requirements. Nevertheless, they require a significant amount of manual precalculation using an external scripting or Excel to create custom schedule objects. As stated by Sanchez et al. [76], designing a custom cooling control model that is not already implemented in the native classes and objects of the tool remains onerous, without requiring external or internal programming. Furthermore, they stay weather-file dependent. Another possible workaround is to utilize the native Energy Management System. This implies coding all custom models (comfort, AC, CF, and control algorithm) in EMS's native language, without access to external libraries like thermodynamic, comfort modeling, and optimization libraries. Regarding the fourth research question of this thesis, which concerns the intention of optimizing performance cascade cooling system control and sizing, we aimed to avoid relying on native object modification and develop the most flexible tool possible. Hence, while the remainder of the proposed framework is a relatively simple proof of concept, we decided to set it up with flexibility and upgradability in mind. We decided to use `EnergyPlus` for the building geometry, envelope composition,

internal loads, and airflow network, thus relying on co-simulation of custom-scripted models for comfort and cooling system modeling.

Co-simulation is an advanced technique that enables different models, sometimes scripted in various languages, to exchange information at predefined timestamps during the simulation. Several examples exist, such as coupling `EnergyPlus` with `MATLAB, Simulink` and `Modelica` (often under `Dymola` environment) [236]–[238] or using the Building Controls Virtual Test Bed (BCVTB) [239]. There are two well-known off-the-shelf options are recently gaining interest, with good interoperability with `EnergyPlus` via the *"ExternalInterface"* objects, namely:

- **The Python Plugin:** It gradually replaces the native Energy Management System of `EnergyPlus`, which provided users with custom function coding within the proprietary platform. In essence, it is an in-process Python runtime with callbacks at each time step of the simulation, providing a comprehensive set of controls and data exchange capabilities via native actuators or sensors. This is made possible through the `EnergyPlus` API and is straightforward to implement [240].
- **The Functional Mock-Up Interface (FMI):** The FMI is a free standard that proposes containers and interfaces for exchanging dynamic simulation models. It uses an XML library and external C code for the process. This distribution is part of the `Modelica` association and is supported by hundreds of tools. In essence, it can import an FMU (Functional Mock-Up) into `EnergyPlus` or export `EnergyPlus` as an FMU to run it under an FMI simulator. For this purpose, the Berkeley Lab developed an `EnergyPlusToFMU` distribution [241]. Control is made easy via a Python environment such as `pyFMI`.

Both tools are equivalent in terms of our study requirements. The Python plugin would simplify the installation compared to the FMI setup. The FMI standard provides greater flexibility and universality when selecting an off-the-shelf model. Its advantage also resides in the granularity of data exchange. Contrary to the Python Plugin, where `EnergyPlus` is the master program, with the FMI co-simulation, `EnergyPlus` becomes a component of an external master program, run with `pyFMI`, for example. Hence, scheduling can be completely independent of the building model, and the master explicitly decides when to send a new command to the building model, thereby offering a more transparent and robust way to implement control. This setup also provides a more efficient way to log all information from the master. It offers the possibility to envision predictive control, by solving objective function over a predefined time horizon [242]. Hence, the Model Predictive Control strategy, which is gaining interest in recent years over the conventional on/off or PID (Proportional Integrated Derivative) control [242], would necessitate a flexible simulation framework to avoid onerous modeling time. Prediction with non-native Python code can also be envisioned through this means, which is less evident with the `Python` Plugin unless `EnergyPlus` is called as a Library. Very advanced coupling could be achieved under outdoor conditions, utilising Solar PV prediction models, state-of-the-art ceiling fan and ventilation models, as illustrated by Ascione et al. [242]. All offering various application perspectives to the proposed flexible

framework.

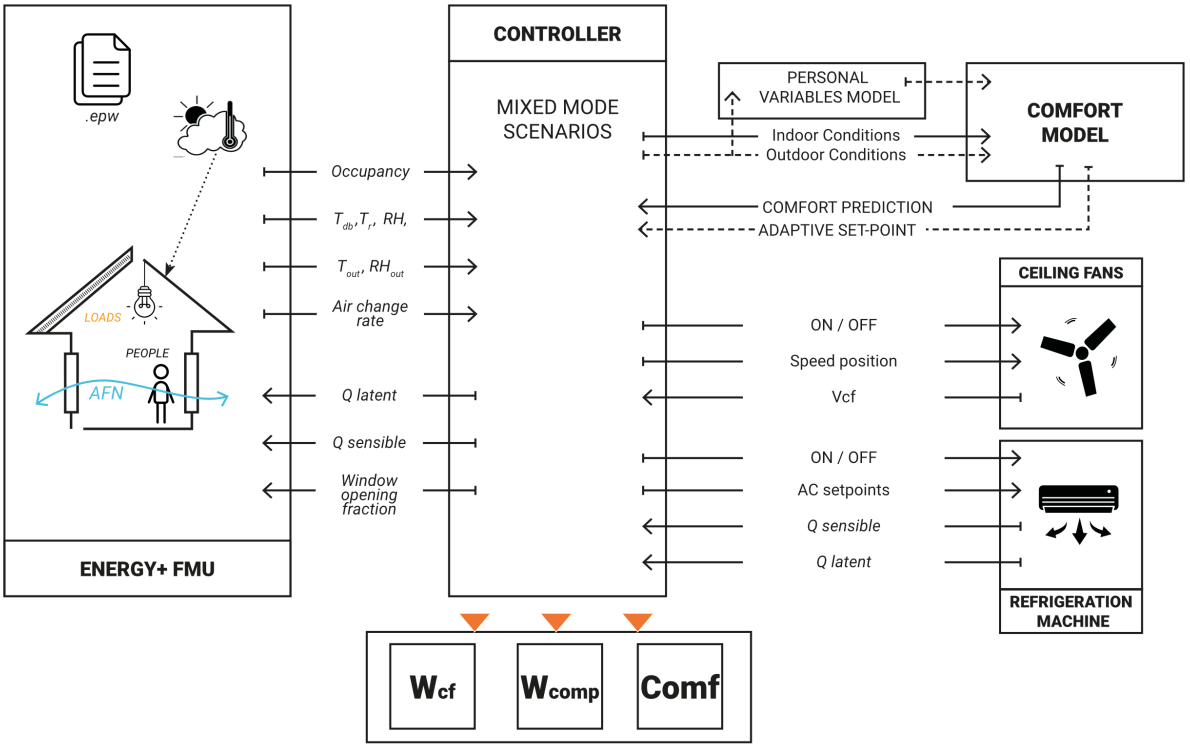

Figure 5.1: *Proposed flexible MM co-simulation framework*

The proposed simulation framework, illustrated by Fig. 5.1 consists in the following submodels:

- the `EnergyPlus FMU`, including building geometry, occupancy, loads, natural ventilation/window opening model, and the weather file.
- the controller implementing scenarios of actions
- the comfort evaluation model
- the ceiling fan model
- the SPLIT air-conditioner / refrigeration machine

They are detailed in the following sections.

5.1.3 Weather file

The `EnergyPlus FMU` embeds the weather file. It is common for Building Energy Simulation (BES) to rely on the typical meteorological year (TMY) formatted in an `EnergyPlus` Weather (EPW) file . For this thesis work, we had access to all necessary weather data from the University of La Réunion's southern campus, located 1 km from the case study building, in order to custom-build weather files closely matching the building's actual conditions. For

this purpose, we utilised the open-source software developed by Big Ladder Software [243] and the Rocky Mountain Institute [244], specifically designed for creating custom `EnergyPlus` weather files. It offers a user-friendly spreadsheet-style interface for copying and pasting, as well as manipulating raw data. The tool ensures coherence of the psychometric state and solar radiation conservation. We built two weather files for 2023 and 2024 to match the energy metering field survey described in chapter 3. For most of the remainder of this study, the 2023 weather file is used. The 2024 EPW file was employed only for a final comparison. The simulation plan, as described later in this chapter, enumerates the investigated cases and related EPW files.

5.1.4 Building geometry and internal loads

`EnergyPlus` does not come with a built-in graphical user interface to model the building geometry. Hence, it relies on third-party software, such as `OpenStudio Coalition`, `DesignBuilder`, or the open-source `SketchUp` plugin `Euclid` (formerly `Legacy OpenStudio`), which is today developed and maintained by the Big Ladder Software company. We use this latter, plugged to `Sketchup` 3D CAD tool, to model the BEM geometry of Coarchitects building and match zones and surfaces to ensure proper heat transfer between zones. Figure 5.2 illustrates a south-east axonometry of the building. The zone wall and roof are respectively coloured in yellow and dark red, while the architectural shading masks (tree, fence, wall, overhang, fins) are highlighted in purple. For simplification, in accordance with the building's actual usage, movable shading masks, such as the MM OpenSpace Zone awning, are considered unfolded during summer time. Shading provided by mango trees is assumed to be constant throughout the year because they have no deciduous leaves. A 60% fraction permeability is considered in such objects in `EnergyPlus`.

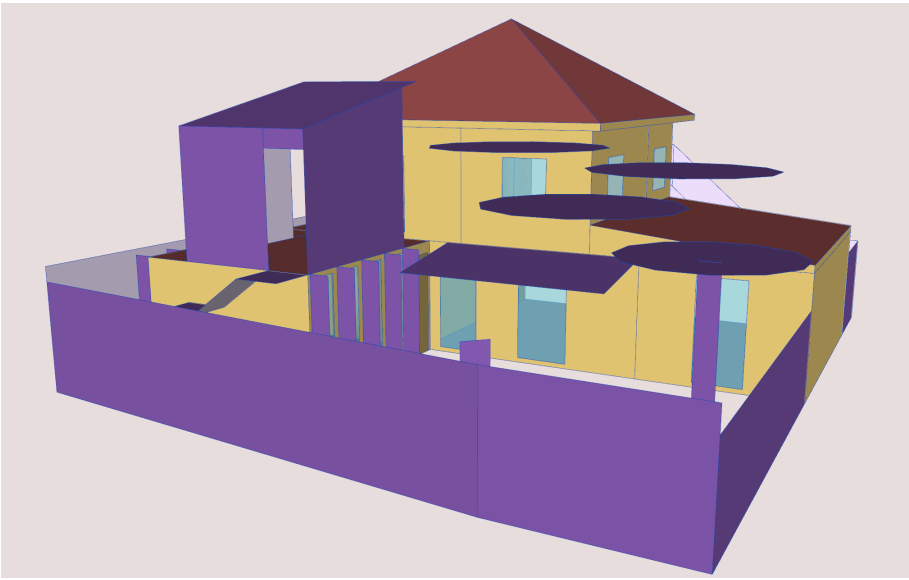

Figure 5.2: *Building energy model geometry - south-east view*

The building envelope and occupation are described in chapter 3 in section 3.2 of the present manuscript. Wall, roof, and window sizes and compositions are detailed in Table 3.1.

The geometry consists of 5 zones, including 3 Coarchitectes office spaces, 1 meeting room, and 1 IT room. For the remainder of the study, we will focus only on the MM Openspace office, being the larger and most occupied office, benefiting from AC and CF cooling systems.

All loads are summarised in Table 5.1. The following assumptions were made to prepare the model:

- The schedule of people's occupancy was assumed from interviews with all employees regarding their habits. Because office times are flexible, it was not possible to perfectly match the recorded conditions and the simulation for all weeks.
- The control of light is manual in the office; lighting control was approximated by using daylighting control at 400 lux (recommended value for typing work). Lighting-related energy use was not measured during the survey, so light is accounted for only as a heat gain.
- Simulations were carried out on the entire year 2023 on a custom-made `EnergyPlus` Weather data file (see section 5.1.3)
- We defined the time step based on AC unit anti short-cycle timer (see next subsection)

Table 5.1: *Internal heat gains*

Heat Gain	**Value**	**Occurrence**
*Occupant**	113 W (sens/lat : 0.67/0.33)	7:00–7:30 : 25% 7:30–8:00 : 50% 8:00–12:00 : 100% 12:00–14:00 : 50% 14:00–18:00 : 50% 18:00–18:30 : 50% 18:30–19:00 : 25%
Screen/PC	2×30 W / 100 W (per person)	According to occupancy
Lighting	4 W.m^{-2}	According to occupancy schedule and when < 400 lux
*Ceiling Fan***	14–39 W	According to building control

** Weekdays only*
*** All ceiling fans are identical, each with three speed settings.*

5.1.5 Natural Ventilation and window openings

The most energy-efficient way to cool a space is to keep the window open when the outdoor temperature is lower than the indoor temperature, or for night/free cooling. In a tropical climate, extensive use of natural cross ventilation with large openings is well integrated by building practitioners. Natural ventilation modelling is an entire domain of research and engineering, and for accurate prediction, it should rely on state-of-the-art Computational Fluid Dynamics (CFD) methods and zonal methods, at the cost of onerous model implementation and computationally intensive processes [245].

Building Energy Models are limited to simple, low-ceiling, and moderately glazed envelopes, being simplistic node-based simulations. Indeed, all calculated variables are nodal, which means that environmental variables used as inputs to comfort models are single values for the thermal zone [232]. Temperature gradients and variations in the air velocity field cannot be directly accounted with this method. CONTAM is a multizone airflow network with extended pollutant transportation, smoke control systems, and ventilation sizing capabilities, as well as pressure-based infiltration airflow calculations and accurate stack effect modelling [246]. However, it is not coupled to any thermal balance, so the temperature must be provided at each time step. Some researchers have coupled `EnergyPlus` with `CONTAM` [247] in order to account more accurately for stack effects in chimneys or interzonal airflow.

`EnergyPlus` Air Flow Network (AFN) is natively coupled to the thermal balance (including walls, inertia, comfort, and loads) of the zones. It is relevant enough for testing the energy and comfort impacts of a natural cross-ventilation strategy (openings, controls) as it provides heat and mass load between the zone and the outdoor within a single tool. The stack effect remains minor compared to wind-driven natural cross ventilation with large openings in the tropics. Other limitations of AFN, such as gravity shafts or multiple pollutant transport consideration, are not an issue for our case study [248]. Those reasons yield to its selection over CONTAM for air change assessment in the model.

The Air Change per Hour (ACH) is the main output of the AFN at the zone level. Nevertheless, the consideration of air velocity induced by windows opening (or ACH) remains challenging to assess for the case of nodal simulation, unless state-of-the-art CFD simulation is used, which, as already stated, is outside the scope of this study. This is one of the significant limitations of the proposed framework. As a rough estimate, we assume that the ACH-dependent indoor velocity is related to the effective surface area of the ventilation section, parallel to the main open facade. This provides a proxy for the average speed that can be attributed to a comfort model, as described by equation 5.1. This simple approach is conservative, as the local desk in the airflow would benefit from a higher velocity than those close to walls and in corners. The air velocity is then added to the ceiling fan's mean velocity, parameterized in the cooling system models.

$$v_{\mathrm{NV}} = \frac{\mathrm{ACH}\, V}{3600\, A_{\mathrm{eff}}} \tag{5.1}$$

Where:

ACH : air changes per hour $\left[\mathrm{h}^{-1}\right]$

V : zone volume $\left[\mathrm{m}^3\right]$

A_{eff} : airflow effective section $\left[\mathrm{m}^2\right]$

v_{NV} : mean air velocity $\left[m.s^{-1}\right]$

For window opening control, allowed stepped fraction openings are defined as in table 5.2 (fully customisable).

Table 5.2: *List of allowed windows positions and corresponding opening fraction*

Window position	win_pos	0	1	2
Opening fraction [-]	-	0	0.5	1.0

5.1.6 Refrigeration Machine model

Mixed-mode cooling involves the use of air conditioners and ceiling fans. Regardless of the type of system, the accuracy of assessing energy use and the cooling capacity for the case of Air-Conditioning (AC) devices is required to optimise the entire cooling strategy. For these purposes, it is crucial to choose a model that best represents the cooling system in question, while also considering the flexibility and upgradability of the simulation framework.

There are three types of modelling techniques in the literature: the white-box, the black-box, and the grey-box modelling [83]. The white-box implements the equations of physics but requires a deep understanding of all subcomponents of the device; it is also computationally intensive. The black-box models are data-driven models that are quick to implement and compute but lack generalizability outside the domain on which they have been built. The grey-box model combines the best of both worlds, retaining the comprehensive knowledge of key thermodynamic principles of the system while reducing computation time through complementary data-driven parameter identification, which would have been onerous to evaluate physically.

Heating Ventilation and Air-Conditioning (HVAC) modelling in `EnergyPlus` consists of connecting multiple components together and thus forming loops. Each piece of equipment is a node with an output that serves as input to the other component. There are loops for the plant and others for air distribution; they can be at the supply level, the return level or the zone level. This modelling concept, which mimics reality, can handle very complex HVAC systems with a high level of detail.

The case study is equipped with SPLIT-system Air conditioners. For modelling such equipment, AirLoopHVAC:UnitarySystem are generally employed in the model. They serve as "parent" system embedding a cooling coil (Coil:Cooling:DX), a fan, and a setpoint control (for controlling the setpoint deadband in the conditioned zone). A more straightforward way to model a SPLIT system is to use a built-in template, such as ZoneHVAC:UnitarySystem. This latter alternative is only valid if the unitary system is ductless, i.e., a wall-mounted air conditioner unit. The performance of DX Coil is parametrizable through inputting its capacity and Energy Input Ratio (EIR). In `EnergyPlus`, such a system does not rely on a detailed thermodynamic cycle, but rather on a grey box model. Its performance is described by :

- a regression curve (biquadratic) for temperature dependency,

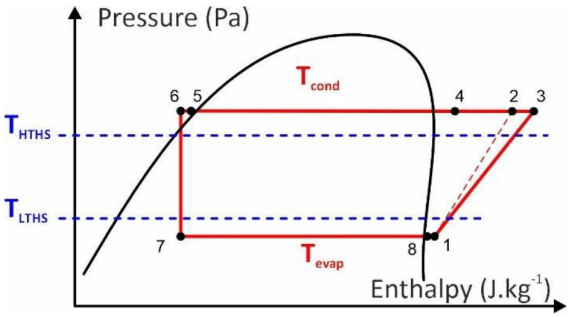

Figure 5.3: *Refrigeration machine cycle on Pressure - Enthalpy Diagram, reproduced from* [83]

- a regression curve (quadratic) for mass flow rate dependency,
- an ADP/BF model and psychrometrics relations are implemented for separation of sensible/latent heat: The Apparatus Dew Point (ADP) is in essence the exchanger all temperature which is fully saturated when deshumidification occurs and the Bypass Factor (BF) correspond to the quantity of humid air which is not in contact with the exchanger wall but remain part of the mixed air in the zone.

In parallel to this thesis work, we developed a dedicated refrigeration machine model with the PIMENT Lab team. The model used in the co-simulation is an extension of the refrigeration machine proposed by Boulinguez et al. [83]. A refrigeration machine has non-ideal components such as the heat exchanger and a compressor. Therefore, an ideal refrigeration cycle, as described in [83], cannot reliably reproduce the system's behaviour because the condensation temperature is higher than the source temperature (Outdoor temperature: High Temperature Heat Source T_{HTHS}). This phenomenon is also applicable to indoor evaporation temperature (indoor temperature: Low Temperature Heat Source, T_{LTHS}), as illustrated in Figure 5.3, representing the non-ideal refrigeration machine cycle. This implies higher energy consumption at the compressor, which must deal with a greater pressure difference than the ideal cycle would require. This model introduces an isentropic temperature and considers UA value (global conductance in $[W\mathring{u}K^{-1}]$) for each exchanger to account for this difference. They are defined by equations 5.2.

$$\tilde{T}_{\text{evap}} = \frac{h_1 - h_7}{s_1 - s_7} \text{ and } \tilde{T}_{\text{cond}} = \frac{h_3 - h_6}{s_3 - s_6} \tag{5.2}$$

The heat balance on the refrigerant fluid side is computed at the inlet and outlet of both exchangers using equations 5.3 and 5.4. Where $LTTF$ and $HTTF$ subscripts stand respectively for the High and Low Temperature Transfer of Fluid (Refrigerant Fluid). The machine is represented by the two exchanger UA values, isentropic temperature, and volumetric efficiency. Manufacturers' data specifications sheets typically include the provision of at least the swept volume of the compressor. An order of magnitude of UA values and isentropic and volumetric efficiencies can be simply evaluated. Manufacturers also offer several sets of conditions and inherent performance of their system, which serve as a base for the indirect identification of missing parameters. Boulinguez et al. [83] provide an example of the identification process using the indirect model and validation with the direct model,

developed under Engineering Equation Solver (EES), in their work. They present three cases from which a SPLIT-system unit can reproduce the manufacturer's performance data with reasonable accuracy (difference under 10%).

$$\begin{aligned}
\dot{Q}_{\text{evap}} &= \dot{m}_{\text{ref}} \cdot (h_8 - h_1) \\
\dot{Q}_{\text{evap}} &= UA_{\text{evap}} \cdot \frac{\left(T_{\text{LTTF, in}} - \tilde{T}_{\text{evap}}\right) - \left(T_{\text{LTF, out}} - \tilde{T}_{\text{evap}}\right)}{\ln \frac{T_{\text{LTTF, in}} - \tilde{T}_{\text{evap}}}{T_{\text{LTTF, out}} - \tilde{T}_{\text{evap}}}} \\
\dot{Q}_{\text{evap}} &= \dot{m}_{\text{LTTF}} \cdot Cp_{\text{LTTF}} \left(T_{\text{LTTF, in}} - T_{\text{LTTF, out}}\right)
\end{aligned} \tag{5.3}$$

$$\begin{aligned}
\dot{Q}_{\text{cond}} &= \dot{m}_{\text{ref}} \cdot (h_3 - h_6) \\
\dot{Q}_{\text{cond}} &= UA_{\text{cond}} \cdot \frac{\left(\tilde{T}_{\text{cond}} - T_{\text{HTTF, in}}\right) - \left(\tilde{T}_{\text{cond}} - T_{\text{HTTF,out}}\right)}{\text{In} \frac{\tilde{T}_{\text{cond}} - T_{\text{HTTF,in}}}{\tilde{T}_{\text{cond}} - T_{\text{HTTF,out}}}} \\
\dot{Q}_{\text{cond}} &= \dot{m}_{\text{HTTF}} \cdot Cp_{\text{HTTF}} \left(T_{\text{HTTF,out}} - T_{\text{HTTF,in}}\right)
\end{aligned} \tag{5.4}$$

The direct model can then be used to predict the system's performance and retrieve information on energy use and heat exchange within the indoor space (evaporative unit), which is of interest to us for cooling an indoor space. An objective function is implemented in this model, but it remains based on the entire heat exchange, providing no information on the sensible and latent parts. The program identifies by optimisation the condensation/evaporation temperatures which close the balance between a mechanical compression cycle and exchangers modelled in UA/LMTD (Log Mean Temperature Difference), then calculates the capacity, the compressor work (energy use), the Energy Efficiency Ratio and the air outlet temperature at the evaporator.

Table 5.3: *Direct model implemented in the BEM co-simulation*

Quantity	**-**	**Value**	**Unit**
Refrigerant	–	R32	
Evaporator superheat	ΔT_{sh}	3	K
Condenser subcooling	ΔT_{sc}	3	K
Isentropic efficiency (compressor)	η_{is}	0.82	–
Volumetric efficiency	η_{vol}	0.68	–
Swept flow rate	$\dot{V}_{\text{swept}}$	60×10^{-5}	m^3/s
Evaporator effectiveness	$\varepsilon_{\text{evap}}$	0.25	–
Condenser effectiveness	$\varepsilon_{\text{cond}}$	0.25	–
Air mass flow (evaporator side)	$\dot{m}_{\text{air,evap}}$	0.2046	kg/s
Air mass flow (condenser side)	$\dot{m}_{\text{air,cond}}$	0.6757	kg/s

In this work, we identify the characteristics of the SPLIT model installed in Coarchitects MM Openspace. They are given in Table 5.3. Furthermore, an extension of the calculation procedure is proposed to account for both the sensible and latent gain so that they can easily be transmitted to the BEM FMU. The objective function is modified by replacing the initial heat transfer at exchangers, which is initially based on UA/LMTD. An effectiveness coefficient ϵ is introduced to model the humid air on both exchangers, considering the evaporative unit wall

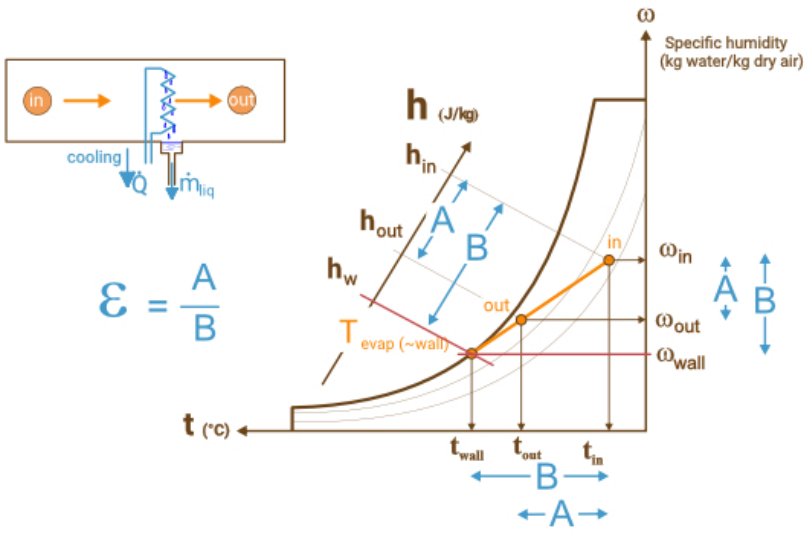

Figure 5.4: *Evaporative unit efficiency definition on the humid-air side*

air saturated in vapour at $\tilde{T}_{evap}$ and no mass transfer on the condensing unit side (outddor heat transfer at constant specific humidity). This process is described in Figure 5.4 for the evaporative unit. For optimal interoperability, the direct model is scripted in `Python` using `Coolprop`, a thermophysical property database with a Python wrapper, which makes access to conventional refrigerant fluids straightforward in Python [249].

For setpoint control, allowed stepped setpoints are defined as in table 5.4. As described in section 3, the minimum setpoint allowed is 26°C in Coarchitects building.

Table 5.4: *List of allowed AC setpoint positions and corresponding setpoint temperature values*

AC Setpoint position	*ac_pos*	0	1	2	3	4
Setpoint value [°C]	-	30	29	28	27	26

5.1.7 Ceiling fans field model

There is no built-in ceiling fan model in `EnergyPlus`. It is possible to add a predefined air velocity schedule to the `People` object so that built-in comfort models can be evaluated with predefined air speed. Nevertheless, the energy use is defined by an additional `Electric Equipment` object, which is composed of a design level (maximum power use) and a schedule of the fraction of power used. The only possible solution to link the air velocity to the power usage is to synchronize both schedules by means of a controller in the built-in `EnergyPlus` EMS. The controller would select the speed of the air velocity schedule and adjust the power level by modifying the fraction of the ceiling fan's `Electric Equipment` design level. From the perspective of using the native `EnergyPlus` comfort model and not performing optimization, this could be a straightforward solution; however, it implies a significant amount of schedule object preparation work. We decided to externalise the ceiling fan by creating a sub-model controlled by the central controller. This allows for all needed flexibility in choosing the type, number of speeds, and quantity of ceiling fans. It can also, in future work, be the

opportunity to implement a ceiling fan library based on Center for Built Environment database of measurements under the Ceiling Fan Tool [36], [250]. It is, to date, the most populated database of ceiling fan performance. For demonstration purposes of this thesis work, a simple 3-speed, 3-power usage model for Hunter Industrie's 132cm was developed based on on-site measurements in the Coarchitects building (referred to as Figure 3.14. It is given as follow in Table 5.5:

Table 5.5: *List of allowed ceiling speed positions and corresponding air velocity and energy usage*

Ceiling fan position	cf_pos	0	1	2	3
Predefined speed	-	v_0	v_1	v_2	v_3
Air velocity	$V_{CF}\,[m.s^{-1}]$	0	0.4	0.8	1.2
Energy Use / Work	$W_{CF}\,[W]$	0	19	28	40

5.1.8 Co-simulation control

This study uses Version 9.6.0 of `EnergyPlus` [251]. It offers, as well as the latest versions, the possibility to export the BEM as an FMU in 2.0 standard supported by the Berkeley Lab distribution `EnergyPlusToFMU` [241]. It is cursory to define the variables exchanged in the native `EnergyPlusToFMU` description file `.idf` before converting it to an FMU. The .FMU file is therefore ready to interact with other models (Python script) or even other FMUs, all controlled by the master program under `pyFMI`.

The Functional Mock-Up Interface (FMI) standard enables the exchange of information between dynamic models, including building envelopes, cooling systems, and the comfort model. Figure 5.1 describes exchanged variables between models at each timestep of the simulation.

During the initialisation step of the co-simulation, heat balance is performed after a warmup of several days in `EnergyPlus`. This initiated heat balance, translated into indoor conditions such as dry bulb and mean radiant temperature, relative humidity, and air change per hour at the zone level, is retrieved from the building model. Climate data and occupancy are also necessary for the controller and retrieved from the `EnergyPlus` FMU. All passive and active cooling system commands are initialized.

The simulation continues with the controller's evaluation of the indoor conditions and occupancy level of the space. If occupancy allows it, it provides the comfort model with indoor conditions (T_{db},T_r, RH) (see Figure 5.1 for reference), assuming natural ventilation contribution to air velocity (v_{NV}) from eq. 5.1 and sum it to the current ceiling fan position air velocity from Table 5.5. The comfort model evaluates the indoor environment and sends feedback to the controller. When an adaptive model is used, outdoor conditions are also sent to the comfort model. The controller uses internal rules, i.e., predefined scenarios, to determine whether the comfort assessment requires taking a *change action* or a *standby action* in

the currently operating cooling system combination. For each command, a minimum time lag is imposed to avoid systematic cooling equipment setpoint modification at each simulation step (an arbitrary set to 30 minutes in our case study, based on an informal exchange with the Coarchitects team). The controller can send an action command to (see Figure 5.1 for reference):

- **the window operation**, by sending a predefined stepped opening fraction (win_pos) to the `EnergyPlus` window schedule.
- **the ceiling fan field model**, by increasing or decreasing its position (cf_pos) based on predefined steps (v_i, e.g., in Table 5.5)
- **the refrigeration machine**, by receiving an on/off command (ac_on)and the AC predefined setpoint (ac_pos), which can be modified if indoor comfort requirements change.
- **a dynamic clothing model** that would alter the initial clothing value of the occupant as per behavioral adaptation. (For the remainder of the study, this option is disabled to allow the study to focus on certain aspects of scenario types and the comfort model's influence on final energy use).

At the end of each step, the energy and state of the cascade cooling system are logged in the controller memory for the next evaluation. This process is repeated at the next time step.

- Comfort evaluation is logged
- The window position state (win_pos) is logged
- The ceiling fan state ((cf_pos) is logged and ceiling power usage is retrieved (W_cf)
- The refrigeration machine sends back to the controller the state (ac_on), the setpoint (ac_pos), and a flag regarding the production of cold (rf_on). The sensible and latent load sent to the zone (Q_{sens}, Q_{lat}) and the compressor work for the cooling step (W_{comp} are retrieved from the refrigeration machine model.

5.1.9 Representativeness of the model

The Building Energy Models of the Coarchitects building aims to best represent the physical mechanism of the actual building to compare scenarios on a relatively close-to-reality model. Matching exact reality necessitates an absolute knowledge of building components and operation. It is a time-consuming validation process. To do so, it is possible to rely on renowned metrics to evaluate error, such as NMBE or CV(RMSE), combined with a conformity threshold at the monthly or hourly level provided by ASHRAE Guideline 14, for example [195], [252]. The Coefficient of Variation of the Root Mean Square Error CV(RMSE) expresses the dispersion of the relative error between the model and the prediction, i.e, indicating the accuracy. The NMBE is the Normalized Mean Bias Error, which represents the relative bias, i.e, the measure of over-/underestimation. Calibration process based on those metrics is often fitted over measured electrical consumption data of fully conditioned buildings, and the tuned parameters are occupancy and equipment schedules.

It is essential to remember that a model remains a simplified representation of reality and is influenced by numerous factors. When investigating the performance gap between first-principle predictions and measurements in an innovative Mixed-Mode cascade cooling system, the gap can be extrapolated because cooling systems do not perform as manufacturers design them to, and occupants' acceptability of the system might also be wrongly assumed [253]. Even with cost-intensive on-site measurement, New et al. [252] state that *it is still impractical to track the exact value of physical parameters for all materials throughout the building as they change in time*. In our case study, accuracy is also limited due to uncertainty regarding several building components (e.g., the detailed envelope composition of an old building) and the hour-to-hour occupancy and operation of each space and desk, which were not recorded over a long period (2 years) of field survey.

The calibration process remains outside the scope of our study; however, creating a nearly actual building model is worthwhile for comparison purposes in various cascade cooling scenarios. For this matter, the Coarchitects BEM was compared to actual measurement during the 2023 summer season. Figure 5.5 presents the actual versus the prediction of the model. Most of the plotted hourly data remains within a $\pm$1°C range. Outliers within a 26°C range of measurement indicate air-conditioned time that could not be predicted. The simulated hourly indoor temperature exceeding 34°C can be explained by discrepancies between the actual opening/closing times of the building and the predefined fixed weekly operation schedule. Figure 5.6 shows a particular week where AC was OFF - hence only relying on wide opening natural ventilation - and the operation schedule is tightly matching the BEM predefined one. One can observe a prediction very close to actual, with an error under 1°C most of the week. Errors exceeding 1°C occur at the building's opening and closing times, as well as during the night, a period when it is difficult to account for internal equipments gains (e.g., forgotten ON PCs or dual screens). For our study objectives, the model appears accurate enough in representing the physics, especially considering that it relies solely on the built-in natural ventilation simplified model to exchange with the outdoors.

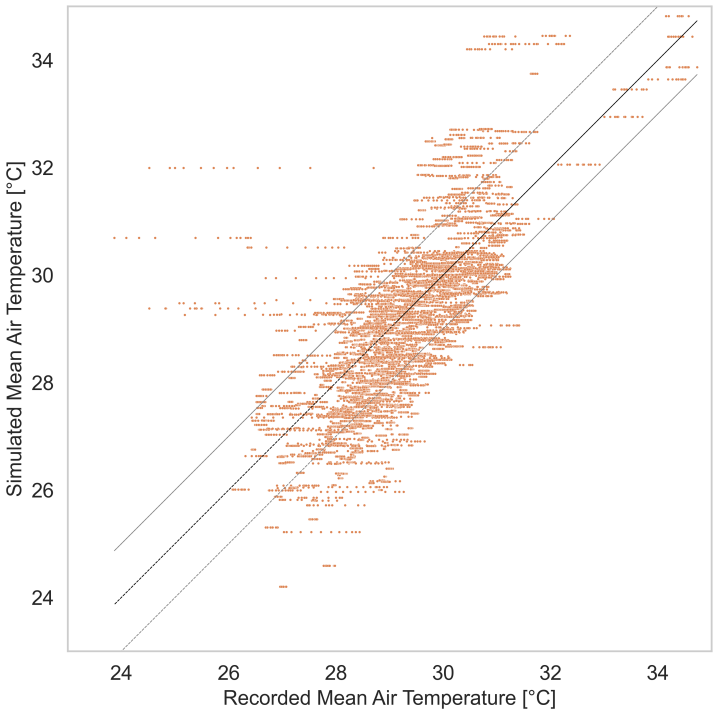

Figure 5.5: *Recorder vs simulated temperature in February and March 2023*

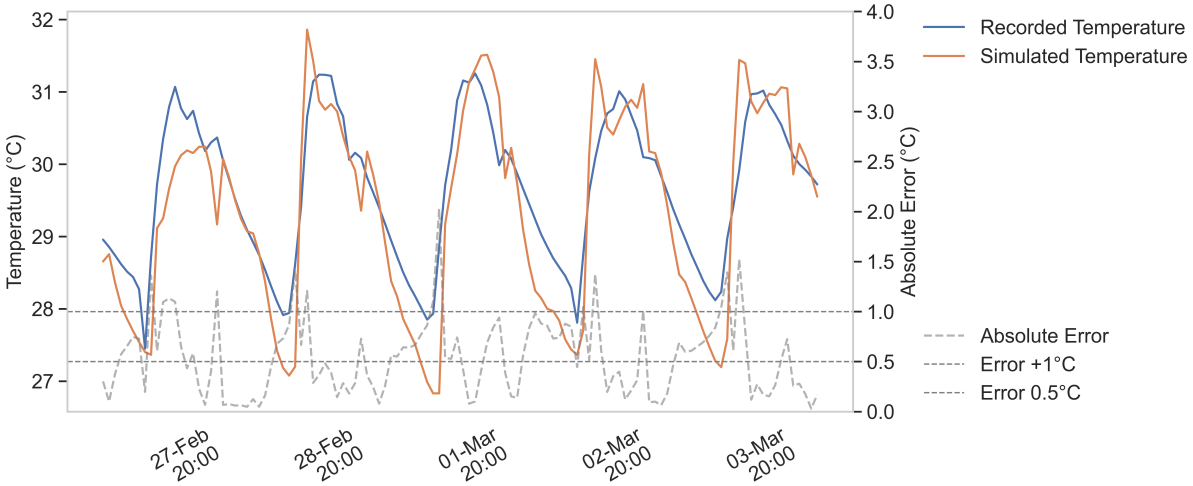

Figure 5.6: *Example of simulated and recorded data in MM Opensapce location from 2023-02-27 to 2023-03-03*

Simulation parameters

Table 5.6: *BEM results across different timestamps for two month simulation of MM (AC+CF) operation*

BEM Timestamp	**1 min**	**2 min**	**3 min**	**6 min**
AC short cycle	6 min	6 min	6 min	6 min
AC short cycle simulation steps	6	3	2	1
Initialisation of the FMU (s)	10	10	10	10
Warmup (s)	95	54	43	35
Simulation (m)	53	27	18	10.1
q_{sens} [Wh]	-217651	-214239	-216788	-195399
q_{lat} [Wh]	-163756	-162223	-164818	-155023
w_{ac} [Wh]	84999	83720	84807	77129
w_{cf} [Wh]	15328	15289	15245	15111
$\text{elec}_{\text{total}}$ [Wh]	100328	99009	100052	92240

Table 5.7: *Solver performance for the refrigeration machine*

Solver	Tolerance	Duration	Iterations
L-BFGS-B	1.e-04	0.36	8
L-BFGS-B	1.e-03	0.36	8
L-BFGS-B	1.e-05	0.39	9
L-BFGS-B	1.e-06	0.40	9
L-BFGS-B	1.e-07	0.40	9
L-BFGS-B	1.e-08	0.43	10
Nelder-Mead	1.e-03	1.14	48
Nelder-Mead	1.e-04	1.23	52
Nelder-Mead	1.e-05	1.47	59
Nelder-Mead	1.e-06	1.51	64
Nelder-Mead	1e-07	1.71	72
Nelder-Mead	1.e-08	1.86	79
Powell	1.e-05	2.30	6
Powell	1.e-04	2.62	7
Powell	1.e-03	2.69	8
Powell	1.e-06	3.57	7
Powell	1.e-07	3.78	7
Powell	1.e-08	4.53	8

Energy Plus offers the possibility to set the simulation timestamp from 60 minutes to as low as 1 minute. Simulating at a fine timestamp allows for a better representation of system dynamics, including the start and stop of the refrigeration machine, hysteresis and deadband/PID regulation, and short-cycle behavior, which an hourly-averaged simulation would mask. Hence, one can benefit from the most accurate compression-based cooling energy usage possible. According to the documentation regarding mechanical system modeling, simulating a timestamp of more than 10 minutes is possible only if the building has no HVAC system and when accuracy is not a concern. It is mentioned that a shorter timestep under 10 minutes enhances the coupling between the air and surface temperature models. It is also possible in `EnergyPlus` to have two different timesteps: one for the simulation (e.g., 10

minutes) and another shorter one for the HVAC system (e.g., a few minutes) to improve HVAC solution convergence. Nevertheless, it is impossible to control the HVAC system on this shorter time step. Non-HVAC simulation should consider a minimum of a 15-minute time step, while HVAC simulation should consider a minimum of a 10-minute time step. We decided to define the simulation timestamp as a multiplier of the AC anti-short-cycle duration of 6 minutes. To define the best accuracy/simulation time, we tested 1, 2, 3, and 6 minutes. Table 5.6 shows the output of a two-month MM (AC+CF) simulation for different time steps. Time steps of 1, 2, and 3 minutes give the same accuracy at 0.3 - 1.3 %. From 6 minutes, an underestimation of energy use of almost 10% occurs, leading to the choice of a three-minute timestep.

Regarding the refrigeration machine, the direct model is computed in the simulation only when the controller calls it. Indeed, it necessitates a solver to minimize the objective function and provide adequate sensible, latent heat, and compression work, which is computationally-intensive. Initial tests were not satisfactory in terms of solving time, often taking over a second to complete, which significantly impacted our co-simulation time. We tested several methods proposed by the `SciPy` `minimise` function [254]. Table 5.7 reports the performance of three solvers - L-BFGS-B, Nelder-Mead, and Powell - among `SciPy` available options. All other solvers failed to converge. We selected the L-BFGS-B solver based on the lowest iteration counts required to find the solution and the total iteration time, which was under 0.4 seconds. It is well-suited to our needs because it allows for setting bounds on the exchangers' temperature and humidity conditions. Tolerance of 10^{-4} and 10^{-3} provides similar iteration times; we therefore chose the tightest.

5.2 Description of MM control scenario

This section presents the different types of scenarios implemented in the controller for this study. Each scenario is built upon available *"commands"*(also called *"actions"*) referenced in Table 5.8. For maximum flexibility, we defined very simple actions for each cooling system, i.e., windows, ceiling fans, and air conditioning. Hence, with the full set of actions, any scenario combining cooling systems could be built. They basically consist of:

- an hold state command
- an increase of the setpoint or the position command
- forcing states commands

Table 5.8 mentions the code, the action/command, the state, the setpoint/position, and the related timer state. The timer state is used to ensure that actions do not change at each time step in a scenario. This remains fully parametrizable.

The following subsections describe three main scenario types studied in this work. Scenarios are either of the *Predefined* (or Uncontrolled) type or the *"Controlled"* type. The first is based on predefined setpoint/positions with no comfort control algorithm. It is essentially an on/off scenario based solely on occupancy. The second implementation is a

Table 5.8: *Actions for windows (W), ceiling fans (CF), and air-conditioning (AC)*

code	action/command W	win_on	win_pos	win_on_timer
W00	Hold state and increment timer	win_on	win_pos	+=1
W01	I open the windows	TRUE	1	0
W02	I keep the windows open	TRUE	win_pos	+=1
W03	I change to a more open position (+cooling)	TRUE	+=1	0
W04	I change to a less open position (+heating)	TRUE	−=1	0
W05	I close the windows completely	FALSE	0	0
W06	I keep the windows closed	FALSE	0	+=1
W07	Force window opening to predefined position	TRUE	predefined_win_pos	0
code	**action/command CF**	**cf_on**	**cf_pos**	**cf_timer_steps**
CF00	Hold state and increment timer	cf_on	cf_pos	+=1
CF01	I turn on the fans at the first speed level	TRUE	1	0
CF02	I keep the fans on without changing speed	TRUE	cf_pos	+=1
CF03	I switch to a higher speed (+cooling)	TRUE	+=1	0
CF04	I switch to a lower speed (+heating)	TRUE	−=1	0
CF05	I turn off the fans	FALSE	0	0
CF06	I keep the fans turned off	FALSE	0	+=1
CF07	Force ceiling to predefined position	TRUE	predefined_cf_pos	0
code	**action/command AC**	**ac_on**	**ac_pos**	**ac_timer_steps**
AC00	Hold state and increment timer	ac_on	ac_pos	+=1
AC01	I turn on the AC (highest ac)	TRUE	1	0
AC02	I keep the AC on without changing the thermostat	TRUE	ac_pos	+=1
AC03	I lower the ac (+cooling)	TRUE	−=1	0
AC04	I raise the ac (+heating)	TRUE	+=1	0
AC05	I turn off the AC	FALSE	0	0
AC06	I keep the AC turned off	FALSE	0	+=1
AC07	Force AC to predefined position	TRUE	predefined_ac_pos	0

comfort-model-based control, which implements various comfort model options (see Chapter 4 for reference) to determine the appropriate cooling command. For each scenario type, a figure (5.7, 5.8, 5.9 or 5.10) shows the mutual influence of control and indoor conditions as well as intrinsic energy usage of the cascade cooling system. Figures represent an example day 2023-03-28, for which the measured indoor and outdoor conditions have already been described in the Experimental Chapter 3 of this manuscript (Figure 3.16). All four figures are constructed the same way for easy comparison. They present three subplots.

- **The upper subplot** shows indoor (blue) and outdoor (grey) temperature (solid line) and relative humidity (dashed line). The y-axis is for temperature, and the right axis is for relative humidity. The x-axis represents the time of the day (2023-03-28). The comfort dead-band is also plotted in solid green colour in accordance with the equivalence table 2.4. In the case of figure 5.7, the SET neutral dead-band is plotted for information (even when the scenario is uncontrolled). The red curve represents the comfort evaluation, in this example case, the SET calculation at each time step.

- **The middle subplot** illustrates usages and occupancy. Left Y-axis is for Air change per hour (blue) (in case of windows are open) calculation and AC set-point (orange). When the set-point is different from zero, it means the AC received a command to be ON. Occupancy is plotted on the right Y-axis in dashed grey together with cooling usages in orange -indicating if the refrigeration machine provide cold to the space-, blue - indicating the fraction of window opening- and green - indicating the speed position of the ceiling fan.
- **The lower subplot** represents the electrical power consumed by the refrigeration machine for cooling the space (when RF is ON - solid orange line on the left Y-axis) as well as the electrical power by the ceiling fans when operating (dashed green line on the right Y-axis)

5.2.1 Predefined NV + CF - Uncontrolled (UC)

Predefined NV + CF - Uncontrolled (UC) scenario is not controlled unless on occupancy. The building relies only on ceiling fans and natural ventilation to maintain occupant comfort conditions. It is, in essence, an entirely naturally operated building with no mechanical cooling systems. Operation is straightforward and illustrated by Figure 5.7. This simple case scenario helps in understanding how to read the figure. It presents a scenario where the windows are fully open (position 2) and the ceiling fan is set to speed 1 (position 1). Before the first occupants arrive and open the windows at 7:00, the indoor temperature is still at around 26°C, while the outdoor temperature is approximately 20°C. There is no possible natural free-cooling in the building, which uses plain timber shutters to secure openings at night. At that time, occupancy reaches 2 persons (dashed grey) and window opening (dashed blue on the middle plot goes to position 2, provoking a fall in indoor temperature to 22°C due to an increase of ACH over 10 vol/h. At that time, one starts to evaluate comfort conditions (upper plot red line)- i.e. SET in this example - while a predefined ceiling fan position to speed 1 is imposed throughout the day (middle plot dashed green line). On this plot, window position is also observable on the middle plot showing position 3, which corresponds to 100% opening (see table 5.2). Occupancy (dashed grey middle plot) continues to increase to 8 persons at 8:00, coinciding with a gradual rise in indoor temperature due to added heat gain (occupancy and corresponding electrical usages). Around 11:00, the comfort evaluation goes outside the green comfort deadband, indicating a drift to the warm side. During lunch break, occupancy is halved, but this does not significantly affect indoor conditions, which are primarily influenced by heat and mass balance from natural ventilation. From 18:00, people start to leave the office, which closes at 19:00. It provokes a slight decrease in indoor temperature and then an increase due to the closing of all doors and poor night ventilation. This straightforward scenario, while not consuming a lot of energy, i.e., 40W constant throughout the day due to ceiling fan power usage (lower plot dashed green), cannot provide neutral conditions according to SET.

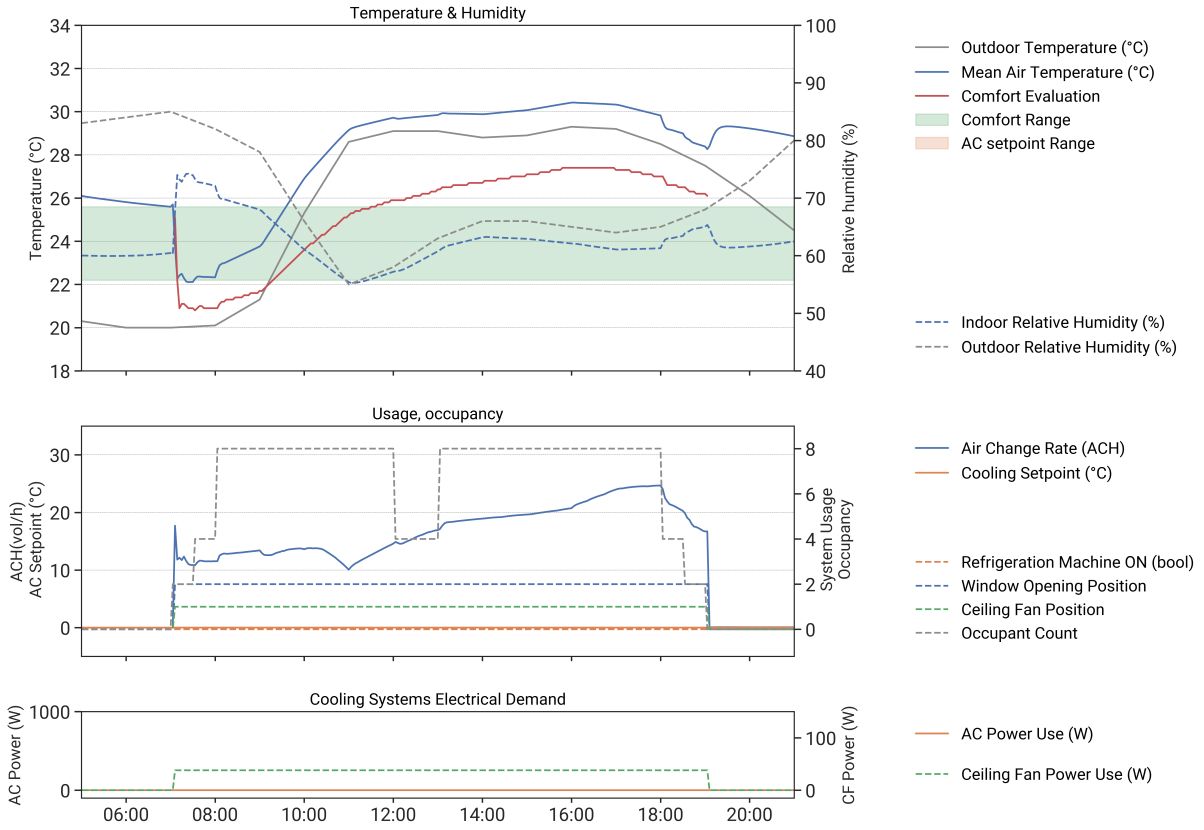

Figure 5.7: *Uncontrolled NV and Ceiling fan use (speed 1) : impact on indoor conditions and energy use*

5.2.2 Predefined AC alone - Uncontrolled (UC)

The second example presents the fully air-conditioned scenario with a predefined setpoint, which is very simple. When occupant arrive, the AC is set to a predefined setpoint of 26°C. The Refrigeration machine deadband is highlighted on the upper plot in plain solid orange when AC is ON. When occupants leave, the AC is shut down. No window opening or ceiling fan use is available, only very minimal infiltration is noticeable. Initial indoor condition are the same of the previous case, around 26°C. When people arrive in the office, the evaluation of the SET gives a condition close to the upper neutral limit. Indeed, while 26°C should sound confortable, in this example air velocity is null and humidity is already over 60%. AC set to 26°C lets the occupant be comfortable until 14:30. During that period, the refrigeration machine regulate to provide an indoor ambiance at 26°C in average. For this machine, while AC is ON (fixed 26°C setpoint highlighted in orange on the midlle plot), the refrigeration machine starts and stop for varous count of steps, sometimes 2 steps at 7:30, sometimes 5-7 steps after 10:30. This is shown by the dashed orange stepped line on the middle plot. After 13:00, the refrigeration machine never stops producing cold because it cannot maintain the predefined 26°C highlighting it might be undersized for this purpose. At the end of the day, occupant start to leave, decrease internal load and making the AC sufficient again to lower the SET evaluation. This is clearly reproduced on the lower plot where ceiling fan is obviously at zero consumption and the refrigeration machine reproduces the trend of cold production.

One can also note that producing cold in the morning cost a bit less than than in the afternoon when outdoor temperature reach 29°C.

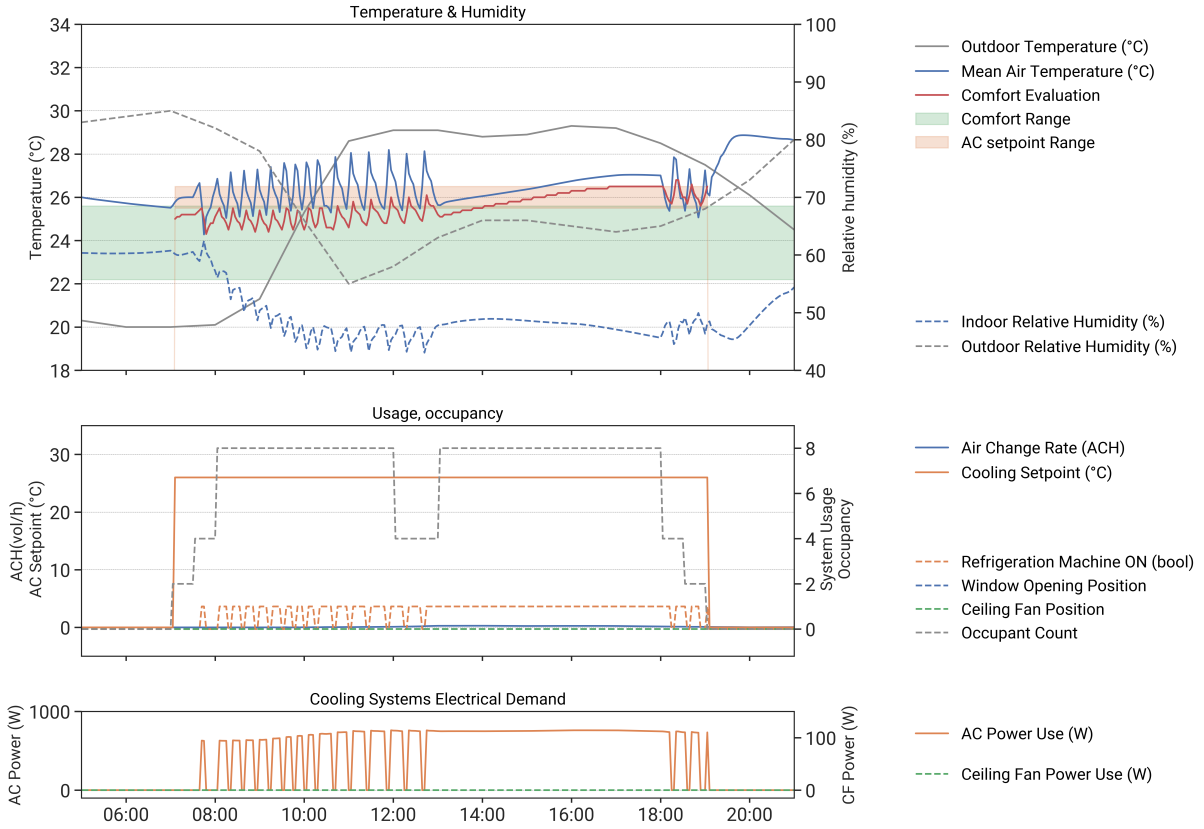

Figure 5.8: *Uncontrolled Predefined AC at 26°C without ceiling fans nor natural ventilation : impact on indoor conditions and energy use*

5.2.3 Predefined AC + CF - Uncontrolled (UC)

The third example investigates the mixed mode solution by only coupling the ceiling fan to the air-conditioning (AC+CF) of the previous case (predefined temperature at 26°C). Windows opening is not available, and the cooling system is still uncontrolled, meaning that the ceiling position and AC setpoint are fixed predefined values. They are set to 26°C for AC and speed 2 for the ceiling fans. One can directly observe a clear drop in SET evaluation. While the indoor temperature is maintained at 26°C, the use of the fan at 0.9 $m.s^{-1}$ reduces the conditions to the slightly cold limit for several hours after first arrival. The air temperature curve has the same pattern as in the previous case, but indoor SET conditions remain in the neutral range three-quarters of the time. Nevertheless, combining both produced an indoor ambience that was too cold in the morning. The middle plot and the lower plot show the usage of the ceiling fan at fixed position 2 (dashed green line) with the corresponding 56W power usage value. AC usage is also presented by the orange line at 26°C and the orange step line for refrigeration machine operation. Energy use follows the same pattern as the previous example. With this predefined coupled solution, comfort is maintained on the warm side but slides to the cold side in the morning due to the uncontrolled character of the coupling. It is

overall far better than the solely 26°C AC alone solution, while only (2x28)W of power usage is added to the hourly energy consumption.

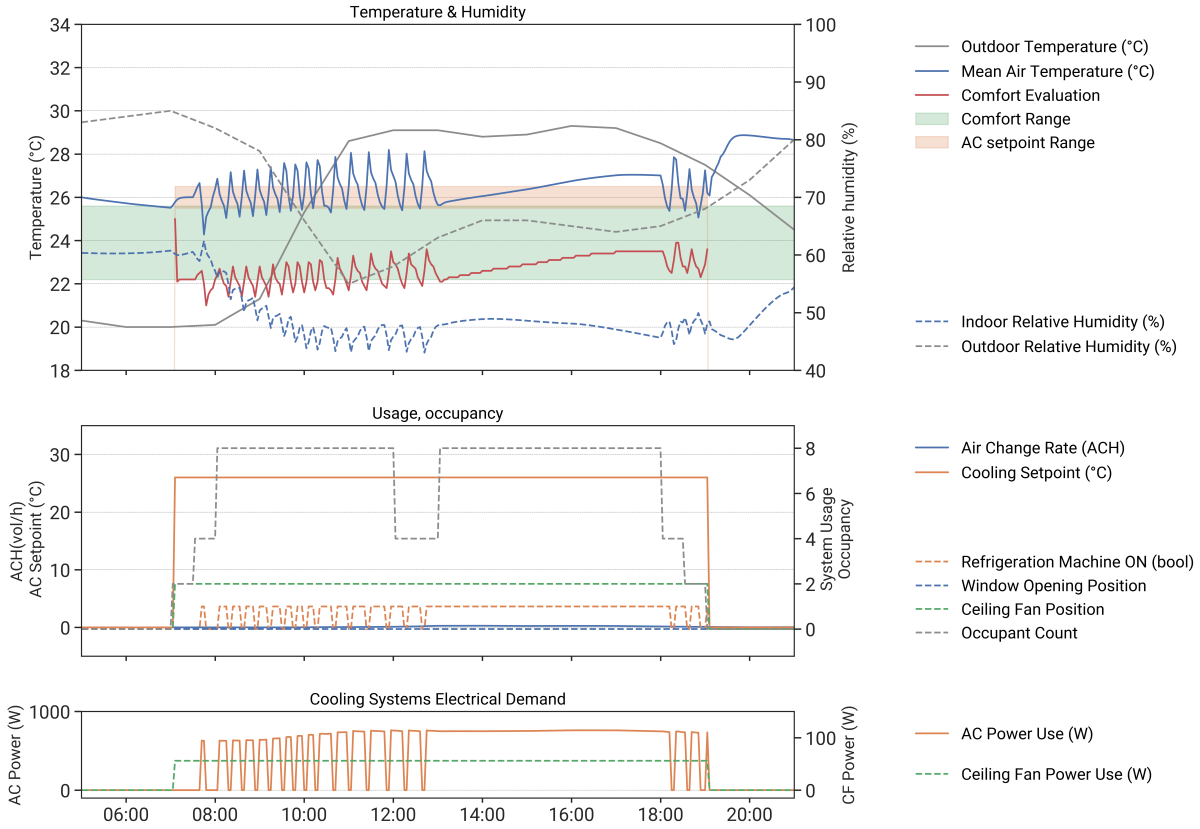

Figure 5.9: *Uncontrolled Predefined AC at 26°C setpoint and CF speed 2 : impact on indoor conditions and energy use*

5.2.4 NV+ AC + CF Mixed-mode Comfort-based (CB) control

The last example presents the operation of this thesis work, a mixed-mode cascade cooling strategy, favouring natural ventilation and ceiling fan when possible, and using AC in conjunction with CF when indoor conditions deteriorate. This more refined scenario disposes of the complete list of system controls, such as three window positions, three speed positions for fans, and five setpoint positions for the AC. This scenario is comfort-controlled; hence, the commands are defined by the controller based on comfort evaluation in the indoor space. For this example, the SET neutral deadband is also used. Initial indoor conditions are in line with the previous examples starting at around 26°C / 63 % RH before the arrival of occupants. At 7:00, the first occupant arrives and opens the window a few tenths of a minute later because indoor SET is in the neutral range until 7:45. 50% of the window opening permits to lower the SET while maintaining it in the neutral deadband until 9:50, where windows get opened fully. The stepped dashed blue line on the middle plot represents the incremental window position. Nevertheless, it does not manage to keep SET in the neutral band and a drift on the warm side is observed from 10:00. The ceiling fan is not activated right after the SET reaches the neutral comfort limit because we implemented a minimal timer of 30 minutes between

two commands. One can observe the start of the ceiling fan in position 1 around 10:30, which results in a drop of the SET value. The two other speeds are incremented in the next few hours to maintain the SET in the neutral deadband. From 14:45, natural ventilation and max ceiling fan speed are not enough, so windows are closed and AC starts at the highest possible setpoint temperature (30°C). The ceiling fan is maintained at its maximum speed. Because 30°C setpoint with speed 3 is not enough, the setpoint decreases gradually until the SET can be kept in its neutral zone. This scenario offers the possibility to control all three cooling systems in a cascade strategy, favouring coupling systems and the least energy-intensive first. It is shown that it is possible to delay the start of the ceiling fans by 2 hours, and the AC by 6 hours, hence limiting their usage. Also, while using the SET, the air velocity of the fan allows the thermostat to be set to 28°C without affecting the theoretical SET neutral range.

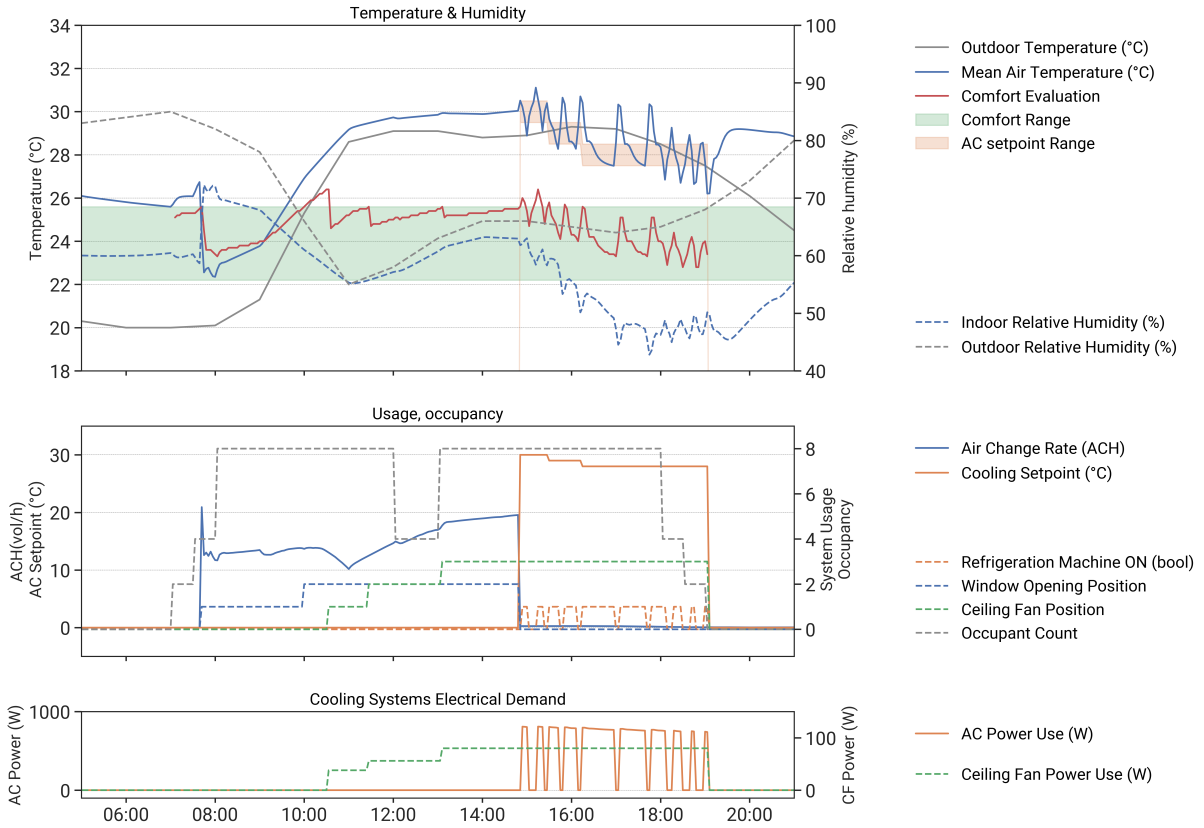

Figure 5.10: *Mixed-mode NV+CF+AC with a comfort-based control : impact on indoor conditions and energy use*

5.3 Simulation of MM control

5.3.1 Simulated cases descriptions

In the previous section, we described the four scenario types. In the present section, we enumerate the uncontrolled and comfort-based controlled cases we investigated in this thesis work. We replicated the four types of scenarios with different predefined settings (UC scenarios) or various comfort models (CB scenarios) to test combinations. Energy use

and comfort are considered for all cases annually. Table 5.9 references Uncontrolled (UC) cases from UC1 to UC12 and table 5.10 comfort-based (CB) controlled cases from CB01 to CB08. CB08 case is simulated with both 2023 and 2024 weather files. Both sub-tables present the combination of cooling system in use and either the predefined position/setpoint or the comfort model implemented for the control.

Table 5.9: *Uncontrolled / Predefined position or setpoint*

Case	Uncontrolled case with predefined position/setpoint	.epw year	NV % opening	CF speed	AC setpoint
UC01	NV + CF	2023	Fully open	1	OFF
UC02	NV + CF	2023	Fully open	2	OFF
UC03	AC	2023	Closed	OFF	26
UC04	AC	2023	Closed	OFF	27
UC05	CF + AC	2023	Closed	2	26
UC06	CF + AC	2023	Closed	3	26
UC07	CF + AC	2023	Closed	2	27
UC08	CF + AC	2023	Closed	3	27
UC09	CF + AC	2023	Closed	2	28
UC10	CF + AC	2023	Closed	3	28
UC11	CF + AC	2023	Closed	2	29
UC12	CF + AC	2023	Closed	3	29

Table 5.10: *Comfort-based control cases with comfort model/indice and target range*

Case	Comfort-based control	.epw year	Model	Indice	Comment
CB01	NV	2023	Gagge	SET	Neutral range
CB02	NV + CF	2023	Gagge	SET	Neutral range
CB03	NV + AC	2023	Gagge	SET	Neutral range
CB04	NV + CF + AC	2023	Gagge	SET	Neutral range
CB05	NV + CF + AC	2023	Gagge	T_{sens}	Neutral range
CB06	NV + CF + AC	2023	Gagge	$PTS_{McIntyre}$	Neutral range
CB07	NV + CF + AC	2023	Fanger	PMV_{iso}	Neutral range
CB08-2023	NV + CF + AC	2023	Parkinson	Adaptive SET	Lower limit set to 22.2 — Upper limit AM SET + 0.5
CB08-2024	NV + CF + AC	2024	Parkinson	Adaptive SET	Lower limit set to 22.2 — Upper limit AM SET + 0.5

5.3.2 Added value to comfort-based MM control

The cases presented in this section are either uncontrolled or controlled on the neutral range of SET values computed from Gagge two-node model, which is referenced in Chapter 2 (Table 2.4). Cases have been previously listed and detailed in Tables 5.9 and 5.10.

Figure 5.11 presents on two subplots the results of the cases UC01 to UC12 and CB01 to CB04. Comfort-based cases are highlighted in red, while uncontrolled cases are in black.

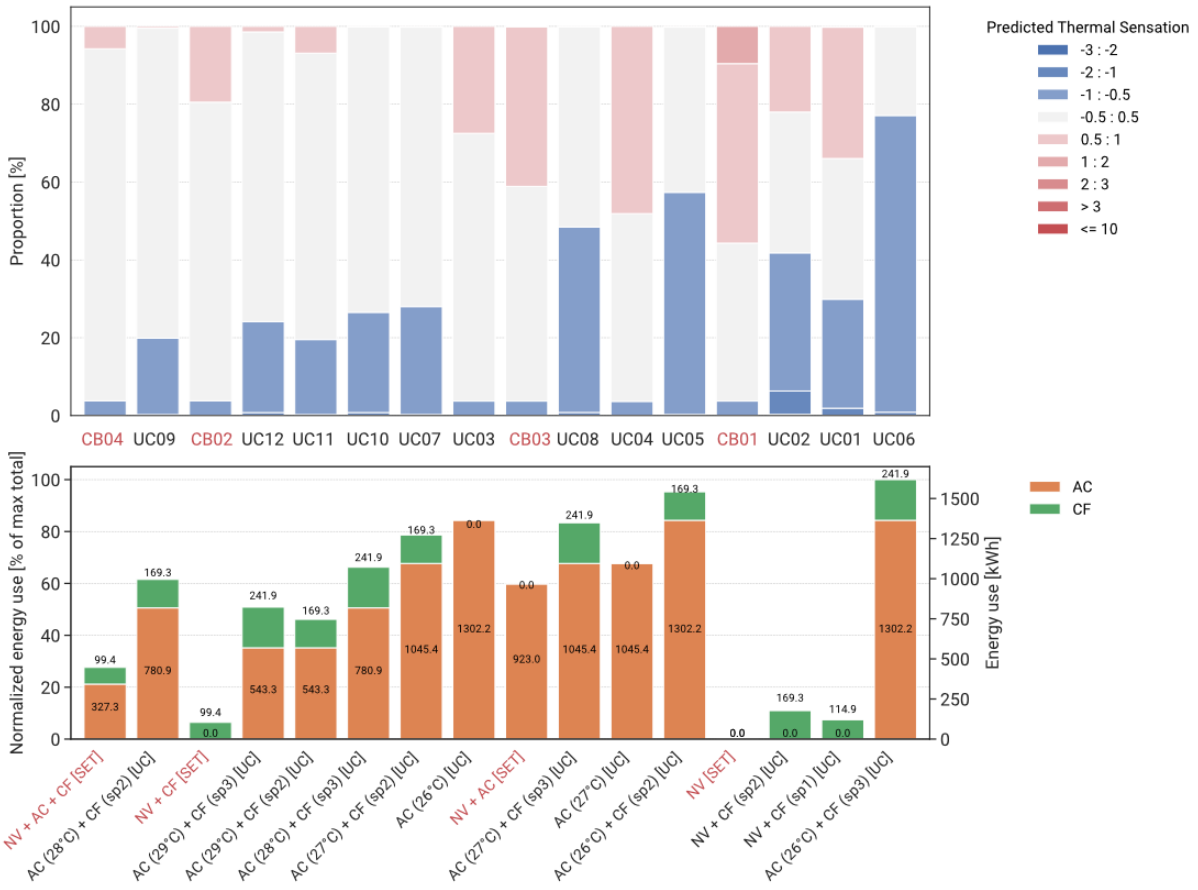

Figure 5.11: *Control cases comparison for year 2023, either uncontrolled (UC) or SET-based controlled*

The lower x-axis presents the summarized descriptions of the cases. The upper part of the figure shows the proportion of predicted thermal sensation of each category according to SET. Neutral is presented in grey, while colors become deeper red on the warm side and deeper blue on the cold side. The lower part of the figure presents the energy use of each cooling system throughout the entire year of simulation. Air-conditioning power usage is printed in an orange barplot, and the ceiling fan energy consumption is stacked above in a green bar plot. The predicted individual energy use for each system is displayed on the bars. The right y-axis displays the predicted energy use in kWh, and the left y-axis shows the proportion of energy use normalized to the most energy-intensive case. This allows for a quick visualisation of the energy proportion difference between cases. Cases are ordered from left to right by the highest neutral sensation prediction proportion, hence the best performer in comfort management.

Figure 5.11 helps in better understanding various options of Mixed-mode cooling solutions. The results are twofold: (1) They highlight the advantage of using a fan as a jointure between natural ventilation and air conditioning in a cascade cooling solution, but (2) they also underline the importance of controlling the systems to avoid unwanted drift on the cold or warm side against an uncontrolled scenario.

First, exploring CB01 case gives a reference. When only NV is available, and the opening of windows is based on the SET neutral range, strong discomfort may occur with over 50% of a slightly warm to warm sensation, representing the worst-case scenario on this side of the sensation scale. When people become warm, they cannot rely on additional cooling from natural ventilation, which is already at its maximum. Nevertheless, it also presents the best-case scenario for managing cold sensations, which are at around 3%. Because when people are getting chilly, they can close the windows. Since no heating systems are installed, this is the best achievable performance. Adding an uncontrolled ceiling fan at speed 1 (UC01) or speed 2 (UC02) partially solves the warmth issue with a total reduction of the warm sensation but at the cost of the apparition of cold sensation for respectively 60-70 % of the time for respectively +114 and +169 kWh. Hence, in mid and cold seasons, minimal control measures need to be investigated to minimize this drift.

The second reference case to investigate is UC03, which corresponds to the more energy-intensive use of AC alone. This scenario consumes 1302 kWh annually. Considering the space is conditioned all year long at 26°C, one could assume it is very comfortable. This is without accounting for the fact that the AC in place fails to provide enough cold to the room, hence provoking warm sensation 23% of the time, just over the neutral limit of 25.6°SET as shown in the Figure 5.8. For cooling at 26°C, one would need an air-conditioner with a greater capacity. Adding an uncontrolled ceiling fan at speed 2 (UC05) or speed 3 (UC06) solves the warmth issue, but completely fails to manage the cold. Hence, uncontrolled coupling of AC at 26°C with the ceiling fan is not recommended in this case. Furthermore, both cases add 169 and 241 kWh of ceiling fan consumption, respectively, to the total cooling bill.

Increasing the setpoint temperature to 27°C (Case UC04) obviously reduced the energy bill from 1302 to 1045 kWh (-13%), but also increased the expected SET-based warm sensation, which was already over 25% with a 26°C setpoint. Nevertheless, using AC at 27°C combined with a ceiling fan starts to address the question. At 27°C and CF speed 3 (case UC08), the AC consumes the same amount of energy as AC alone at 26°C (approximately 1300 kWh) and cancels the warm sensation, but at the cost of an increase in cold sensation, as the systems are not controlled by a building management system or the users themselves. Lowering the ceiling fan speed to speed 2 (case UC07) saves approximately 80 kWh annually, reducing the risk of cold without impacting the warm sensations. With these configurations (AC at 27°C with CF at speed 2 or 3), the AC unit is perfectly sized to deal with warm sensation.

It is still possible to maintain decent indoor conditions while again increasing the setpoint temperature of the uncontrolled AC+CF scenario. At 28 °C with CF speed 3, the sensation distribution is almost identical to AC 27°C and CF speed 2, with approximately 77% of neutral predicted SET, while saving 15% of energy. Counter-intuitively, at 27°C with the same speed 3 (UC08), it consumed more with less neutral sensation prediction, again highlighting the necessity of a minimal seasonal control. AC at 28°C and CF speed 2 (case UC09) offers the highest performance in neutral conditions prediction for an uncontrolled case, while still consuming almost 950kWh annually. This case scores second for neutral sensation prediction. Increasing up to 29°C and combining with a ceiling fan at speed 2 or 3 (cases UC11 and UC12) offer the better sweet spots in terms of sensation prediction (under 5%) and energy use scoring at 712 and 784 kWh, hence almost 25% less than UC09 (AC28 + CF2) at minimal warm sensation drift. Nevertheless, necessitating a minimal seasonal system control to avoid drift on the cold side.

Finally, when it comes to cutting energy use, the best performers are found among the Mixed-mode scenarios. Indeed, SET-controlled NV (CB01) and NV+AC (CB03) alone fail to reduce the warm sensation proportion below 40%, highlighting the undersizing of the AC unit and, as already mentioned, the inability to reach the neutral target with passive means only (NV). When coupling Natural Ventilation with a ceiling fan and controlling both opening fraction and ceiling fan speed based on calculated SET, it brings the cold prediction to its minimum (as in reference case CB01) and a warm sensation to 20%, which is in agreement with low expectancy naturally ventilated buildings. Controlling a fully mixed-mode cascade cooling scenario implying NV, CF and AC as described by figure 5.10 permit to manage both cold and warm sensation in the building (<5%, primarily because of the latence time of 30 minutes between two possible actions in the model) together with reducing energy use reaching overall 426 kWh composed of one fourth of CF consumption and three fouth of AC power usage. It offers the best comfort of all test cases at the cost of more than half the energy use compared with uncontrolled AC only at a 27°C setpoint (UC04) or SET-controlled NV+AC (CB03). Compared with the AC-only reference case (26 °C setpoint), warm-sensation management improves fivefold while energy use is reduced to less than one third. It is noteworthy that the AC system is undersized for this case study, running at 26°C

(UC05) and consuming 1302 kWh. However, even if one could size it up to correctly to predict warm sensation so that it matches the best-case controlled scenario (Warm sensation at 5% (CB04)), it would certainly consume more than 1302 kWh and never reach the performance of the UC04 MM control scenario, which consumes 446 kWh.

5.3.3 Comfort model comparison

In this subsection, we investigate five variants of the cascade cooling strategy case CB05, encompassing all three cooling systems: natural ventilation, ceiling fans, and air conditioning. Each variant employs a distinct comfort model and index, which are derived from the comfort model selection methodology presented in Chapter 4. The aim of this section is to appreciate the difference in energy use that would result from the choice of the sensation model. Selected indices are detailed in 5.10. SET-based control is reproduced here as the reference case from the previous section. It is compared to the Gagge T_{sens}, which should provide similar results, to the $PTS_{McIntyre}$, which is regressed from SET, and to the conventional PMV_{ISO}, included in the EN-16798 standard. A tentative attempt to implement the Parkinson et al.[78] adaptive model is proposed. Nevertheless, because the authors provide the neutral building SET, we proposed a custom extended acceptability range based on AM SET regression for MM buildings. Figure 5.12 illustrates the comparison between the original SET neutral (acceptable) range in grey and the custom-defined extended range based on Parkinson's AM SET model [78], in yellow.

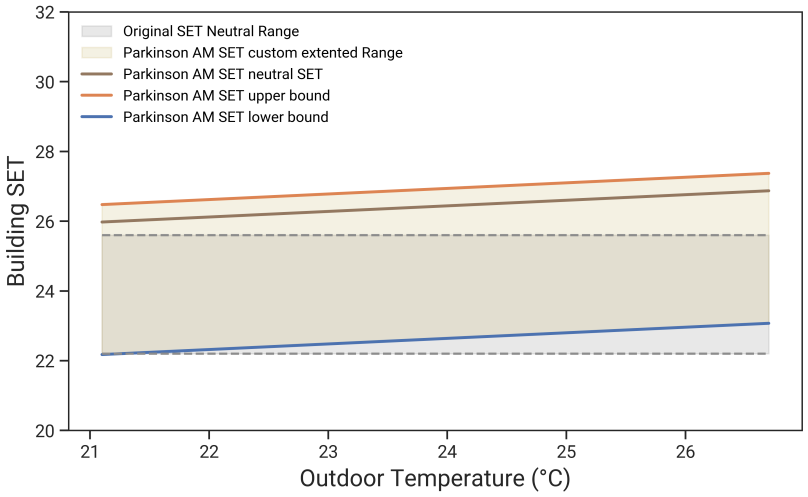

Figure 5.12: *Comparison between original SET acceptable range and custom extended range based on Parkison's AM SET*

- The comfortable SET (Brown line) is defined according to the Parkinson AM model for mixed-mode buildings, according to equation 2.89, mentioned in section 2.3.5. We consider that the extension of the neutral SET range would only apply to the upper bound of the neutral limit.
- The upper bond (Orange line) is calculated based on AM SET neutral SET for mixed mode building, to which we added an arbitrary +0.5°SET. Hence, instead of

a conventional constant 25.6°SET upper limit, the custom-made range upper limits vary from 26.5 ° in winter to 27.4 ° in summer (i.e., right in the middle of the conventional slightly warm range in sensation scale table 2.4

- Regarding the lower bound (Blue line), while people can be neutral in warmer conditions, they remain neutral close to the original lower bound of 22.2°C. Hence, the lower bound is assumed from the original neutral range lower bound of the Gagge sensation model (22.2°SET) for the coldest month. The same slope is applied to compute the lower bounds for the other months. Instead of a 22.2°SET constant bound, the lower bound ranges from 22.2 °SET in winter to 23.1 °SET in summer.
- *For reference, Table 2.4 mentions a neutral range between 22.2° and 25.6°C SET for the original model, highlighted in grey in figure 5.12.*

Please note that the above-mentioned proposed neutral range for Parkinson's SET-based model (*extended - Parkinson AM Model*) is for demonstration only. It would require further investigation to define the exact range based on the satisfaction of the surveyed population.

Figure 5.13 follows precisely the same construction as the previous figure 5.11, respecting a neutral sensation proportion decreasing order from left to right. The only difference is that the predicted sensation distribution is determined from the original sensation of the computed model. (SET uses the conversion table from SET to -3/3 scale, while PMV directly outputs the right scale). All presented models perform equally in terms of sensation prediction distribution, as one would expect from a perfectly controlled cooling system. As anticipated, SET-based on T_{sens}-based controls are very similar. Slight discrepancies could be explained by the averaging of the SET sensation correspondence table proposed by Gagge against the accurate calculation of the Thermal Sensation T_{sens}. There would be no significant difference in controlling with SET or T_{sens}. Nevertheless, the Predicted thermal Sensation PTS mentioned by Gao et al.[156] and Schweiker et al. [157], [183], [184], which is based on a regression sourced from McIntyre's book [114], is less energy intensive than SET/T_{sens}. It permits a 55% reduction in overall energy use. On the contrary, conventional PMV_{ISO}, which is known for overestimating warm conditions, is clearly the most energy-consuming of all models, reaching 575 kWh, whereas the SET-based model is at around 420kWh.

All those consumption estimates are still far from the measured energy use of cooling systems in the case study. Proposing an extension of the Parkinson model, which remains to be investigated, offers interesting perspectives. Indeed, when simulating both 2023 and 2024 years with the custom-built adaptive SET range, one can obtain a very close approximation to the actual measured energy for both the air conditioning of the MM openspace and the ceiling fans. Indeed, as from chapter 3.3.5, MM Openspace AC consumes 36kWh in 2023, whereas the simulated BC05 case with the *extended Parkison AM Model* predicts an overall energy use of 30.1 kWh. The same trend can be observed in 2024, with higher energy use for AC at 112 kWh, closely predicted by the model at 106.6 kWh. It is more challenging to compare CF power use because energy meters measure several units at once, but a rough breakdown would give 56

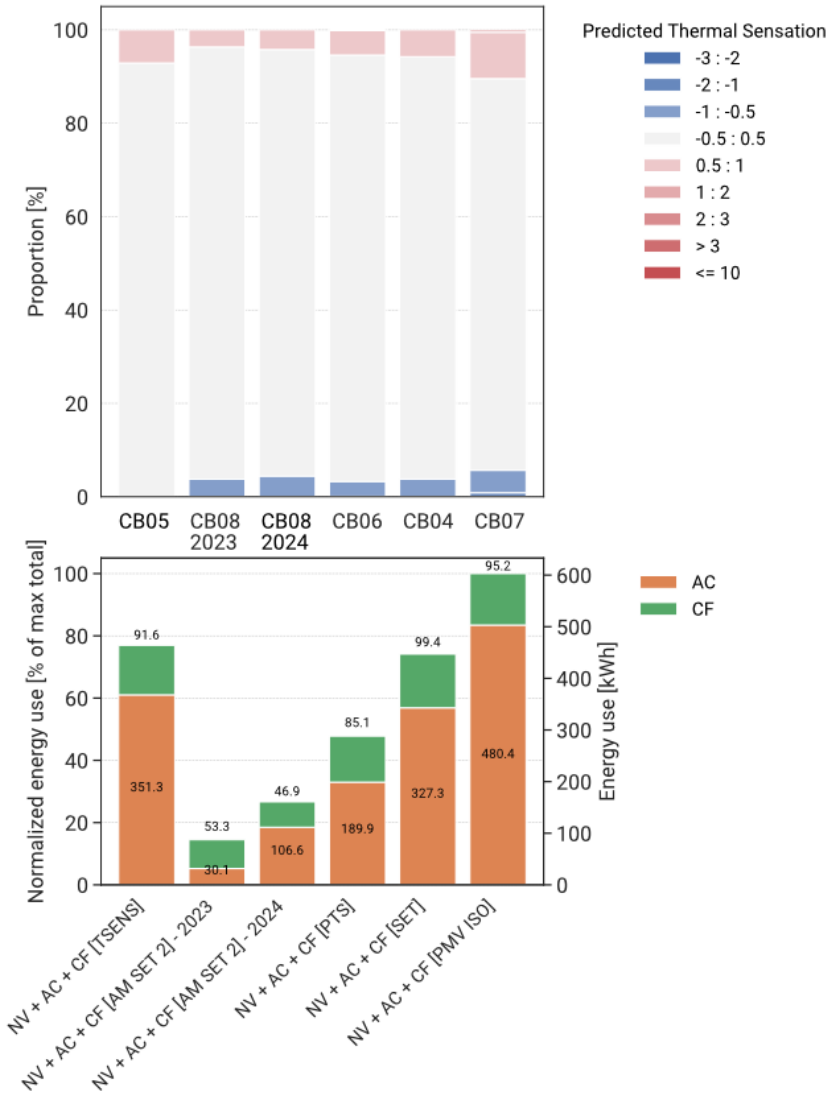

Figure 5.13: *Comparison between a selection of comfort models on NV+CF+AC Mixed-mode control*

kWh in 2023 and 48 kWh in 2024, when the simulation predicts 53 and 46 kWh. Because they are highly dependent on this case study, those results must be considered with great care. Nevertheless, they offer an encouraging perspective to complement the Parkinson model with a proper neutral satisfaction range and implement the model for mixed-mode applications.

5.4 Conclusive remarks

In this concluding chapter, we propose a flexible framework for simulating the entire cascade cooling strategy in operation at the Coarchitects building. Both Research Question 4 and Technical Question 1 are addressed in this final chapter, which investigates the influence of comfort-based mixed-mode cooling strategies against predefined scenarios.

We detailed the simulation framework proposition in the first section. It offers the possibility to assess energy and comfort performance of a full range of scenarios and cooling systems combinations. It is built with flexibility and upgradability in mind. Indeed, the proposed framework consists of a controller that connects the building energy model and the weather file (combined in an FMU unit) to cooling systems, including a simplified ceiling fan field model and an in-Lab developed grey-box model of a refrigeration machine based on the thermodynamic cycle. The proposed framework would be suitable for linking the building model to any other cooling system model developed in Python or built as an FMU to exchange information.

The model was simulated with custom-made weather files corresponding to the two years of energy metering. Although not calibrated according to a state-of-the-art definition, the model provides a good representation of the physics involved in the actual building, making it suitable for relative comparison of scenarios. Various basic, uncontrolled scenarios are described with predefined setpoints for the position of cooling systems, such as ceiling fan-aided naturally ventilated operation, solely air-conditioned scenarios, or ceiling fan-assisted air-conditioned ones. They are confronted with a comfort-based scenario employing a cascade cooling strategy, making good joint use of window openings, ceiling fan, and air-conditioning. The Standard Effective Temperature from Gagge Two-node is first investigated as a comprehensive comfort objective function. It highlights that the SET-based MM cooling strategy is by far the highest scorer in both comfort and energy usage perspectives. Energy usage is reduced by 3 compared to a conventional 26°C air-conditioned simulated building, which offers higher comfort performance.

The SET index is compared to other selected indices from the case study comparison. The ceiling fan-assisted mixed-mode cooling scenario is used for this comparison. It quantifies the impact of the model choice on power use. SET and T_{sens} are obviously of the same vein. The European PMV kept as a reference is the highest consumer by far. The Predicted Thermal Sensation based on SET proposed by McIntyre/Gao is far less consuming. Furthermore, the

Parkinson SET-based adaptive model, considering the assumed neutral range, is indeed the closest in energy performance to our case study's actual energy use. It offers insights to further investigate its construction concerning acceptability and satisfaction, and further implement it in mixed-mode applications.

6
General conclusions

6.1 Contributions

This PhD aimed to contribute to a better understanding of Mixed-Mode cooling in office buildings in tropical conditions and to propose a simulation framework for investigating fan-assisted cooling strategies. This study was unique in employing a methodology that combined both qualitative and quantitative analysis to select the most appropriate comfort model for simulating the mixed-mode cascade cooling strategy. Furthermore, it is strongly interlaced with an experimental energy and comfort survey underlying the extent to which a fan-assisted Mixed-Mode operation can benefit high overall comfort perception and radically low energy use.

The contributions of the present work are illustrated by figure 6.1. Each chapter of this manuscript has fully or partially addressed a research question and has been subject to a scientific contribution by means of a journal or conference article. The figure also highlights the connection between each chapter.

Several insights emerged while defining a mixed-mode cooling strategy for hot and tropical conditions. With the ever-growing energy demand for cooling in tropical regions and the significant role cooling plays in a building's total energy bill, a shift in mindset is necessary. There is a pressing need to rethink the way thermal comfort in buildings is considered. Less energy-intensive cooling solutions should be adopted by the Architecture, Engineering and Construction industry. Mixed-mode cooling, particularly fan-assisted mixed-mode cooling, is gaining interest for its capabilities to enhance comfort and reduce energy use. The adoption of this approach remains limited due to (i) the lack of performance evaluation studies and (ii) the need for a flexible, easy-to-implement tool chain.

Research question 1 (RQ1) addresses the performance of mixed-mode buildings by exploring the extent to which they can be comfortable and energy efficient. The investigated case study matched perfectly the fan-assisted mixed-mode operation in the tropical conditions

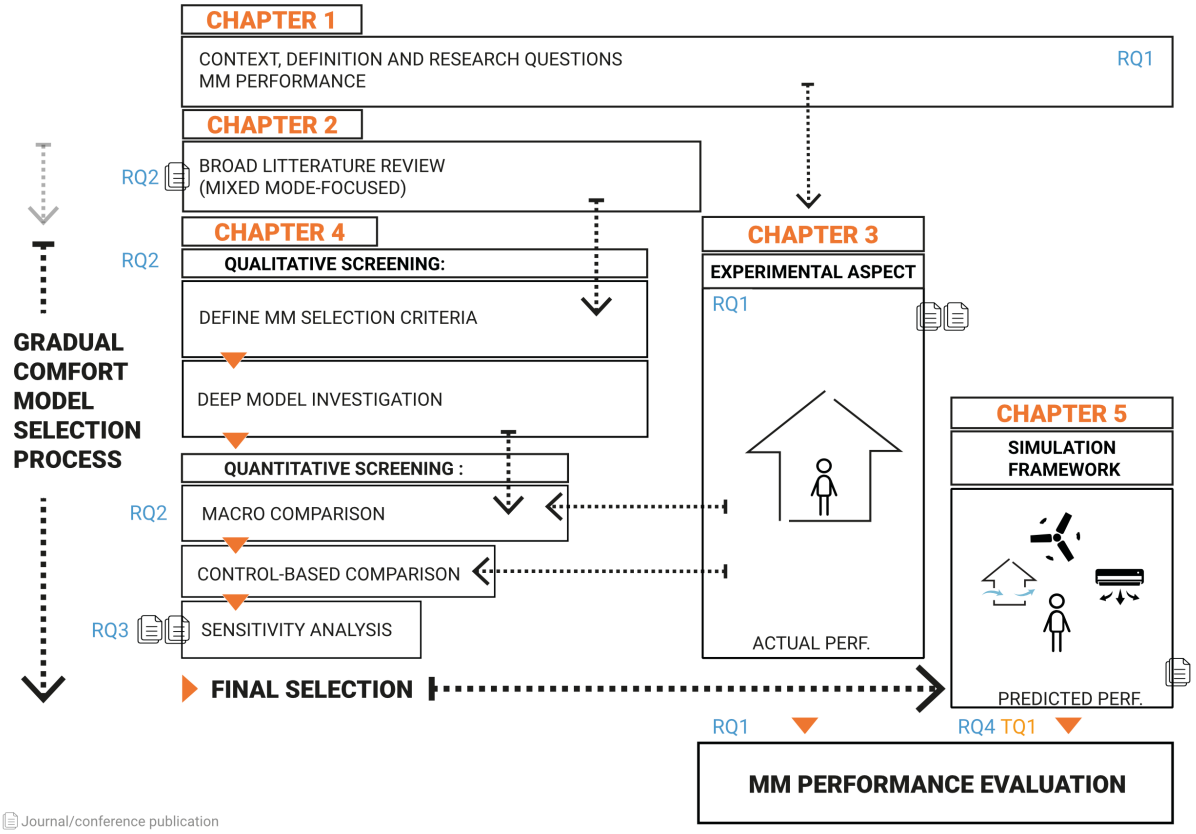

Figure 6.1: *Alignment of Research Questions (RQ), Chapters, and Papers*

of La Reunion. The users' awareness of energy use and the building's environmental impact could be seen as a limitation for generalization, but the actual case study demonstrates how performant mixed-mode operation can be. Overall, the experimental analysis confirmed what several studies highlighted, that mixed-mode operation is perceived as comfortable and acceptable [86] by the occupants and permits the use of less energy for cooling. However, it goes far beyond demonstrating very low energy use for air-conditioning, which was available to the occupants. The total AC consumption is up to four times less than the conventional building power usage. The ceiling fans, to which users are accustomed, significantly delay the use of AC and result in maintaining a higher setpoint than what is usually reported in studies. The survey also showed that people accustomed to using ceiling fans in the hot tropical summer found that air-conditioning alone failed to deliver acceptable conditions, with its use primarily triggered by a relative humidity threshold around 68% [86]. This has been demonstrated when recorded sensations matched those experienced in the presence of ceiling fans.

Regarding the need for a tool to facilitate the MM operation adoption in new and refurbished buildings, one could think that it is straightforward to implement a coupled AC and CF system. In essence, it is. Nevertheless, when it comes to the design of the entire coupled system, things become less trivial than they initially appeared. Indeed, efficient tropical cascade Mixed-mode cooling solutions rely first on fan-aided natural ventilation. This involves sizing the windows for proper warmth discharge. When conditions deteriorate, an

AC unit complements the use of fans. In this configuration, selecting the type and number of fans to ensure proper air movement and adequately sizing the AC unit to maintain a non-conventional, elevated indoor air temperature set-point should be done at the lowest energy cost. Moreover, switching between NV, NV+CF, and CF+AC modes implies relying on comfort models that reproduce the indoor occupant perception of comfort. This suggests relying on a comfort model compatible with tropical climates and an index with a wide range of controllable input variables, in accordance with building energy modeling control.

The state of the art in chapter 2 has provided a wide range of possibilities to model comfort in the built environment, partially illustrated in [82]. The review has shown that early research on Thermal Heat-balance models and comprehensive comfort indices has emerged to address the growing development of Heating, Ventilation, and Air Conditioning systems in the construction industry. Standards and building codes quickly adopted these models, and the increasing availability of computational tools facilitated their widespread use, leading to a certain standardization and, some would argue, a Western-centric, narrowish definition of comfortable indoor conditions. In contrast to air-conditioned buildings, naturally ventilated buildings were thoroughly investigated to better understand discrepancies in users' expectations regarding comfort. By the end of the 1990s, a new approach using adaptive models was proposed. Hence, two concepts were opposed: the passive, user-centred comfort of an air-conditioned building, modelled like heat load systems, and the active, adaptive user of a naturally ventilated building, which values psychological, behavioural, and physiological adaptation through a data-based simplified model. More than twenty years after the introduction of the adaptive theory in building codes, the case of mixed-mode building is partially addressed in temperate regions, advocating the use of AM for summer conditions, only when there are no mechanical systems installed in the building. Hot and tropical regions still lack guidance on selecting the most appropriate comfort model for the entire cascade cooling strategy, and the literature review did not highlight a specific off-the-shelf solution. However, the last twenty years of research have been prolific in developing new alternatives that aim to bridge the gap between the Thermal Heat-balance approach and the adaptive theory. Only one model stands out for its applicability to control, the Parkinson SET-based adaptive model, but it still lacks a clear definition of the SET acceptability range.

We proposed a gradual selection methodology to address the questions advocating a comfort model among the various off-the-shelf options and its relevance to mixed-mode controllable parameters (respectively, Research Questions 2 and 3). The qualitative screening step narrows the selection by defining precise criteria to match MM control applications in tropical conditions and to investigate the foundation of various models based on those criteria. From this deeper exploration, the Gagge Two-node appeared the most promising, as the evapotranspiration heat exchange model was adequately constructed to handle hot and humid conditions. The profusion of late development bridging the gap between adaptive and thermal heat balance required deeper investigation because these concepts were rarely confronted with real measured data from mixed-mode buildings. The quantitative screening

used the experimental comfort database developed in this thesis to assess the discrepancy between the predicted and measured mean sensation votes. It showed that a control parameter binned approach is preferred when comparing model predictions to actual votes in building energy model control applications. Gagge SET-based indices confirmed their adequacy, as did the ATHB framework. The first was selected for the final step, which involves two sensitivity analyses [80], [84]. Both confirmed the significant influence of adaptive variables, such as clothing and air velocity, against air temperature, again confirming the applicability of the SET-based indices for MM control. The methodology scheme can be reproduced and adapted to any climate type or system to be controlled. It should be considered as a tool for selecting the most appropriate model in new construction, even without a priori knowledge of indoor conditions, and in refurbished construction when actual data can be collected.

Finally, an EnergyPlus-Python co-simulation framework is proposed to address the question of a flexible tool to simulate mixed-mode cooling scenarios and size coupled systems in accordance (RQ4 and TQ1). Based on the Functional Mockup Interface Standard, the proposed framework offers the possibility to simulate any comfort, ceiling fan, or air-conditioning model without relying on native EnergyPlus objects. For this study, a simplified refrigeration machine model is adapted from [83]. It is based on a thermodynamic cycle that can be easily constructed with minimal manufacturer data and parameter identification. We showed that the comfort-based mixed mode scenarios are significantly more efficient in terms of both energy use and comfort compared to the referenced uncontrolled scenario conventionally used in the AEC industry in La Reunion. Again, we demonstrated the significant influence of using various comfort models for system modelling control. The SET-based model is far less energy-intensive than the conventional PMV model. We also introduced a research perspective of using the SET-based Adaptive Model, recently proposed by Parkinson et al.[78] to better match the energy use of our case study.

6.2 Limitations and recommendations for further research

The results of this work should be considered in light of several limitations described hereafter. A selection of the ideas and recommendations that emerged throughout this research is also mentioned. The studied population, with great awareness of environmental concerns, could induce a bias as its behaviour falls outside the conventional use of AC and CF in buildings. The comfort survey-related IEQ measurements were conducted in a real-life office building with numerous constraints. A lab experiment allows for avoiding such constraints as occupant sample construction, sensor positioning, data management, and vote monitoring. Hence, the uncertainties related to the long-term comfort survey may influence the comparison between the actual votes and the model prediction. While representative of a part of the building sector in La Reunion, the size of the building remains relatively small to be generalisable to other regions of the tropical belt. The proposed methodology should be validated on a larger scale of buildings and population. The study is also limited to off-the-shelf models that can be compared with punctual votes. Hence, the dynamic of

the comfort perception over time in such a mixed-mode scenario could not be accounted for. Furthermore, most models are sensation models. Results from our case study showed different acceptability and satisfaction rates, while the warm sensation remained identical, raising questions about how thermal comfort is accounted for in indoor environments. Those comfort-related drawbacks could be addressed in several ways:

- First, comfort models, such as thermal heat balance models, should provide both a comprehensive physical output, such as the sensation, and be complemented by a judgment output, such as acceptability or satisfaction scales for thermal environment and air movement. The SET-based Adaptive model would be a good candidate for exploring judgment model building based on the ASHRAE Global Comfort Database II. This would also imply considering state-of-the-art techniques for modelling with categorical variables.
- Second, comfort survey in a mixed-mode operated building should consider the stepped change provoked by the abrupt change in temperature and airflow, which are to date only studied in Laboratory experiments. Developing a comprehensive measurement methodology for stepped change conditions in a real occupied building will enable the confrontation of dynamic sensation models with actual data. A judgment model should also complement them.
- Third, the adoption of such a system relies on the acceptability of the solution. Hence, research on socio-cultural factors influencing the adoption of new, flexible methods to maintain comfort should complement physics-based research on thermal comfort.

The simulation framework is designed to be upgradable and versatile for any models. However, the study presented here remains a proof of concept, limited by the simple case study and the implemented models. While the envelop model, based on the EnergyPlus Heat balance equation, is not questioned here, the proposed framework lacks models for cooling systems.

- First, ceiling fan field models should be developed and implemented based on recent research and experimental measurements. A methodology to assess the influence of personal comfort devices at each desk in a single node zone could complement this development.
- Second, the main drawback concerns the way the natural ventilation-induced air velocity is assumed in the zone. Air Flow Network (AFN) only provides the simulation with air change between the outdoor and the zones, or between zones. Better assuming a mean air velocity based on air change without the need to perform CFD simulation remains an open research question that needs to be addressed.

Although this ambitious research agenda will yield more accurate estimates of comfort and energy use, it should not hinder the adoption of mixed-mode cooling in the construction industry. Further work and targeted dissemination are planned.

- The development of a coupled system sizing methodology enhances the proposed framework with multizone and optimization capabilities. This work is planned as part

of the National French Research Agency-funded project named COOLDOWN, with expected outcomes by the end of 2026.

- The dissemination of this work is twofold. Research papers will showcase the case study findings, the proposed comfort model selection methodology, and the simulation framework. In parallel, the results will inform new guidelines for the AEC industry, supporting practitioners and building operation managers. Part of this work will also be proposed to contribute to the *Fans for Cooling People Guidebook* initiative [75].
- Furthermore, the simulation framework, in its current form, could already be adapted to meet the needs of engineering firms. This proposal represents a first step toward integrating mixed-mode operation into the sizing of fan-assisted air conditioning systems.

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References

[1] S. Jim and P. R. Shukla, *IPCC AR6 WGIII FullReport - Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2022.

[2] United Nations, *Paris Agreement*, 2015.

[3] OECD Urban Studies, "Zero-Carbon Buildings in Cities - A Whole Life-Cycle Approach," Feb. 20, 2025.

[4] European Commission, *Strategic Foresight Report*, English, 2022.

[5] CODA Stratégies - ADEME, "La climatisation dans le bâtiment.," Tech. Rep., 2021.

[6] International Energy Agency, "World energy outlook," 2024.

[7] L. Agbemabiese and K. Berko, "Air Conditioning in the Tropics: Cool Comfort or Cultural Conditioning?" en, p. 9,

[8] G. Prins, "On condis and coolth," en, *Energy and Buildings*, vol. 18, no. 3-4, pp. 251–258, Jan. 1992, ISSN: 03787788. DOI: 10.1016/0378-7788(92)90017-B.

[9] G. S. Brager, E. Ring, and K. Powell, "Mixed-mode ventilation: HVAC meets mother nature.," May 1, 2000.

[10] C. M. Rodriguez and M. D'Alessandro, "Indoor thermal comfort review: The tropics as the next frontier," en, *Urban Climate*, vol. 29, p. 100 488, Sep. 2019, ISSN: 22120955. DOI: 10.1016/j.uclim.2019.100488.

[11] L. Biardeau, L. Davis, P. Gertler, and C. Wolfram, "Heat exposure and global air conditioning," *Nature Sustainability*, vol. 3, pp. 1–4, Jan. 1, 2020. DOI: 10.1038/s41893-019-0441-9.

[12] *2018-Adoption-of-Adaptive-Thermal-Comfort-Standards-in-2030.pdf*.

[13] S. Haddad, A. Barker, J. Yang, *et al.*, "On the potential of building adaptation measures to counterbalance the impact of climatic change in the tropics," en, *Energy and Buildings*, vol. 229, p. 110 494, Dec. 2020, ISSN: 03787788. DOI: 10.1016/j.enbuild.2020.110494.

[14] T. Hill, ""Freezing in the tropics: Asean's air-con conundrum," *2018 Eco-Business* -, 2018.

[15] A. Auliciems and S. Szokolay, *THERMAL COMFORT*. Jan. 2007, vol. 182, ISBN: 978-0-86776-729-2. DOI: 10.1243/PIME_CONF_1967_182_147_02.

[16] M. Vellei, R. de Dear, C. Inard, and O. Jay, "Dynamic thermal perception: A review and agenda for future experimental research," *Building and Environment*, vol. 205, p. 108 269, Nov. 2021, ISSN: 03601323. DOI: 10.1016/j.buildenv.2021.108269.

[17] R. J. de Dear, K. G. Leow, and S. C. Foo, "Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore," *International Journal of Biometeorology*, vol. 34, no. 4, pp. 259–265, Dec. 1991, ISSN: 0020-7128, 1432-1254. DOI: 10.1007/BF01041840.

[18] F. Nicol, "Adaptive thermal comfort standards in the hot–humid tropics," en, *Energy and Buildings*, vol. 36, no. 7, pp. 628–637, Jul. 2004, ISSN: 03787788. DOI: 10.1016/j.enbuild.2004.01.016.

[19] R. J. de Dear and G. S. Brager, "Thermal comfort in naturally ventilated buildings: Revisions to ASHRAE Standard 55," en, *Energy and Buildings*, vol. 34, no. 6, pp. 549–561, Jul. 2002, ISSN: 03787788. DOI: 10.1016/S0378-7788(02)00005-1.

[20] M. Beccali, V. Strazzeri, M. L. Germanà, V. Melluso, and A. Galatioto, "Vernacular and bioclimatic architecture and indoor thermal comfort implications in hot-humid climates: An overview," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 1726–1736, Feb. 1, 2018, ISSN: 1364-0321. DOI: 10.1016/j.rser.2017.06.062.

[21] F. Tartarini, S. Schiavon, O. Jay, E. Arens, and C. Huizenga, "Application of Gagge's energy balance model to determine humidity-dependent temperature thresholds for healthy adults using electric fans during heatwaves," *Building and Environment*, vol. 207, p. 108 437, Jan. 2022, ISSN: 03601323. DOI: 10.1016/j.buildenv.2021.108437.

[22] A. Malik, C. Bongers, B. McBain, *et al.*, "The potential for indoor fans to change air conditioning use while maintaining human thermal comfort during hot weather: An analysis of energy demand and associated greenhouse gas emissions," *The Lancet Planetary Health*, vol. 6, no. 4, e301–e309, Apr. 1, 2022, ISSN: 2542-5196. DOI: 10.1016/S2542-5196(22)00042-0. pmid: 35397218.

[23] S. Schiavon and A. K. Melikov, "Energy saving and improved comfort by increased air movement," Jan. 2008.

[24] F. Allard, *Natural Ventilation in Buildings, a Design Handbook*. James, 1998.

[25] K. K. Juhoor, L. Lemaitre, M. Boulinguez, and A. Bastide, *Conflict Investigation between Thermal Comfort and Fire Safety in Naturally Ventilated Building Located in Tropical and Hot Climate.* 2017.

[26] F. H. Rohles, S. A. Konz, and B. W. Jones, "Enhancing Thermal Comfort with Ceiling Fans," en, p. 6, 1982.

[27] M. Fountain and E. Arens, "Air movement and thermal comfort," *Ashrae Journal - ASHRAE J*, vol. 35, pp. 26–29, Jan. 1, 1993.

[28] S. H. Ho, L. Rosario, and M. M. Rahman, "Thermal comfort enhancement by using a ceiling fan," en, *Applied Thermal Engineering*, vol. 29, no. 8-9, pp. 1648–1656, Jun. 2009, ISSN: 13594311. DOI: 10.1016/j.applthermaleng.2008.07.015.

[29] S. Schiavon, A. K. Melikov, and C. Sekhar, "Energy analysis of the personalized ventilation system in hot and humid climates," *Energy and Buildings*, vol. 42, no. 5, pp. 699–707, May 2010, ISSN: 03787788. DOI: 10.1016/j.enbuild.2009.11.009.

[30] Y. Zhai, H. Zhang, Y. Zhang, W. Pasut, E. Arens, and Q. Meng, "Comfort under personally controlled air movement in warm and humid environments," *Building and Environment*, vol. 65, pp. 109–117, Jul. 2013, ISSN: 03601323. DOI: 10.1016/j.buildenv.2013.03.022.

[31] Y. Zhai, C. Elsworth, E. Arens, H. Zhang, Y. Zhang, and L. Zhao, "Using air movement for comfort during moderate exercise," *Building and Environment*, vol. 94, pp. 344–352, Dec. 2015, ISSN: 03601323. DOI: 10.1016/j.buildenv.2015.08.026.

[32] Y. Zhai, Y. Zhang, H. Zhang, W. Pasut, E. Arens, and Q. Meng, "Human comfort and perceived air quality in warm and humid environments with ceiling fans," *Building and Environment*, vol. 90, pp. 178–185, Aug. 2015, ISSN: 03601323. DOI: 10.1016/j.buildenv.2015.04.003.

[33] Y. Zhai, E. Arens, K. Elsworth, and H. Zhang, "Selecting air speeds for cooling at sedentary and non-sedentary office activity levels," *Building and Environment*, vol. 122, pp. 247–257, Sep. 2017, ISSN: 03601323. DOI: 10.1016/j.buildenv.2017.06.027.

[34] E. Present, P. Raftery, G. Brager, and L. Graham, "Ceiling fans in commercial buildings: In situ airspeeds & practitioner experience," *Building and Environment*, vol. 147, Oct. 2018. DOI: 10.1016/j.buildenv.2018.10.012.

[35] H.-H. Lin, "Improvement of Human Thermal Comfort by Optimizing the Airflow Induced by a Ceiling Fan," *Sustainability*, vol. 11, no. 12, p. 3370, Jun. 2019, ISSN: 2071-1050. DOI: 10.3390/su11123370.

[36] P. Raftery, J. Fizer, W. Chen, *et al.*, "Ceiling fans: Predicting indoor air speeds based on full scale laboratory measurements," *Building and Environment*, vol. 155, pp. 210–223, May 2019, ISSN: 03601323. DOI: 10.1016/j.buildenv.2019.03.040.

[37] Y. He, N. Li, H. Zhang, Y. Han, J. Lu, and Z. Linxuan, "Air-conditioning use behaviors when elevated air movement is available," *Energy and Buildings*, vol. 225, p. 110 370, Aug. 2020. DOI: 10.1016/j.enbuild.2020.110370.

[38] M. Luo, H. Zhang, P. Raftery, *et al.*, "Detailed measured air speed distribution in four commercial buildings with ceiling fans," *Building and Environment*, vol. 200, p. 107 979, Aug. 2021, ISSN: 03601323. DOI: 10.1016/j.buildenv.2021.107979.

[39] S. Omrani, S. Matour, K. Bamdad, and N. Izadyar, "Ceiling fans as ventilation assisting devices in buildings: A critical review," *Building and Environment*, vol. 201, p. 108 010, Aug. 2021, ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2021.108010.

[40] R. Rissetto, M. Schweiker, and A. Wagner, "Personalized ceiling fans: Effects of air motion, air direction and personal control on thermal comfort," *Energy and Buildings*, vol. 235, p. 110 721, Jan. 2021. DOI: 10.1016/j.enbuild.2021.110721.

[41] Center for the Built Environment, *Alternatives to Air Conditioning: Fans as a Path to Resilience*, Nov. 2021.

[42] *EN-16798 : Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6*. May 2019.

[43] S. Atthajariyakul and C. Lertsatittanakorn, "Small fan assisted air conditioner for thermal comfort and energy saving in Thailand," *Energy Conversion and Management*, vol. 49, no. 10, pp. 2499–2504, Oct. 2008, ISSN: 01968904. DOI: 10.1016/j.enconman.2008.05.028.

[44] W. Chen, H. Zhang, E. Arens, *et al.*, "Ceiling-fan-integrated air conditioning: Airflow and temperature characteristics of a sidewall-supply jet interacting with a ceiling fan," en, *Building*

and Environment, vol. 171, p. 106 660, Mar. 2020, ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.106660.

[45] S. Liu, L. Yin, S. Schiavon, W. Khueng Ho, and K. Voon Ling, "Coordinate control of air movement for optimal thermal comfort," *Science and Technology for the Built Environment*, vol. 24, no. 8, pp. 886–896, Sep. 2018, ISSN: 2374-4731. DOI: 10.1080/23744731.2018.1452508.

[46] S. Gokarakonda, C. Treeck, and R. Rawal, "Investigating Optimum Cooling Set Point Temperature and Air Velocity for Thermal Comfort and Energy Conservation in Mixed-Mode Buildings in India," *Energies*, Mar. 19, 2022. DOI: 10.3390/en15062259.

[47] M. G. Kent, N. K. Huynh, A. K. Mishra, *et al.*, "Energy savings and thermal comfort in a zero energy office building with fans in Singapore," *Building and Environment*, vol. 243, p. 110 674, Sep. 2023, ISSN: 03601323. DOI: 10.1016/j.buildenv.2023.110674.

[48] D. Miller, P. Raftery, M. Nakajima, *et al.*, "Cooling energy savings and occupant feedback in a two year retrofit evaluation of 99 automated ceiling fans staged with air conditioning," *Energy and Buildings*, vol. 251, p. 111 319, Nov. 2021, ISSN: 03787788. DOI: 10.1016/j.enbuild.2021.111319.

[49] R. Rugani, M. Picco, D. Khovalyg, G. Salvadori, and F. Fantozzi, *Personalised Environmental Control Systems (Pecs) Usage Thresholds: A Dynamic Simulation Approach to Assess Energy, Cost, and Emissions Saving*, 2024. DOI: 10.2139/ssrn.5062110.

[50] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World Map of the Köppen-Geiger climate classification updated," en, *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263, Jul. 2006, ISSN: 0941-2948. DOI: 10.1127/0941-2948/2006/0130.

[51] M. Belda, E. Holtanová, T. Halenka, and J. Kalvová, "Climate classification revisited: From Köppen to Trewartha," en, *Climate Research*, vol. 59, no. 1, pp. 1–13, Feb. 2014, ISSN: 0936-577X, 1616-1572. DOI: 10.3354/cr01204.

[52] H. E. Beck, N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood, "Present and future Köppen-Geiger climate classification maps at 1-km resolution," en, *Scientific Data*, vol. 5, no. 1, p. 180 214, Dec. 2018, ISSN: 2052-4463. DOI: 10.1038/sdata.2018.214.

[53] F. Rubel and M. Kottek, "Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification," en, *Meteorologische Zeitschrift*, vol. 19, no. 2, pp. 135–141, Apr. 2010, ISSN: 0941-2948. DOI: 10.1127/0941-2948/2010/0430.

[54] D. J. Seidel, Q. Fu, W. J. Randel, and T. J. Reichler, "Widening of the tropical belt in a changing climate," *Nature Geoscience*, vol. 1, no. 1, pp. 21–24, Jan. 2008, ISSN: 1752-0894, 1752-0908. DOI: 10.1038/ngeo.2007.38.

[55] B. Givoni, *Man, Climate and Architecture* (Elsevier Architectural Science Serie). Elsevier Publishing Company Ltd, 1969.

[56] S. Carlucci, L. Bai, R. de Dear, and L. Yang, "Review of adaptive thermal comfort models in built environmental regulatory documents," en, *Building and Environment*, vol. 137, pp. 73–89, Jun. 2018, ISSN: 03601323. DOI: 10.1016/j.buildenv.2018.03.053.

[57] A. Perrau, "Towards a Wind Urbanism in Tropical Environments," en, *Journal of Architectural/Planning Research and Studies (JARS)*, vol. 20, no. 2, pp. 85–104, 2023, Number: 2, ISSN: 2773-8868. DOI: 10.56261/jars.v20.252710.

[58] Y. Pan, W. Zhong, X. Zheng, H. Xu, and T. Zhang, "Natural ventilation in vernacular architecture: A systematic review of bioclimatic ventilation design and its performance evaluation," *Building and Environment*, vol. 253, p. 111 317, Apr. 1, 2024, ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2024.111317.

[59] J. Drew, I. Jackson, M. Fry, and H. L. Ford, *Village Housing in the Tropics: With Special Reference to West Africa*. Routledge, 2013.

[60] N. Khan, Y. Su, and S. B. Riffat, "A review on wind driven ventilation techniques," *Energy and Buildings*, vol. 40, no. 8, pp. 1586–1604, Jan. 2008, ISSN: 03787788. DOI: 10.1016/j.enbuild.2008.02.015.

[61] E. Arens and G. Paliaga, "Moving air for comfort," *ASHRAE Journal*, p. 10, 2009.

[62] B. Givoni, "Building Design Principles for Hot Humid Regions," p. 9,

[63] A. Lenoir, "On Comfort in Tropical Climates. The Design and Operation of Net Zero Energy Buildings.," p. 236, 2015.

[64] A. Lenoir, G. Baird, and F. Garde, "Post-occupancy evaluation and experimental feedback of a net zero-energy building in a tropical climate," en, *Architectural Science Review*, vol. 55, no. 3, pp. 156–168, Aug. 2012, ISSN: 0003-8628, 1758-9622. DOI: 10.1080/00038628.2012.702449.

[65] A. Lenoir, F. Thellier, and F. Garde, "Towards net zero energy buildings in hot climates. Part 2: Experimental feedback.," en, p. 9,

[66] M. Payet, M. David, J. Gandemer, and F. Garde, "Performance evaluation and post-occupancy evaluation of a naturally ventilated lecture theatre in Reunion Island," en, *Journal of Physics: Conference Series*, vol. 1343, no. 1, p. 012 189, Nov. 2019, ISSN: 1742-6588, 1742-6596. DOI: 10.1088/1742-6596/1343/1/012189.

[67] G. Brager, S. Borgeson, and Y. S. Lee, "Summary Report: Control Strategies for Mixed-Mode Buildings," p. 82, 2007.

[68] G. Brager and L. Baker, "Occupant satisfaction in mixed-mode buildings," en, *Building Research & Information*, vol. 37, no. 4, pp. 369–380, Aug. 2009, ISSN: 0961-3218, 1466-4321. DOI: 10.1080/09613210902899785.

[69] G. Brager, "Mixed-mode cooling.," 2006.

[70] G. Brager and M. Pigman, "Adaptive Comfort in Mixed-Mode Buildings: Research Support Facility, National Renewable Energy Lab," Apr. 1, 2013.

[71] W. Bordass, *Mixed-Mode ventilation and cooling systems in buildings*, William Bordass Associates London, 1996.

[72] D. E. Kalz and J. Pfafferott, *Thermal Comfort and Energy-Efficient Cooling of Nonresidential Buildings* (SpringerBriefs in Applied Sciences and Technology). Cham: Springer International Publishing, 2014, ISBN: 978-3-319-04581-8. DOI: 10.1007/978-3-319-04582-5.

[73] ANSI, *ANSI/ASHRAE Standard 55-2017– Thermal Environmental Conditions for Human Occupancy*.

[74] Z. Tian, B. Si, Y. Wu, X. Zhou, and X. Shi, "Multi-objective optimization model predictive dispatch precooling and ceiling fans in office buildings under different summer weather conditions," *Building Simulation*, vol. 12, no. 6, pp. 999–1012, Dec. 2019, ISSN: 1996-3599, 1996-8744. DOI: 10.1007/s12273-019-0543-3.

[75] P. Raftery, T. Cheung, S. Schiavon, *et al.*, *Fans for cooling people guidebook*, Jul. 2023.

[76] D. Sánchez-García, J. Martínez-Crespo, U. R.-R. Hernando, and C. Alonso, "A detailed view of the Adaptive-Comfort-Control-Implementation Script (ACCIS): The capabilities of the automation system for adaptive setpoint temperatures in building energy models," *Energy and Buildings*, vol. 288, p. 113 019, Jun. 2023, ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2023.113019.

[77] S. Borgeson and G. Brager, "Comfort standards and variations in exceedance for mixed-mode buildings," *Building Research & Information*, vol. 39, no. 2, pp. 118–133, Apr. 2011, ISSN: 0961-3218, 1466-4321. DOI: 10.1080/09613218.2011.556345.

[78] T. Parkinson, R. de Dear, and G. Brager, "Nudging the adaptive thermal comfort model," *Energy and Buildings*, vol. 206, p. 109 559, Jan. 2020, ISSN: 03787788. DOI: 10.1016/j.enbuild.2019.109559.

[79] R. de Dear, J. Xiong, J. Kim, and B. Cao, "A review of adaptive thermal comfort research since 1998," *Energy and Buildings*, vol. 214, p. 109 893, May 2020, ISSN: 03787788. DOI: 10.1016/j.enbuild.2020.109893.

[80] M. Boulinguez, A. Foucquier, and J. Castaing-Lasvignottes, "Sensitivity analysis of Gagge's Standard Effective Temperature for fan-first cooling control strategy in tropical mixed-mode buildings," *Building and Environment*, vol. 272, p. 112 667, Mar. 2025, ISSN: 03601323. DOI: 10.1016/j.buildenv.2025.112667.

[81] M. Payet, M. Boulinguez, and V. Fargeas, "COOLIBRI project. Lowering cooling energy use by coupling ceiling fans to air conditioners: An adaptive user perspective," in *Journal of Physics : Conference Series*, Lausane, Nov. 2025.

[82] M. Boulinguez, A. Foucquier, O. Marc, and Castaing-Lasvignottes, "Cartographie des modèles de confort : Application aux bâtiments en rafraîchissement mixte en climat tropical," in *Conférence IBPSA France 2022*, Châlons-en-champagne, May 2022, p. 8.

[83] M. Boulinguez, O. Marc, and J. Castaing-Lasvignottes, "Development of a simplified model for evaluating refrigeration capacity and power consumption of air conditioning units based on heat exchanger entropic temperature definition," in *International Congress of Refrigeration 2023*, Paris, 2023. DOI: 10.18462/iir.icr.2023.0781.

[84] M. Boulinguez, J. Castaing-Lasvignottes, and A. Foucquier, "Pilotage des systèmes en rafraichissement mixte centré sur le confort: une étude de sensibilité du modèle de Gagge pour une application en climat tropical.," in *Conférence IBPSA France 2024*, La Rochelle, May 2024.

[85] A. Jay, A. Foucquier, M. Boulinguez, *et al.*, "Towards an alternative cooling: Optimisation of the successive use of the cooling systems from passive to active - Development of design and control strategies of the hybrid cooling," in *Ventilation, IEQ and Health in Sustainable Buildings*, Copenhaguen Danemark.

[86] G. Haese, M. Boulinguez, P. Bernaud, and A. Couzinet, "An innovative approach to better understand hot discomfort, based on the measurement of global human responses, including physiological and sensory indicators - application to end users of mixed mode cooled buildings under tropical climate conditions," in *Ventilation, IEQ and Health in Sustainable Buildings*, Aalborg University, Copenhagen, Denmark, 2023.

[87] M. Payet, M. Boulinguez, M. David, P. Lauret, and F. Garde, "Windows and ceiling fan occupant behaviour model coupling methodology with building energy models, a tropical case study," in *Ventilation, IEQ and Health in Sustainable Buildings*, Copenhaguen Danemark, 2023.

[88] N. Djongyang, R. Tchinda, and D. Njomo, "Thermal comfort: A review paper," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 2626–2640, Dec. 2010, ISSN: 13640321. DOI: 10.1016/j.rser.2010.07.040.

[89] J. J. Hensen. "On the thermal interaction of building structure and heating and ventilating system." (1991), https://research.tue.nl/en/publications/on-the-thermal-interaction-of-building-structure-and-heating-and-ventilating-system(02f2cc60-ac61-4167-a58c-5e4cf485292f).html 03/17/2025, pre-published.

[90] "Standard 55 – Thermal Environmental Conditions for Human Occupancy." (), https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy 03/17/2025.

[91] M. Jowkar, H. B. Rijal, A. Montazami, J. Brusey, and A. Temeljotov-Salaj, "The influence of acclimatization, age and gender-related differences on thermal perception in university buildings: Case studies in Scotland and England," *Building and Environment*, vol. 179, p. 106 933, Jul. 2020, ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.106933.

[92] M. Vellei, I. Pigliautile, and A. L. Pisello, "Effect of time-of-day on human dynamic thermal perception," *Scientific Reports*, vol. 13, Feb. 9, 2023. DOI: 10.1038/s41598-023-29615-8.

[93] H. Zhao, W. Ji, S. Deng, Z. Wang, and S. Liu, "A review of dynamic thermal comfort influenced by environmental parameters and human factors," *Energy and Buildings*, vol. 318, p. 114 467, Sep. 1, 2024, ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2024.114467.

[94] E. H. Wissler, *Human Temperature Control: A Quantitative Approach*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2018. DOI: 10.1007/978-3-662-57397-6.

[95] "ISO 7730:2005(en), Ergonomics of the thermal environment — Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria." (), https://www.iso.org/obp/ui/#iso:std:iso:7730:ed-3:v1:en 03/17/2025.

[96] M. Favero, "Occupant-centric models for thermal comfort in buildings: Theoretical and experimental analysis of methods for enhancing user comfort in dynamic thermal indoor environments," Doctoral thesis, NTNU, 2022, ISBN: 9788232669097.

[97] S. Khadka, H. B. Rijal, K. Amano, *et al.*, "Development of adaptive behaviour models for thermal comfort: Longitudinal investigation in Japanese office buildings and literature review," *Journal of Building Engineering*, vol. 89, p. 109 220, Jul. 2024, ISSN: 23527102. DOI: 10.1016/j.jobe.2024.109220.

[98] F. d'Ambrosio Alfano, B. Olesen, B. Palella, D. Pepe, and G. Riccio, "Fifty Years of PMV Model: Reliability, Implementation and Design of Software for Its Calculation," *Atmosphere*, vol. 11, no. 1, p. 49, Dec. 29, 2019, ISSN: 2073-4433. DOI: 10.3390/atmos11010049.

[99] *EN ISO 7730:2005 - Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005)*, 2006.

[100] "ISO 9920:2007 Ergonomics of the thermal environment — Estimation of thermal insulation and water vapour resistance of a clothing ensemble," ISO. (), https://www.iso.org/standard/39257.html 03/18/2025.

[101] R. Nielsen, B. W. Olesen, and P. O. Fanger, "Effect of physical activity and air velocity on the thermal insulation of clothing," *Ergonomics*, vol. 28, no. 12, pp. 1617–1631, Dec. 1985, ISSN: 0014-0139, 1366-5847. DOI: 10.1080/00140138508963299.

[102] R. Yao, S. Zhang, C. Du, *et al.*, "Evolution and performance analysis of adaptive thermal comfort models – A comprehensive literature review," *Building and Environment*, vol. 217, p. 109 020, Jun. 2022, ISSN: 03601323. DOI: 10.1016/j.buildenv.2022.109020.

[103] H. Liu, Y. Wu, B. Li, Y. Cheng, and R. Yao, "Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China," *Energy and Buildings*, vol. 140, pp. 9–18, Apr. 2017, ISSN: 03787788. DOI: 10.1016/j.enbuild.2017.01.066.

[104] *ANSI/ASHRAE Standard 55-2023 – Thermal Environmental Conditions for Human Occupancy*, 2023.

[105] S. Schiavon and K. H. Lee, "Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures," *Building and Environment*, vol. 59, pp. 250–260, Jan. 2013, ISSN: 03601323. DOI: 10.1016/j.buildenv.2012.08.024.

[106] J. Ngarambe, G. Y. Yun, and G. Kim, "Prediction of indoor clothing insulation levels: A deep learning approach," *Energy and Buildings*, vol. 202, p. 109 402, Nov. 2019, ISSN: 03787788. DOI: 10.1016/j.enbuild.2019.109402.

[107] K. C. Parsons, *Human Thermal Comfort* (CRC Focus). Boca Raton London New York: CRC Press/Taylor & Francis Group, 2020, 132 pp., ISBN: 978-0-367-26193-1.

[108] "ISO 7726:1998 Ergonomics of the thermal environment — Instruments for measuring physical quantities," ISO. (), https://www.iso.org/standard/14562.html 03/18/2025.

[109] V. Földváry Ličina, T. Cheung, H. Zhang, *et al.*, "Development of the ASHRAE Global Thermal Comfort Database II," *Building and Environment*, vol. 142, pp. 502–512, Sep. 2018, ISSN: 03601323. DOI: 10.1016/j.buildenv.2018.06.022.

[110] M. Schweiker, X. Fuchs, S. Becker, *et al.*, "Challenging the assumptions for thermal sensation scales," *Building Research & Information*, vol. 45, no. 5, pp. 572–589, Jul. 4, 2017, ISSN: 0961-3218, 1466-4321. DOI: 10.1080/09613218.2016.1183185.

[111] *ISO 10551:2019 Ergonomics of the physical environment — Subjective judgement scales for assessing physical environments*.

[112] M. A. Humphreys, J. F. Nicol, and I. A. Raja, "Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach," *Advances in Building Energy Research*, vol. 1, no. 1, pp. 55–88, Jan. 2007, ISSN: 1751-2549, 1756-2201. DOI: 10.1080/17512549.2007.9687269.

[113] M. André, R. De Vecchi, and R. Lamberts, "User-centered environmental control: A review of current findings on personal conditioning systems and personal comfort models," *Energy and Buildings*, vol. 222, p. 110 011, Sep. 2020, ISSN: 03787788. DOI: 10.1016/j.enbuild.2020.110011.

[114] McIntyre, *Indoor Climate*. 1980.

[115] R. J. de Dear and G. S. Brager, "Developing an Adaptive Model of Thermal Comfort and Preference," p. 19, 1998.

[116] M. Schweiker, M. André, F. Al-Atrash, *et al.*, "Evaluating assumptions of scales for subjective assessment of thermal environments – Do laypersons perceive them the way, we researchers believe?" *Energy and Buildings*, vol. 211, p. 109 761, Mar. 2020, ISSN: 03787788. DOI: 10.1016/j.enbuild.2020.109761.

[117] T. Cheung, S. Schiavon, T. Parkinson, P. Li, and G. Brager, "Analysis of the accuracy on PMV – PPD model using the ASHRAE Global Thermal Comfort Database II," *Building and Environment*, vol. 153, pp. 205–217, Apr. 2019, ISSN: 03601323. DOI: 10.1016/j.buildenv.2019.01.055.

[118] K. Karyono, B. M. Abdullah, A. J. Cotgrave, and A. Bras, "The adaptive thermal comfort review from the 1920s, the present, and the future," *Developments in the Built Environment*, vol. 4, p. 100 032, Nov. 2020, ISSN: 26661659. DOI: 10.1016/j.dibe.2020.100032.

[119] P. O. FANGER, *Thermal Comfort Analysis and Applications in Environmental Engineering*, Danish technical Press Copenhaguen. 1970.

[120] A. P. Gagge, J. A. J. Stolwijk, and Y. Nishi, "An Effective Temperature Scale Based on a Simple Model of Human Physiological Regulatiry Response," p. 17, 1972.

[121] A. P. Gagge, A. P. Fobelets, and L. G. Berglund, "A Standard Predictive Index of Human Response to the Thermal Environment," *Ashrae Trans*, vol. 92 part 2B, p. 23, 1986.

[122] R. de Dear, G. Brager, and D. Cooper, "Developing an Adaptive Model of Thermal Comfort and Preference- Final Report Ashrae Rp- 884," 1997.

[123] F. Nicol and M. Humphreys, "Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251," *Building and Environment*, vol. 45, no. 1, pp. 11–17, Jan. 2010, ISSN: 03601323. DOI: 10.1016/j.buildenv.2008.12.013.

[124] J. Nicol and M. Humphreys, "Adaptive thermal comfort and sustainable thermal standards for buildings," *Energy and Buildings*, vol. 34, no. 6, pp. 563–572, Jul. 2002, ISSN: 03787788. DOI: 10.1016/S0378-7788(02)00006-3.

[125] C. G. Webb, "An Analysis of Some Observations of Thermal Comfort in an Equatorial Climate," *British Journal of Industrial Medicine*, vol. 16, no. 4, pp. 297–310, Oct. 1959, ISSN: 0007-1072.

[126] F. Binarti, M. D. Koerniawan, S. Triyadi, S. S. Utami, and A. Matzarakis, "A review of outdoor thermal comfort indices and neutral ranges for hot-humid regions," *Urban Climate*, vol. 31, p. 100 531, Mar. 2020, ISSN: 22120955. DOI: 10.1016/j.uclim.2019.100531.

[127] P. Lazaro and M. Momayez, "Development of a modified predicted heat strain model for hot work environments," *International Journal of Mining Science and Technology*, vol. 30, no. 4, pp. 477–481, Jul. 2020, ISSN: 20952686. DOI: 10.1016/j.ijmst.2020.05.009.

[128] F. Tartarini and S. Schiavon, "Pythermalcomfort: A Python package for thermal comfort research," *SoftwareX*, vol. 12, p. 100 578, Jul. 2020, ISSN: 23527110. DOI: 10.1016/j.softx.2020.100578.

[129] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, and B. Tinz, "Comparison of UTCI to selected thermal indices," *International Journal of Biometeorology*, vol. 56, no. 3, pp. 515–535, May 2012, ISSN: 0020-7128, 1432-1254. DOI: 10.1007/s00484-011-0453-2.

[130] N. Aste, F. M. Butera, R. S. Adhikari, and F. Leonforte, "Sustainable Building Design for Tropical Climates," in *Innovative Models for Sustainable Development in Emerging African Countries*, N. Aste,

S. Della Torre, C. Talamo, R. S. Adhikari, and C. Rossi, Eds., Cham: Springer International Publishing, 2020, pp. 37–46, ISBN: 978-3-030-33322-5. DOI: 10.1007/978-3-030-33323-2_4.

[131] B. Givoni, "Comfort, climate analysis and building design guidelines," en, *Energy and Buildings*, vol. 18, no. 1, pp. 11–23, Jan. 1992, ISSN: 03787788. DOI: 10.1016/0378-7788(92)90047-K.

[132] N. A. Al-Azri, Y. H. Zurigat, and N. Z. Al-Rawahi, "Development of bioclimatic chart for passive building design," *International Journal of Sustainable Energy*, vol. 32, no. 6, pp. 713–723, Dec. 2013, ISSN: 1478-6451, 1478-646X. DOI: 10.1080/14786451.2013.813026.

[133] E. Teitelbaum, C. Miller, and F. Meggers, "Highway to the Comfort Zone: History of the Psychrometric Chart," *Buildings*, vol. 13, no. 3, p. 797, 3 Mar. 2023, ISSN: 2075-5309. DOI: 10.3390/buildings13030797.

[134] S. Kumar, J. Mathur, S. Mathur, M. K. Singh, and V. Loftness, "An adaptive approach to define thermal comfort zones on psychrometric chart for naturally ventilated buildings in composite climate of India," *Building and Environment*, vol. 109, pp. 135–153, Nov. 2016, ISSN: 03601323. DOI: 10.1016/j.buildenv.2016.09.023.

[135] V. Olgyay, *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton University Press, 2015.

[136] G. Havenith and D. Fiala, "Thermal Indices and Thermophysiological Modeling for Heat Stress," *Comprehensive Physiology*, vol. 6, pp. 255–302, Jan. 12, 2016, ISSN: 9780470650714. DOI: 10.1002/cphy.c140051.

[137] B. MOUJALLED, "Modélisation dynamique du confort thermique dans les bâtiments naturellement ventilés," p. 330,

[138] S. Takada, S. Matsumoto, and T. Matsushita, "Prediction of whole-body thermal sensation in the non-steady state based on skin temperature," *Building and Environment*, vol. 68, pp. 123–133, Oct. 1, 2013, ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2013.06.004.

[139] K. Katić, R. Li, and W. Zeiler, "Thermophysiological models and their applications: A review," *Building and Environment*, vol. 106, pp. 286–300, Sep. 2016, ISSN: 03601323. DOI: 10.1016/j.buildenv.2016.06.031.

[140] M. Vellei and J. L. Dréau, "On the prediction of dynamic thermal comfort under uniform environments," p. 17, 2020.

[141] A. Gagge, Y. Nishi, and R. Gonzalez, "Standard effective temperature - A single temperature index of temperature sensation and thermal discomfort," *Proceeding of the CIB commission W45 symposium London 1972*, pp. 229–250, Jan. 1, 1972.

[142] N. Gagge A. Pharo, *Effet of Energy Conservation Guidelines on Comfort, Acceptability and Heath. Final Report* (A Sorlc:; Of Laboratory and Field Studies). JOHN n. PIERCE FOUNDATION.

[143] M. E. El Kadri, "Modèle thermo-neurophysiologique du corps humain pour l'étude du confort thermique en conditions climatiques hétérogènes et instationnaires," p. 222, 2021.

[144] S. Attia and S. Carlucci, "Impact of different thermal comfort models on zero energy residential buildings in hot climate," *Energy and Buildings*, vol. 102, pp. 117–128, Sep. 2015, ISSN: 03787788. DOI: 10.1016/j.enbuild.2015.05.017.

[145] P. Fanger, A. Melikov, H. Hanzawa, and J. Ring, "Air turbulence and sensation of draught," *Energy and Buildings*, vol. 12, no. 1, pp. 21–39, Apr. 1988, ISSN: 03787788. DOI: 10.1016/0378-7788(88)90053-9.

[146] S. Liu, S. Schiavon, A. Kabanshi, and W. W. Nazaroff, "Predicted percentage dissatisfied with ankle draft," *Indoor Air*, vol. 27, no. 4, pp. 852–862, 2017, ISSN: 1600-0668. DOI: 10.1111/ina.12364.

[147] M. Hostein, "Évaluation de l'impact du changement climatique sur le confort thermique des bâtiments en tenant compte du comportement des occupants et du contexte urbain - Application aux stratégies passives d'amélioration du confort thermique d'été."

[148] F. Tartarini, T. Cheung, S. Schiavon, and E. Arens, "The Prediction Accuracy of Different Predicted Mean Vote (PMV) Model Formulations," in *Proceedings of the 5th International Conference on Building Energy and Environment*, L. L. Wang, H. Ge, Z. J. Zhai, *et al.*, Eds., Singapore: Springer Nature, 2023, pp. 2363–2370, ISBN: 978-981-19982-2-5. DOI: 10.1007/978-981-19-9822-5_255.

[149] F. Tartarini and S. Schiavon, "Comparative analysis of PMV Models accuracy implemented in the ISO 7730:2005 and ASHRAE 55:2023," *Building and Environment*, vol. 275, p. 112 766, May 2025, ISSN: 03601323. DOI: 10.1016/j.buildenv.2025.112766.

[150] W. Ji, Y. Zhu, H. Du, *et al.*, "Interpretation of standard effective temperature (SET) and explorations on its modification and development," *Building and Environment*, vol. 210, p. 108 714, Feb. 2022, ISSN: 03601323. DOI: 10.1016/j.buildenv.2021.108714.

[151] S. Takada, T. Sakiyama, and T. Matsushita, "Validity of the two-node model for predicting steady-state skin temperature," *Building and Environment*, vol. 46, no. 3, pp. 597–604, Mar. 2011, ISSN: 03601323. DOI: 10.1016/j.buildenv.2010.09.008.

[152] T. Doherty and E. Arens, "Evaluation of the Physiological Bases of Thermal Comfort Models," *ASHRAE Transactions*, vol. 94, pp. 1371–1385, Jan. 1, 1988.

[153] R. Gonzalez, Y. Nishi, and A. Gagge, "Experimental evaluation of standard effective temperature a new biometeorological index of man's thermal discomfort," *International journal of biometeorology*, vol. 18, pp. 1–15, Apr. 1, 1974. DOI: 10.1007/BF01450660.

[154] X. Jia, S. Li, Y. Zhu, Z. Du, and B. Cao, "Development of the Universal Standard Effective Temperature for evaluating thermal comfort across different metabolic rates," *Building and Environment*, vol. 250, p. 111 149, Feb. 2024, ISSN: 03601323. DOI: 10.1016/j.buildenv.2023.111149.

[155] L. G. Berglund and D. J. Cunningham, "Parameters of Human Discomfort in Warm Environments," 1986.

[156] J. Gao, Y. Wang, and P. Wargocki, "Comparative analysis of modified PMV models and SET models to predict human thermal sensation in naturally ventilated buildings," *Building and Environment*, vol. 92, pp. 200–208, Oct. 2015, ISSN: 03601323. DOI: 10.1016/j.buildenv.2015.04.030.

[157] M. Schweiker and A. Wagner, "Influences on the predictive performance of thermal sensation indices," *Building Research & Information*, vol. 45, no. 7, pp. 745–758, Oct. 3, 2017, ISSN: 0961-3218, 1466-4321. DOI: 10.1080/09613218.2017.1256673.

[158] F. H. Mallick, "Thermal comfort and building design in the tropical climates," p. 7, 1996.

[159] S. Manu, Y. Shukla, R. Rawal, L. E. Thomas, and R. de Dear, "Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC)," *Building and Environment*, vol. 98, pp. 55–70, Mar. 1, 2016, ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2015.12.019.

[160] G. S. Brager and R. de Dear, "Climate, Comfort & Natural Ventilation: A new adaptive comfort standard for ASHRAE Standard 55,"

[161] F. Tartarini, S. Schiavon, T. Cheung, and T. Hoyt, "CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations," *SoftwareX*, vol. 12, p. 100 563, Jul. 2020, ISSN: 23527110. DOI: 10.1016/j.softx.2020.100563.

[162] S. Herb, S. Wolk, and C. Reinhart, "Beyond the bioclimatic chart: An automated simulation-based method for the assessment of natural ventilation and passive design potential," *Building and Environment*, vol. 269, p. 112 362, Feb. 2025, ISSN: 03601323. DOI: 10.1016/j.buildenv.2024.112362.

[163] E. Teitelbaum, "Design with Comfort: Expanding the psychrometric chart with radiation and convection dimensions," p. 10, 2020.

[164] E. Teitelbaum and F. Meggers, "Expanded psychrometric landscapes for radiant cooling and natural ventilation system design and optimization," *Energy Procedia*, vol. 122, pp. 1129–1134, Sep. 2017, ISSN: 18766102. DOI: 10.1016/j.egypro.2017.07.436.

[165] S. Schiavon, T. Hoyt, and A. Piccioli, "Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55," *Building Simulation*, vol. 7, no. 4, pp. 321–334, Aug. 1, 2014, ISSN: 1996-8744. DOI: 10.1007/s12273-013-0162-3.

[166] A. Omidvar and J. Kim, "Modification of sweat evaporative heat loss in the PMV/PPD model to improve thermal comfort prediction in warm climates," *Building and Environment*, vol. 176, p. 106 868, Jun. 2020, ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.106868.

[167] P. Ole Fanger and J. Toftum, "Extension of the PMV model to non-air-conditioned buildings in warm climates," *Energy and Buildings*, vol. 34, no. 6, pp. 533–536, Jul. 2002, ISSN: 03787788. DOI: 10.1016/S0378-7788(02)00003-8.

[168] S. Zhang and Z. Lin, "Predicted Mean Vote with skin temperature from standard effective temperature model," *Building and Environment*, vol. 183, p. 107 133, Oct. 2020, ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.107133.

[169] S. Zhang and Z. Lin, "Predicted Mean Vote with skin wettedness from standard effective temperature model," *Building and Environment*, vol. 187, p. 107 412, Jan. 2021, ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.107412.

[170] L. Ji, A. Laouadi, L. Wang, and M. Lacasse, "Development of a bioheat model for older people under hot and cold exposures," *Building Simulation*, vol. 15, Mar. 2022. DOI: 10.1007/s12273-022-0890-3.

[171] H. Du and C. Yang, "Re-visitation of the thermal environment evaluation index standard effective temperature (SET*) based on the two-node model," *Sustainable Cities and Society*, vol. 53, p. 101 899, Feb. 2020, ISSN: 22106707. DOI: 10.1016/j.scs.2019.101899.

[172] W. Ji, Y. Zhu, and B. Cao, "Development of the Predicted Thermal Sensation (PTS) model using the ASHRAE Global Thermal Comfort Database," *Energy and Buildings*, vol. 211, p. 109 780, Mar. 2020, ISSN: 03787788. DOI: 10.1016/j.enbuild.2020.109780.

[173] M. Vellei and J. Le Dréau, "A novel model for evaluating dynamic thermal comfort under demand response events," *Building and Environment*, vol. 160, p. 106 215, Aug. 2019, ISSN: 03601323. DOI: 10.1016/j.buildenv.2019.106215.

[174] M. Vellei, "Derivation and validation of a whole-body dynamic mean thermal sensation model," *Building and Environment*, vol. 256, p. 111 469, May 2024, ISSN: 03601323. DOI: 10.1016/j.buildenv.2024.111469.

[175] J. A. Orosa and A. C. Oliveira, "A new thermal comfort approach comparing adaptive and PMV models," *Renewable Energy*, vol. 36, no. 3, pp. 951–956, Mar. 2011, ISSN: 09601481. DOI: 10.1016/j.renene.2010.09.013.

[176] M. Vellei, M. Herrera, D. Fosas, and S. Natarajan, "The influence of relative humidity on adaptive thermal comfort," *Building and Environment*, vol. 124, pp. 171–185, Nov. 2017, ISSN: 03601323. DOI: 10.1016/j.buildenv.2017.08.005.

[177] S. Zhang and Z. Lin, "Extending Predicted Mean Vote using adaptive approach," *Building and Environment*, vol. 171, p. 106 665, Mar. 2020, ISSN: 03601323. DOI: 10.1016/j.buildenv.2020.106665.

[178] M. A. Humphreys and J. Fergus Nicol, "The validity of ISO-PMV for predicting comfort votes in every-day thermal environments," *Energy and Buildings*, vol. 34, no. 6, pp. 667–684, Jul. 2002, ISSN: 03787788. DOI: 10.1016/S0378-7788(02)00018-X.

[179] R. Yao, B. Li, and J. Liu, "A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV)," *Building and Environment*, vol. 44, no. 10, pp. 2089–2096, Oct. 2009, ISSN: 03601323. DOI: 10.1016/j.buildenv.2009.02.014.

[180] S. Zhang, Y. Cheng, Z. Fang, and Z. Lin, "Improved algorithm for adaptive coefficient of adaptive Predicted Mean Vote (aPMV)," *Building and Environment*, vol. 163, p. 106 318, Oct. 2019, ISSN: 0360-1323. DOI: 10.1016/j.buildenv.2019.106318.

[181] S. Zhang and Z. Lin, "Adaptive-rational thermal comfort model: Adaptive predicted mean vote with variable adaptive coefficient," *Indoor Air*, vol. 30, no. 5, pp. 1052–1062, Sep. 2020, ISSN: 0905-6947, 1600-0668. DOI: 10.1111/ina.12665.

[182] S. Zhang and Z. Lin, "Standard effective temperature based adaptive-rational thermal comfort model," *Applied Energy*, vol. 264, p. 114 723, Apr. 15, 2020, ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2020.114723.

[183] M. Schweiker and A. Wagner, "A framework for an adaptive thermal heat balance model (ATHB)," *Building and Environment*, vol. 94, pp. 252–262, Dec. 2015, ISSN: 03601323. DOI: 10.1016/j.buildenv.2015.08.018.

[184] M. Schweiker, "Combining adaptive and heat balance models for thermal sensation prediction: A new approach towards a theory and data-driven adaptive thermal heat balance model," *Indoor Air*, vol. 32, no. 3, Mar. 2022, ISSN: 0905-6947, 1600-0668. DOI: 10.1111/ina.13018.

[185] S. Zhang, Y. Cheng, M. Olaide Oladokun, Y. Wu, and Z. Lin, "Improving predicted mean vote with inversely determined metabolic rate," *Sustainable Cities and Society*, vol. 53, p. 101 870, Feb. 2020, ISSN: 22106707. DOI: 10.1016/j.scs.2019.101870.

[186] R. de Dear, G. Brager, and D. Cooper, "FINAL REPORT ASHRAE RP- 884," p. 312,

[187] F. N. R. Agency. "COOLDOWN Project Towards an alternative cooling : Optimization of the successive use of the cooling system from passive to active - Development of design and control strategies of the hybrid cooling," Agence nationale de la recherche. (), https://anr.fr/Project-ANR-22-CE22-0014 05/17/2025.

[188] M. El Kadri, F. De Oliveira, C. Inard, and F. Demouge, "New neurophysiological human thermal model based on thermoreceptor responses," *International Journal of Biometeorology*, vol. 64, no. 12, pp. 2007–2017, Dec. 2020, ISSN: 0020-7128, 1432-1254. DOI: 10.1007/s00484-020-01990-1.

[189] M. Payet, M. David, P. Lauret, M. Amayri, S. Ploix, and F. Garde, "Modelling of occupant behaviour in non-residential mixed-mode buildings: The distinctive features of tropical climates," en, *Energy and Buildings*, vol. 259, p. 111 895, Mar. 2022, ISSN: 03787788. DOI: 10.1016/j.enbuild.2022.111895.

[190] *Climat de La Réunion*, in *Wikipédia*, Mar. 16, 2025.

[191] *PERENE Réunion, Mise à jour 2009. Règles de conception thermique et énergétique des bâtiments tertiaires et résidentiels adaptées aux zones climatiques de l'Ile de La Réunion*, 2009.

[192] F. Manzano-Agugliaro, F. G. Montoya, A. Sabio-Ortega, and A. García-Cruz, "Review of bioclimatic architecture strategies for achieving thermal comfort," *Renewable and Sustainable Energy Reviews*, vol. 49, pp. 736–755, Sep. 2015, ISSN: 13640321. DOI: 10.1016/j.rser.2015.04.095.

[193] "General Data Protection Regulation (GDPR) – Legal Text," General Data Protection Regulation (GDPR). (), https://gdpr-info.eu/ 05/17/2025.

[194] *ISO 7726:2021 Ergonomics of the thermal environment - Instruments for measuring and monitoring physical quantities*, 2023.

[195] M. Payet, "Simulation du comportement des usagers dans les bâtiments tertiaires à faible consommation énergétique, en zone tropicale," Ph.D. dissertation, Université de la Réunion, Oct. 2022.

[196] ARTELIA, D. ENERGY, and IPSOS, "REX des consommations d'électricité des bâtiments tertiaires à La Réunion et en Guadeloupe," Tech. Rep., 2020.

[197] F. Babich, M. Cook, D. Loveday, R. Rawal, and Y. Shukla, "A New Methodological Approach for Estimating Energy Savings due to Air Movement in Mixed-Mode Buildings," in *BSA Conference 2017*, ser. BSA Conference, vol. 3, IBPSA-Italy, 2017, pp. 53–60, ISBN: 978-88-6046-136-0.

[198] K. W. H. Mui and W. T. D. Chan, "Adaptive comfort temperature model of air-conditioned building in Hong Kong," *Building and Environment*, vol. 38, no. 6, pp. 837–852, Jun. 2003, ISSN: 03601323. DOI: 10.1016/S0360-1323(03)00020-9.

[199] Y. Zhang, J. Mai, M. Zhang, F. Wang, and Y. Zhai, "Adaptation-based indoor environment control in a hot-humid area," *Building and Environment*, vol. 117, pp. 238–247, May 2017, ISSN: 03601323. DOI: 10.1016/j.buildenv.2017.03.022.

[200] D. Sánchez-García, D. Bienvenido-Huertas, and C. Rubio-Bellido, "Computational approach to extend the air-conditioning usage to adaptive comfort: Adaptive-Comfort-Control-Implementation Script," *Automation in Construction*, vol. 131, p. 103 900, Nov. 2021, ISSN: 09265805. DOI: 10.1016/j.autcon.2021.103900.

[201] T. Hoyt, E. Arens, and H. Zhang, "Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings," *Building and Environment*, vol. 88, pp. 89–96, Jun. 2015, ISSN: 03601323. DOI: 10.1016/j.buildenv.2014.09.010.

[202] R. T. Hellwig, D. Teli, M. Schweiker, *et al.*, "A framework for adopting adaptive thermal comfort principles in design and operation of buildings," *Energy and Buildings*, vol. 205, p. 109 476, Dec. 2019, ISSN: 03787788. DOI: 10.1016/j.enbuild.2019.109476.

[203] R. T. Hellwig, M. Schweiker, R. Mora, *et al.*, "Guidelines for low energy building design based on the adaptive thermal comfort concept - Technical report: IEA EBC Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings.," Aalborg University, Tech. Rep., 2022. DOI: 10.54337/aau510903564.

[204] F. Nicol, Ed., *Standards for Thermal Comfort: Indoor Air Temperature Standards for the 21st Century*, 1. ed. London: Chapman & Hall, 1995, ISBN: 978-0-419-20420-6.

[205] J. Zhou, X. Zhang, J. Xie, and J. Liu, "Effects of elevated air speed on thermal comfort in hot-humid climate and the extended summer comfort zone," *Energy and Buildings*, vol. 287, p. 112 953, May 2023, ISSN: 03787788. DOI: 10.1016/j.enbuild.2023.112953.

[206] M. Vellei, "Thermal Comfort, Control and Energy Use," Ph.D. dissertation, Univeristy of Bath, 2017.

[207] L. Huang, Q. Ouyang, Y. Zhu, and L. Jiang, "A study about the demand for air movement in warm environment," *Building and Environment*, vol. 61, pp. 27–33, Mar. 2013, ISSN: 03601323. DOI: 10.1016/j.buildenv.2012.12.002.

[208] L. Ji, A. Laouadi, C. Shu, L. Wang, and M. A. Lacasse, "Evaluation and improvement of the thermoregulatory system for the two-node bioheat model," *Energy and Buildings*, vol. 249, p. 111 235, Oct. 15, 2021, ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2021.111235.

[209] S. Carlucci, S. Erba, L. Pagliano, and R. de Dear, "ASHRAE Likelihood of Dissatisfaction: A new right-here and right-now thermal comfort index for assessing the Likelihood of dissatisfaction according to the ASHRAE adaptive comfort model," *Energy and Buildings*, vol. 250, p. 111 286, Nov. 2021, ISSN: 03787788. DOI: 10.1016/j.enbuild.2021.111286.

[210] M. Schweiker, S. Mueller, M. Kleber, *et al.*, *Comf: Models and Equations for Human Comfort Research*, Jan. 2024.

[211] W. Tian, "A review of sensitivity analysis methods in building energy analysis," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 411–419, Apr. 2013, ISSN: 13640321. DOI: 10.1016/j.rser.2012.12.014.

[212] S. de Wit and G. Augenbroe, "Analysis of uncertainty in building design evaluations and its implications," *Energy and Buildings*, vol. 34, no. 9, pp. 951–958, Oct. 2002, ISSN: 03787788. DOI: 10.1016/S0378-7788(02)00070-1.

[213] S. Bontemps, L. Mora, and b. geraud, "Reliability of dynamic simulation models for building energy in the context of low-energy buildings," in *13th Conference of International Building Performance Simulation Association*, Chambéry, France, 2013.

[214] H. Breesch and A. Janssens, "Uncertainty and sensitivity analysis of the performances of natural night ventilation," p. 6,

[215] H. Breesch, *Natural Night Ventilation in Office Buildings*. 2006.

[216] R. Moutela, J. Dias Carrilho, and M. Gameiro da Silva, "SENSITIVITY OF THE PMV INDEX TO THE THERMAL COMFORT PARAMETERS," in *Sustainable Cities: Designing for People and the Planet*, Coimbra, May 2015. DOI: 10.13140/RG.2.1.3936.1447.

[217] M. H. Hasan, F. M. Alsaleem, and M. Rafaie, "Sensitivity Analysis for the PMV Thermal Comfort Model and the Use of Wearable Devices to Enhance Its Accuracy," 2016.

[218] B. Iooss and P. Lemaître, *A review on global sensitivity analysis methods*, Apr. 2014. DOI: 10.48550/arXiv.1404.2405. arXiv: 1404.2405 [math, stat].

[219] A. Machard, C. Inard, J.-M. Alessandrini, C. Pelé, and J. Ribéron, "Sensitivity analysis of the input parameters impacting summer thermal discomfort in buildings under future climate in Paris," in *IBPSA France 2020*, Nov. 2020.

[220] J. Goffart and M. Woloszyn, "RBD-FAST: une méthode d'analyse de sensibilité rapide et rigoureuse pour la garantie de performance énergétique," 2018.

[221] A. Machard, "Towards mitigation and adaptation to climate change : Contribution to Building Design," Ph.D. dissertation, Université de La Rochelle, Jul. 2021.

[222] T. A. Mara and W. E. Becker, "Polynomial chaos expansion for sensitivity analysis of model output with dependent inputs," *Reliability Engineering and System Safety*, vol. 214, p. 107 795, Oct. 2021. DOI: 10.1016/j.ress.2021.107795.

[223] J. Goffart and M. Woloszyn, "EASI RBD-FAST: An efficient method of global sensitivity analysis for present and future challenges in building performance simulation," *Journal of Building Engineering*, vol. 43, p. 103 129, Nov. 2021, ISSN: 2352-7102. DOI: 10.1016/j.jobe.2021.103129.

[224] J. Herman and W. Usher, "SALib: An open-source Python library for Sensitivity Analysis," *Journal of Open Source Software*, vol. 2, no. 9, p. 97, Jan. 2017, ISSN: 2475-9066. DOI: 10.21105/joss.00097.

[225] B. Iooss and C. Prieur, *Shapley effects for sensitivity analysis with correlated inputs: Comparisons with Sobol' indices, numerical estimation and applications*, Nov. 2019. arXiv: 1707.01334 [math, stat].

[226] A. B. Owen, "Sobol' Indices and Shapley Value," *SIAM/ASA Journal on Uncertainty Quantification*, vol. 2, no. 1, pp. 245–251, Jan. 2014. DOI: 10.1137/130936233.

[227] E. Song, B. L. Nelson, and J. Staum, "Shapley Effects for Global Sensitivity Analysis: Theory and Computation," *SIAM/ASA Journal on Uncertainty Quantification*, vol. 4, no. 1, pp. 1060–1083, Jan. 2016. DOI: 10.1137/15M1048070.

[228] N. Benoumechiara and K. Elie-Dit-Cosaque, "Shapley effects for sensitivity analysis with dependent inputs: Bootstrap and kriging-based algorithms," *ESAIM: Proceedings and Surveys*, vol. 65, B. Bouchard, J.-F. Chassagneux, F. Delarue, E. Gobet, and J. Lelong, Eds., pp. 266–293, 2019, ISSN: 2267-3059. DOI: 10.1051/proc/201965266.

[229] B. Broto, F. Bachoc, and M. Depecker, "Variance Reduction for Estimation of Shapley Effects and Adaptation to Unknown Input Distribution," *SIAM/ASA Journal on Uncertainty Quantification*, vol. 8, no. 2, pp. 693–716, Jan. 2020, ISSN: 2166-2525. DOI: 10.1137/18M1234631.

[230] M. B. Heredia, C. Prieur, and N. Eckert, "Global sensitivity analysis with aggregated Shapley effects, application to avalanche hazard assessment," *Reliability Engineering & System Safety*, vol. 222, p. 108 420, Jun. 2022, ISSN: 09518320. DOI: 10.1016/j.ress.2022.108420.

[231] B. Iooss and B. Broto, *R Sensitivity Package - Global Sensitivity Analysis of Model Outputs and Importance Measures*, 2024.

[232] E. Walther, M. Bogdan, F. Peyre, and C. Inard, "Spatial distribution of thermal comfort: A case study in Paris' station," in *Building Simulation 2021*, ser. Building Simulation, vol. 17, IBPSA, 2021, pp. 1254–1261, ISBN: 978-1-77505-202-9. DOI: 10.26868/25222708.2021.30230.

[233] P. A. Mirzaei, "Recent challenges in modeling of urban heat island," *Sustainable Cities and Society*, vol. 19, pp. 200–206, Dec. 2015, ISSN: 22106707. DOI: 10.1016/j.scs.2015.04.001.

[234] M. Magni, F. Ochs, S. de Vries, A. Maccarini, and F. Sigg, "Detailed cross comparison of building energy simulation tools results using a reference office building as a case study," *Energy and Buildings*, vol. 250, p. 111 260, Nov. 2021, ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2021.111260.

[235] J. Sousa, "Energy Simulation Software for Buildings: Review and Comparison," *International Workshop on Information Technology for Energy Applicatons - IT4Energy - Lisabon*, 2012.

[236] T. Nghiem, *MLE+: A Matlab-EnergyPlus Co-simulation Interface*. Aug. 2015. DOI: 10.13140/RG.2.1.1127.0880.

[237] M. Wetter, "Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed," *Journal of Building Performance Simulation*, vol. 4, pp. 185–203, Sep. 2011. DOI: 10.1080/19401493.2010.518631.

[238] T. Nouidui, M. Wetter, and W. Zuo, "Functional mock-up unit for co-simulation import in EnergyPlus," *Journal of Building Performance Simulation*, vol. 7, May 2014. DOI: 10.1080/19401493.2013.808265.

[239] P. Haves and P. Xu, "THE BUILDING CONTROLS VIRTUAL TEST BED – A SIMULATION ENVIRONMENT FOR DEVELOPING AND TESTING CONTROL ALGORITHMS, STRATEGIES AND SYSTEMS," *Building Simulation*, 2007.

[240] E. Bonnema, A. Allen, E. Lee, M. S. Mitchell, and R. Meyer, "Flexible Integration of Diverse HVAC Technologies in EnergyPlus via Python-Enabled Workflows," *Renewable Energy*, 2025.

[241] B. Lab, M. Wetter, and D. M. Lorenzetti, *EnergyPlusToFMU*.

[242] F. Ascione, N. Bianco, C. De Stasio, G. M. Mauro, and G. P. Vanoli, "Simulation-based model predictive control by the multi-objective optimization of building energy performance and thermal comfort," *Energy and Buildings*, vol. 111, pp. 131–144, Jan. 2016, ISSN: 03787788. DOI: 10.1016/j.enbuild.2015.11.033.

[243] *Elements - big ladder software : Https://bigladdersoftware.com/projects/elements/*.

[244] Rocky Moutain Institute, *Deep retrofit tools and resources : Rmi.org/our-work/buildings/*.

[245] A. Foucquier, S. Robert, F. Suard, L. Stéphan, and A. Jay, "State of the art in building modelling and energy performances prediction: A review," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 272–288, Jul. 2013, ISSN: 13640321. DOI: 10.1016/j.rser.2013.03.004.

[246] W. S. Dols, S. J. Emmerich, and B. J. Polidoro, "Coupling the multizone airflow and contaminant transport software CONTAM with EnergyPlus using co-simulation," *Building Simulation*, vol. 9, no. 4, pp. 469–479, Aug. 2016, ISSN: 1996-3599, 1996-8744. DOI: 10.1007/s12273-016-0279-2.

[247] NIST, *CONTAM : nist.gov/el/beed/nist-multizone-modeling/software/contam*, Mar. 2012.

[248] I. Sarna and J. Ferdyn-Grygierek, "Natural ventilation for thermal comfort: A simulation-based comparison of manual and automated window control strategies in temperate climate housing," *Building and Environment*, vol. 285, p. 113 551, Nov. 2025, ISSN: 03601323. DOI: 10.1016/j.buildenv.2025.113551.

[249] I. H. Bell, J. Wronski, S. Quoilin, and V. Lemort, "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp," *Industrial & Engineering Chemistry Research*, vol. 53, no. 6, pp. 2498–2508, Feb. 2014, ISSN: 0888-5885, 1520-5045. DOI: 10.1021/ie4033999.

[250] P. Raftery, *CBE Fan Tool*, https://centerforthebuiltenvironment.github.io/fan-tool/, 2019.

[251] *EnergyPlus : EnergyPlus.net*.

[252] J. New, "Suitability of ASHRAE Guideline 14 Metrics for Calibration," *ASHRAE Transactions*, Jan. 2016.

[253] P. De Wilde, "The gap between predicted and measured energy performance of buildings: A framework for investigation," *Automation in Construction*, vol. 41, pp. 40–49, May 2014, ISSN: 09265805. DOI: 10.1016/j.autcon.2014.02.009.

[254] P. Virtanen, R. Gommers, T. E. Oliphant, *et al.*, "SciPy 1.0: Fundamental algorithms for scientific computing in Python," *Nature Methods*, vol. 17, no. 3, pp. 261–272, Mar. 2020, ISSN: 1548-7105. DOI: 10.1038/s41592-019-0686-2.

A

Appendix A : Chapter 3 - GDPR-compliant agreement for surveyed occupants

Projet CoolDown

Convention pour la participation au questionnaire préalable et aux tests relatifs à l'évaluation du confort thermique ressenti

Entre :

Le Centre Scientifique et Technique du Bâtiment (CSTB), établissement public à caractère industriel et commercial, dont le siège social est situé au 84, avenue Jean Jaurès à 77420 - Champs-sur-Marne, immatriculé au Registre du Commerce et des Sociétés de Meaux sous le numéro 775 688 229, représenté par _____

Ci-après dénommé le « CSTB »

ET

M/Mme_____,

demeurant à _____

_____

Ci-après dénommé le « Participant ».

Le CSTB et le Participant sont collectivement dénommés les « Parties ».

Préambule

Le projet CoolDown, porté conjointement par le Centre Scientifique et Technique du Bâtiment (CSTB), le CEA, LEU Réunion, PIMENT, le LOCIE et Bluetek et financé par l'Agence Nationale de la Recherche, ambitionne de freiner la croissance de la consommation de climatisation en améliorant le confort d'été et en maîtrisant la facture énergétique.

Dans le cadre du projet CoolDown, le CSTB est chargé de la réalisation d'enquêtes de terrain dans le cadre de la campagne expérimentale, au service de la mesure du confort des usagers de bureaux. Ces enquêtes auront pour objectif au travers des mesures qui seront déployées, de permettre d'une part, de préciser la situation actuelle en termes de consommations d'énergie, et d'autre part les conditions de confort des usagers (ci-après « l'Etude »). Le CSTB souhaite se rapprocher d'usagers de bâtiments de bureaux :

- afin de leur poser les questions figurant dans le questionnaire inséré en annexe 1 de la présente convention. Ces questions sont relatives à leurs habitudes de consommation énergétiques, ainsi qu'à leur comportement dans des ambiances chaudes ou froides (ci-après dénommé le « Questionnaire »),

- et de leur proposer de participer à des tests dans le cadre de l'Etude.

La présente convention définit les conditions dans lesquelles le Participant accepte de répondre au Questionnaire, puis de participer à l'Etude.

Article 1 : Engagements du Participant

1.1 Participation au Questionnaire

Le Participant accepte de répondre aux questions figurant dans le Questionnaire figurant en annexe 1.

1.2 Participation à l'Etude (tests)

But de l'Etude :

Une fois le Questionnaire complété, le Participant accepte de participer durant une semaine à des tests durant lesquels des mesures physiologiques seront réalisées sur ses avant-bras, son torse et son tibia droit

L'Etude vise également à évaluer le confort thermique ressenti au cours des tests.

L'Etude permettra aussi de mieux comprendre les mécanismes qui entrent en jeu lors de la perception du confort thermique, en tentant de réaliser des liens entre les variations thermiques de l'environnement, les réponses physiologiques et le ressenti déclaré. **Déroulement des tests** :

Durant les tests, le Participant devra :

- Respecter les consignes qui lui seront données avant et pendant les tests.
- Répondre à des questionnaires sur sa perception du confort thermique.
- Accepter des mesures indolores, sans danger et superficielles pour évaluer les propriétés biophysiques de sa peau et son état physiologique :
  - Fréquence cardiaque : signal cardiaque recueilli par un bracelet cardiofréquencemètre.
  - Température de peau : mesure par l'application de 3 thermo boutons, fixés sur la peau grâce à des pansements biomédicaux.
  - Température centrale : mesure par l'application d'un thermo bouton fixé sous l'aisselle droite grâce à des pansements biomédicaux.
  - Rayonnement, température et humidité locales : mesure par le port d'un thermo-hygro bouton, fixé sur un vêtement.

La durée totale des tests pour chaque participant est d'une semaine de travail, répétée toutes les 6 à 8 semaines pour atteindre un nombre de 6 campagnes.

Les résultats des mesures des tests ne sont pas communiqués au Participant. Seuls les membres du consortium de cette étude y auront accès.

Les résultats des tests ne pourront être communiqués au public par le CSTB qu'à la condition d'avoir été préalablement anonymisés.

Conditions à remplir pour pouvoir participer à l'Etude et consignes à respecter

Le Participant certifie qu'il remplit les conditions ci-dessous, nécessaires à sa participation à l'Etude :

- Ne suivre aucun traitement médical autre que la contraception orale et ne pas être porteur d'un pacemaker.
- Pour les femmes, ne pas être enceinte ni allaiter.
- Ne pas avoir d'allergies cutanées ou alimentaires.

Le Participant s'engage à signaler au CSTB toute modification intervenant durant l'Etude. **Article 2 : Données personnelles**

Le CSTB recueille les données personnelles suivantes lors de la participation du Participant au Questionnaire :

- nom du Participant
- prénom du Participant
- email du Participant
- téléphone du Participant
- âge du Participant
- sexe du Participant
- les données de santé suivantes : taille, poids, grossesse et allaitement, consommation de tabac, consommation d'alcool, activité physique, traitement médical.

Ci-après dénommées les « Données personnelles du Questionnaire ».

Par la suite, dans le cadre des tests réalisés durant l'Etude sur le Participant, le CSTB recueille les données personnelles suivantes :

- Le nom,
- Prénom,
- Adresse du Participant,
- Fréquence cardiaque du Participant enregistrée durant sa participation à l'Etude,
- Température de la peau et température centrale du Participant enregistrée durant l'Etude.

Ci-après les « Données personnelles recueillies durant les tests ».

Les Données personnelles du Questionnaire et les Données personnelles recueillies durant les tests sont ci-après collectivement dénommées les « Données personnelles ».

Le CSTB est responsable de ces Données personnelles en sa qualité de responsable de traitement.

Ces Données personnelles sont destinées à la Direction Eau du CSTB.

Les Données personnelles ne sont pas transférées hors de l'Union Européenne.

Le CSTB s'engage à préserver l'intégrité et la confidentialité des Données personnelles.

Dans les limites posées par la loi, le Participant dispose d'un droit d'accès, de rectification, d'effacement de ses Données Personnelles. Il peut également retirer son consentement, s'opposer au traitement réalisé, en demander la limitation, formuler une demande de portabilité de ses Données Personnelles ainsi que déterminer leur sort post-mortem.

Il peut exercer l'ensemble de ces droits en s'adressant par email à : dpo@cstb.fr, ou lui adresser ses questions relatives à la gestion de ses données. En cas d'absence de réponse en dehors des délais légaux, il dispose de la possibilité de s'adresser à la Commission Nationale de l'Informatique et des Libertés (CNIL), autorité de contrôle en charge du respect des obligations en matière de données à caractère personnel en France.

Article 3 : Indemnisation

Le Participant s'engage à ne réclamer aucune indemnité au CSTB pour sa participation à l'Etude.

Signé à SAINT PIERRE, le 13/02/2023

En deux exemplaires,

Pour le CSTB

Le Participant

Annexe 1 : Questionnaire PULSE

SCREENING PULSE	
Les questions de la première partie de ce questionnaire (âge, sexe, taille et poids) permettront de définir votre profil de métabolisme, c'est-à dire d'estimer votre consommation d'énergie, notamment lorsque vous êtes au repos. Les questions portant sur votre région d'habitat usuelle permettent de savoir si vous avez l'habitude de vivre avec ce climat ou si c'est relativement nouveau pour vous.	
Age occupant	Age de la personne : ⌊_⌊_⌋ *(ans)*
Sexe occupant	Sexe de la personne : ☐ Femme ☐ Homme ☐ Autre : ⌊_____⌋ ☐ Je ne souhaite pas répondre
Taille	Taille de la personne : ⌊___⌊___⌊___⌋ *(en cm)*
Poids	Poids de la personne : ⌊___⌊___⌋ *(en kg)*
Habitat région	Quelle région habitez-vous ?
Temps région	Depuis combien de temps habitez-vous cette région ? *(Une seule réponse possible)* ☐ Moins de 6 mois ☐ Entre 6 mois et 1 an ☐ Entre 1 an et 3 ans ☐ Plus de 3 ans

<table>
<tr><td colspan="2">Les questions suivantes concernent les aspects « santé » qui permettront de savoir si vous pouvez participer à l'étude PULSE en toute sécurité, si vos sensations et perceptions du confort thermique peuvent être affectées par certains paramètres (prise de médicaments par exemple) et de connaître vos habitudes de vie afin d'interpréter au mieux les données physiologiques récoltées.</td></tr>
<tr><td>Contre-indications</td><td>Avez-vous une de ces contre-indications ?

- J'allaite, je suis enceinte ou cherche à l'être
- Je suis un traitement médical (autre que contraceptif)
- Je porte un pacemaker
- J'ai des allergies alimentaires ou cutanées
☐ Oui, je ne pourrais pas participer à cette étude
☐ Non</td></tr>
<tr><td>Activité physique</td><td>Pratiquez-vous une activité physique ?

(Une seule réponse possible)

☐ Oui, régulièrement
☐ Oui, occasionnellement
☐ Oui, rarement
☐ Non, jamais</td></tr>
<tr><td>Tabac</td><td>Fumez-vous ?

(Une seule réponse possible)

☐ Oui, tous les jours
☐ Oui, occasionnellement
☐ Non</td></tr>
<tr><td>Boissons alcoolisées</td><td>Consommez-vous des boissons alcoolisées ?

(Une seule réponse possible)

☐ Oui, moins d'1 unité d'alcool* par jour
☐ Oui entre 1 et 2 unités d'alcool par jour
☐ Oui, entre 3 et 4 unités d'alcool par jour
☐ Oui, plus de 4 unités d'alcool par jour
☐ Non

*Une bière, un verre de whisky, un verre de vin ou encore un pastis tels qu'on les sert dans les bars contiennent tous approximativement la même quantité d'alcool pur : environ 10 grammes. C'est ce qu'on appelle un verre standard ou encore une unité alcool (source : https://www.alcool-info-service.fr).

</td></tr>
</table>

Les questions suivantes portent sur votre comportement en ambiance chaude et en ambiance froide afin de déterminer si vous êtes sensible ou non aux changements de température.	
Comportement en ambiance chaude	D'après vous, êtes-vous sensible à la chaleur ? *(Une seule réponse possible)* ☐ Oui ☐ Non ☐ Ne sais pas vraiment Etes-vous sensible à des augmentations de la température d'air ? *(Une seule réponse possible)* ☐ Oui ☐ Non Dans une ambiance chaude, sentez-vous que vous avez moins chaud que les autres personnes autour de vous ? *(Une seule réponse possible)* ☐ Oui ☐ Non Dans une ambiance chaude, suez-vous moins que les autres personnes autour de vous ? *(Une seule réponse possible)* ☐ Oui ☐ Non Dans une ambiance chaude, avez-vous tendance à être plus vêtu que les personnes qui vous entourent ? *(Une seule réponse possible)* ☐ Oui ☐ Non Lorsqu'il fait chaud, avez-vous tendance à vous exposer au soleil sans être incommodé par la chaleur ? *(Une seule réponse possible)* ☐ Oui ☐ Non Pouvez-vous rester plus longtemps que les autres dans une ambiance très chaude ? *(Une seule réponse possible)* ☐ Oui ☐ Non Préférez-vous avoir trop chaud plutôt que trop froid ?

(Une seule réponse possible)

☐ Oui
☐ Non
☐Je ne sais pas

Quand vous avez chaud, avez-vous tendance à :

(Une seule réponse possible par ligne)

	Oui	Non	Je ne sais pas
Mettre en marche les brasseurs d'air, ventilateurs ou la climatisation ?	☐	☐	☐
Ouvrir les fenêtres ?	☐	☐	☐
Vous abriter du soleil ?	☐	☐	☐
Boire de l'eau fraîche ?	☐	☐	☐
Prendre une douche rafraîchissante ?	☐	☐	☐
└_____┘	☐	☐	☐
└_____┘	☐	☐	☐

<table>
<tr>
<td>Comportement en ambiance fraîche</td>
<td>
D'après vous, êtes-vous frileux ?
(Une seule réponse possible)
☐ Oui
☐ Non
☐ Ne sais pas vraiment

Etes-vous sensible à des réductions de la température d'air ?
(Une seule réponse possible)
☐ Oui
☐ Non

Dans une ambiance froide, sentez-vous que vous êtes plus frileux ou sensible au changement de température que les autres personnes autour de vous ?
(Une seule réponse possible)
☐ Oui
☐ Non

Parfois, avez-vous froid même quand la température extérieure est douce ?
(Une seule réponse possible)
☐ Oui
☐ Non

Est-ce que vous n'aimez pas être pieds nus même quand la température extérieure est douce, à cause du froid que vous ressentez ?
(Une seule réponse possible)
☐ Oui
☐ Non

La climatisation ou le rafraîchissement par brasseur d’air ou ventilateur peuvent vous perturber : de quelles façons ?
(Plusieurs réponses possibles)
☐ Sécheresse et irritation des yeux, de la bouche, de la gorge ou des voies nasales
☐ Maux de tête
☐ Maux de gorge
☐ Extinction de voix
☐ Maladie de Raynaud (trouble de la circulation sanguine au niveau des doigts et des orteils)
☐ Arthrite
</td>
</tr>
</table>

Avez-vous froid dans une pièce climatisée ou rafraîchie par des brasseurs d'air ou ventilateurs alors que la majorité des gens se sentent confortables ?

(Une seule réponse possible)

☐ Oui
☐ Non

En général, portez-vous des vêtements plus épais que les personnes autour de vous ?

(Une seule réponse possible)

☐ Oui
☐ Non

Lorsqu'il fait froid, mettez-vous des vêtements plus chauds pour dormir ?

(Une seule réponse possible)

☐ Oui
☐ Non

Lorsqu'il fait froid la nuit, vous réveillez-vous souvent en raison de la fraîcheur ou de la froideur de vos extrémités ?

(Une seule réponse possible)

☐ Oui
☐ Non

Lorsqu'il fait froid à l'extérieur, que vous rentrez chez vous, qu'il fait froid et que vous cherchez à vous réchauffer, avez-vous tendance à :

(Plusieurs réponses possibles)

☐ Rajouter une épaisseur de vêtements
☐ Augmenter la température du chauffage
☐ Rester près du radiateur ou d'une source de chaleur
☐ Prendre une douche chaude
☐ Bouger
☐ Rien faire de particulier
☐ └──────────┘
☐ └──────────┘

Lorsqu'il fait froid,

<table>
<tr><td></td><td>

(Une seule réponse possible par ligne)

	Oui	Non
Mettez-vous plusieurs épaisseurs de vêtements ?	☐	☐
Vous arrive-t-il de mettre des gants ?	☐	☐
Vous arrive-t-il de mettre un bonnet ?	☐	☐
Vous arrive-t-il de mettre de grosses chaussettes ou plusieurs chaussettes ?	☐	☐

Lorsqu'il fait froid, avez-vous tendance à avoir ... ?

(Une seule réponse possible par ligne)

	Non	Oui, SANS sensation de douleur	Oui, AVEC sensation de douleur	Je ne sais pas
Les mains froides	☐	☐	☐	☐
Les pieds froids	☐	☐	☐	☐
Le nez froid	☐	☐	☐	☐

</td></tr>
<tr><td>Participation étude PULSE</td><td>

Accepteriez-vous de participer à une étude scientifique pour évaluer l'appréciation du confort thermique dans les bureaux ?

☐ Oui
☐ Non

</td></tr>
<tr><td>Pose de capteurs</td><td>

Dans ce contexte, accepteriez-vous de porter des capteurs non invasifs (capteurs de température de peau, montre cardiofréquencemètre) ?

☐ Oui
☐ Non

</td></tr>
</table>

B

Appendix B : Chapter 3 - ISO9920 Clothing values for the case study

B.1 Women-specific top and bottom clothing ensembles (Part 1)

Table B.1: *ISO 9920 clothing Top + bottom possible combinations for Women used in the survey application - part 1*

CLO ID	Sleeves	ISO 9920	Possible Top	Clo Min	Clo Max	Bottom Length	Bottom Fabric	ISO 9920	Possible Bottom	Clo Min	Clo Max	Comb. Clo Min	Comb. Clo Max	Dress Eq.
F000	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Short	Light fabric	83, 303	Short shorts or A-line skirt (15 cm above the knee)	0.06	0.10	0.11	0.16	–
F001	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Short	Heavy fabric	99	Short shorts	0.08	–	0.13	0.14	–
F010	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Mid	Light fabric	97, 304	City shorts or knee-length A-line skirt	0.08	0.14	0.13	0.20	A
F011	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Mid	Heavy fabric	98	City shorts	0.17	–	0.22	0.23	B
F020	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Long	Light fabric	Table B1	Light trousers	0.20	–	0.25	0.26	–
F021	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Long	Heavy fabric	Table B2	Standard trousers	0.25	–	0.30	0.31	–
F100	Short sleeves	30, 77	T-shirt (100% cotton jersey); short-sleeve shirt (fine poplin)	0.08	0.19	Short	Light fabric	83, 303	Short shorts or A-line skirt (15 cm above the knee)	0.06	0.10	0.14	0.29	–
F101	Short sleeves	30, 78	T-shirt (100% cotton jersey); short-sleeve shirt (fine poplin)	0.08	0.19	Short	Heavy fabric	99	Short shorts	0.08	–	0.16	0.27	–
F110	Short sleeves	30, 79	T-shirt (100% cotton jersey); short-sleeve shirt (fine poplin)	0.08	0.19	Mid	Light fabric	97, 304	City shorts or knee-length A-line skirt	0.08	0.14	0.16	0.33	C
F111	Short sleeves	30, 80	T-shirt (100% cotton jersey); short-sleeve shirt (fine poplin)	0.08	0.19	Mid	Heavy fabric	98	City shorts	0.17	–	0.25	0.36	–
F120	Short sleeves	30, 81	T-shirt (100% cotton jersey); short-sleeve shirt (fine poplin)	0.08	0.19	Long	Light fabric	Table B1	Light trousers	0.20	–	0.28	0.39	–
F121	Short sleeves	30, 82	T-shirt (100% cotton jersey); short-sleeve shirt (fine poplin)	0.08	0.19	Long	Heavy fabric	Table B2	Standard trousers	0.25	–	0.33	0.44	–

B.2 Women-specific top and bottom clothing ensembles (Part 2)

Table B.2: *ISO 9920 clothing Top + bottom possible combinations for Women used in the survey application - part 2*

CLO ID	Sleeves	ISO 9920	Possible Top	Clo Min	Clo Max	Bottom Length	Bottom Fabric	ISO 9920	Possible Bottom	Clo Min	Clo Max	Comb. Clo Min	Comb. Clo Max	Dress Eq.
F200	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Short	Light fabric	83, 303	Short shorts or A-line skirt (15 cm above the knee)	0.06	0.10	0.17	0.21	–
F201	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Short	Heavy fabric	99	Short shorts	0.08	–	0.19	0.19	–
F210	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Mid	Light fabric	97, 304	City shorts or knee-length A-line skirt	0.08	0.14	0.19	0.25	D
F211	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Mid	Heavy fabric	98	City shorts	0.17	–	0.28	0.28	E
F220	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Long	Light fabric	Table B1	Light trousers	0.20	–	0.31	0.31	–
F221	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Long	Heavy fabric	Table B2	Standard trousers	0.25	–	0.36	0.36	–

B.3 Women-specific dress alternatives

Table B.3: *ISO 9920 : Women dress options*

Dress Equivalence	CLO ID	Length	Fabric type	ISO 9920	Description	Clo
A	F010	Mid-length	Light fabric	334	Scoop neckline, sleeveless, A-line cut (fine poplin)	0.23
B	F011	Mid-length	Heavy fabric	335	Scoop neckline, sleeveless, A-line cut (tweed / woven fabric)	0.27
C	F110	Mid-length	Light fabric	333	Short-sleeve shirt collar, A-line cut, belt (fine poplin)	0.29
D	F210	Mid-length	Light fabric	331	Short-sleeve shirt collar, A-line cut, belt (fine poplin)	0.32
E	F211	Mid-length	Heavy fabric	332	Short-sleeve shirt collar, A-line cut, belt (tweed / woven fabric)	0.47

B.4 Men-specific top and bottom clothing ensembles

Table B.4: *ISO 9920 clothing Top + bottom possible combinations for Men used in the survey application - part 1*

CLO ID	Sleeves	ISO 9920	Possible Top	Clo Min	Clo Max	Bottom Length	Bottom Fabric	ISO 9920	Possible Bottom	Clo Min	Clo Max	Dress Eq.
M000	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Short	Light fabric	83	Short shorts	0.06	0.11	0.12
M001	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Short	Heavy fabric	99	Short shorts	0.08	0.13	0.14
M010	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Mid	Light fabric	97	City shorts	0.08	0.13	0.14
M011	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Mid	Heavy fabric	98	City shorts	0.17	0.22	0.23
M020	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Long	Light fabric	Table B1	Light trousers	0.20	0.25	0.26
M021	Sleeveless	13 or 29	Sleeveless shirt	0.06	0.05	Long	Heavy fabric	Table B2	Standard trousers	0.25	0.30	0.31
M100	Short sleeves	30, 77	T-shirt (100% cotton jersey) Short-sleeve shirt	0.08	0.19	Short	Light fabric	83	Short shorts	0.06	0.14	0.25
M101	Short sleeves	30, 78	T-shirt (100% cotton jersey) Short-sleeve shirt	0.08	0.19	Short	Heavy fabric	99	Short shorts	0.08	0.16	0.27
M110	Short sleeves	30, 79	T-shirt (100% cotton jersey) Short-sleeve shirt	0.08	0.19	Mid	Light fabric	97	City shorts	0.08	0.16	0.27
M111	Short sleeves	30, 80	T-shirt (100% cotton jersey) Short-sleeve shirt	0.08	0.19	Mid	Heavy fabric	98	City shorts	0.17	0.25	0.36
M120	Short sleeves	30, 81	T-shirt (100% cotton jersey) Short-sleeve shirt	0.08	0.19	Long	Light fabric	Table B1	Light trousers	0.20	0.28	0.39
M121	Short sleeves	30, 82	T-shirt (100% cotton jersey) Short-sleeve shirt	0.08	0.19	Long	Heavy fabric	Table B2	Standard trousers	0.25	0.33	0.44
M200	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Short	Light fabric	83	Short shorts	0.06	0.17	0.17
M201	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Short	Heavy fabric	99	Short shorts	0.08	0.19	0.19
M210	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Mid	Light fabric	97	City shorts	0.08	0.19	0.19
M211	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Mid	Heavy fabric	98	City shorts	0.17	0.28	0.28
M220	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Long	Light fabric	Table B1	Light trousers	0.20	0.31	0.31
M221	Long sleeves	47	Long-sleeve shirt (modal, cotton)	0.11	–	Long	Heavy fabric	Table B2	Standard trousers	0.25	0.36	0.36

B.5 Men and Women complementary garments

Table B.5: *ISO 9920 Clothing Items – Underwear, Additional Top Layer, and Footwear*

Gender	Body Part	ISO 9920	Possible Clothing Items (ISO 9920)	Clo Min	Clo Max
Underwear					
M	Lower body	6, 8, 20, 23	Underpants	0.04	–
F	Lower body	1	Briefs	0.03	–
F	Upper body	2	Bra	0.01	–
Additional Top Layer (Top_2)					
M/F	None	–	No additional layer	0.00	–
M/F	Long sleeves	135, 136	V-neck long-sleeve top, wool cardigan with long sleeves, light knitwear	0.23	0.25
M/F	Sweater	142, 143	Crew-neck long-sleeve sweater	0.31	0.36
Footwear					
M/F	Bare feet	–	Barefoot	–	–
M/F	Sandals / barefoot (or socks only)	272	Flip-flops, vinyl sandals	0.02	–
M/F	Shoes without socks	262, 255	Soft-soled athletic shoes (canvas), suede shoes with rubber soles	0.02	–
M/F	Shoes with socks	262/255 + 253	Athletic shoes with ankle socks	0.04	–
M/F	Shoes with thick socks	262/255 + 264/265	Athletic mid-calf socks or men's dress socks (mid-calf)	0.05	–

C

Appendix C : Chapter 4 - Published Building And Environment article

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Sensitivity analysis of Gagge's Standard Effective Temperature for fan-first cooling control strategy in tropical mixed-mode buildings

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ABSTRACT

Mixed-mode (MM) cooling solutions integrate ceiling fans (CF) and traditional air conditioning (AC) simultaneously in a "*Fan-first*" scenario, enhancing comfort while reducing energy use. However, this dual approach complicates system sizing and consumption assessment due to the added layer of comfort control. To address this, we advocate using Gagge's Standard Effective Temperature (SET) for MM cooling control in the tropics. We also evaluate its sensitivity to air velocity, clothing, and temperature, emphasising its applicability for control algorithms in Building Energy Models (BEM). BEM cooling algorithm should leverage fans' air velocity and clothing flexibility as adaptive opportunities. This study first highlights the relevance of SET over alternative models found in the literature for tropical applications. Second, we use environmental datasets to assess air velocity and clothing contributions alongside temperature setpoints through two Sensitivity Analysis (SA) techniques. Traditional Sobol's indices, assuming input independence, confirm that temperature is not the sole parameter influencing SET. More advanced Shapley Effect techniques, accommodating representative input distributions, reveal that air velocity and clothing outweigh temperature within an airspeed range of [0–2 $m.s^{-1}$]. This work provides new insights for designing actionable and adaptive control strategies for comfort in tropical indoor conditions to simulate and size MM-coupled cooling systems effectively. It also underscores the benefits of advanced SA techniques in evaluating comfort models.

1. Introduction

With growing demographics and the densification of urbanised territories, by 2030, nearly 60 % of the population will live in tropical cities and half of the population in the tropics by 2050 [1]. Adopting air conditioning as the only means of maintaining comfort conditions in tropical belt countries is the leading cause of the energy demand increase [2]. Comfort level, which tends to westernise, pushes designers to find alternatives to the exclusive use of mechanical compression cooling solutions to achieve comfort objectives. At the border between naturally ventilated buildings (NV) and fully air-conditioned buildings (AC), mixed-mode buildings (MM) offer the flexibility to target both comfort and lower energy use in tropical climates. Such performance is achieved primarily through natural ventilation and ceiling fans, which are used most of the time and paired with AC systems when indoor conditions deteriorate (Fig. 1). Users are also encouraged to adapt their clothing accordingly. Malik et al. work [3] describes these so-called "*Fan-First scenarios*" regarding energy use performance. Ceiling fans permit first to delay the start of AC units and, secondly, to raise the setpoints. These shifts are possible because air velocity increases convection transfer on occupants' skin, enhancing evapotranspiration heat loss. It thus leads to comfortable conditions at higher temperatures or relative humidity than with still air. The cooling effect of ceiling fans permits a rise by at least 2–3 °C typical setpoint [3–5], increasing it over the 24–26 °C/70 % RH range of a traditional Predicted Mean Vote (PMV) comfort zone.

Abbreviations: ANOVA, Analysis of variance; ASHRAE, American Society of Heating, Refrigerating and Air-conditioning Engineers; CF, Ceiling Fan; FAST, Fourier Amplitude Sensitivity Test; GSA, Global Sensitivity Analysis; HVAC, Heating Ventilation Air Conditioning; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization; KNN, K-Nearest-Neighbours; LHS, Latin Hypercube Sampling; MEP, Mechanical, Electrical and Plumping; MM, Mixed-mode; NV, Natural Ventilation / Naturally Ventilated; NZEB, Net Zero Energy Building; OAT, One-factor-at-A-Time; PCD, Personal Comfort Device; PERENE, Reference framework for Bioclimatic design of buildings in La Reunion; PMV, Predicted Mean Vote; RBD, Random Balanced Design; RBD-FAST, Random Balance Design Fourier Amplitude Sensitivity Test; SA, Sensitivity Analysis; SET, Standard Effective Temperature; THM, Thermal Heat-balance Model.

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Nomenclature

CLO	Clothing, *clo*
MET	Metabolism, *met*
RH	Relative Humidity, *%*
S_i	First order Sobol indice *i, a.*u.
S_{ij}	Second order Sobol indice *ij, a.*u.
T_{db}	Dry bulb temperature, °C
T_g	Globe temperature, °C
T_r	Mean radiant temperature, °C
T_{rm}	Running mean outdoor temperature, °C
V	Air velocity, $m.s^{-1}$
X_i	Input variable *i, a.*u.
ϕ_i	Shapley value of variable *Xi, a.*u.

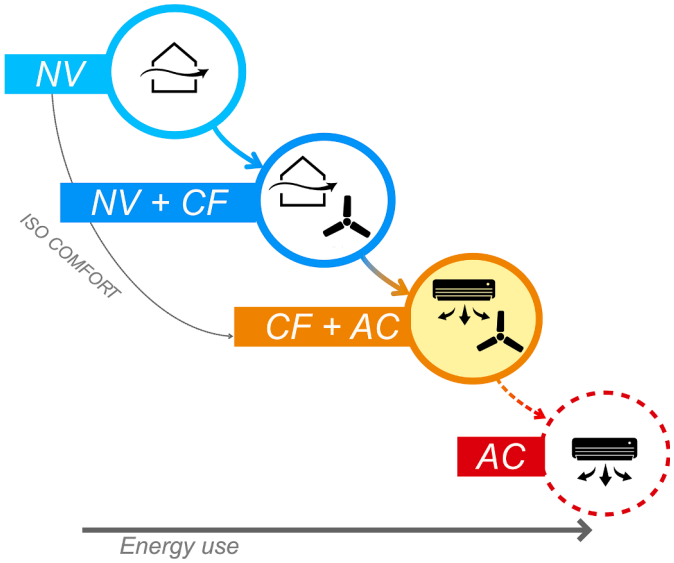

Fig. 1. Fan-First cooling strategy for Mixed-mode systems at isocomfort.

1.1. Designing MM Fan-First coupled system challenges

This type of operation has been subject to numerous field survey research over the last few years. Although they highlighted the advantages of this type of design over traditional air-conditioned buildings in the tropics, neither of them described how designers should control the coupled CF and AC equipment nor simulate them in a Building Energy Model (BEM) control algorithm. Gokarakonda et al. [6] investigated MM cooling solutions in residential bedrooms in India. Their research aimed to analyse the impact of AC and fan usage behaviour on energy use conservation. Kent et al. [5]. led a comfort and energy use field survey of over 35 occupants of a Net Zero Energy Building (NZEB) in Singapore for 11 weeks. They could measure the direct influence of desk and ceiling fan use by raising the thermostat setpoint by 2.5 °C up to 26.5 °C without changing the occupant's thermal satisfaction or air movement dissatisfaction. This study highlights an energy use reduction potential of 32 %. It also illustrates that the combined use of ceiling fans with AC could lead to under-sizing the chillers, pumps, and cooling towers due to higher nominal setpoints. Consequently, this can reduce the overall investment and operating costs. Hence, selecting the appropriate comfort model as an objective function is key to optimising MM-coupled system operation scenario.

The adaptive model [7], dedicated initially to NV buildings, appears as a good candidate for the MM building's comfort assessment, as shown by Parkinson et al. [8]. Unfortunately, it cannot account for the demand for ceiling fans use energy. In a BEM simulation, the controlling algorithm simulates a cooling system. It is necessary in such cases to define rules to more efficiently target comfort, i.e. with less energy consumption. This adaptive model has been implemented in the Energy Plus Building simulation program in the native Energy Plus Building Management System and via a Python Plugin by Sanchez et al. [9,10]. Although it allows the designer to calculate an adaptative AC setpoint temperature, it does not offer the possibility to simulate ceiling fan use or clothing flexibility. Thus, it is only possible to assess AC energy use. Personal Comfort Devices (PCD), such as ceiling and desk fans, are not accounted for in the energy balance, making it challenging to optimise for the best operation scenario.

Thermal Heat-balance (THM) models are more adapted to simulate MM cooling control possibilities in BEM. THM depends on the four environmental parameters (air temperature (*t*), radiant temperature (*tr*), air velocity (*v*), relative humidity (*rh*) and individual parameters (clothing (*clo*), metabolism (*met*)). Unfortunately, the well-established ISO Predicted Mean Vote (PMV) model falls outside the typical tropical indoor condition range for what it considers its validity in terms of maximum temperature (30 °C) and maximum airspeed ($1 ms^{-1}$) [11]. It is also prone to low accuracy when prediction falls outside the neutrality range. Gagge's two-node [12] model, which calculates the Standard Effective Temperature, disposes of a more refined thermoregulatory system suited for warm conditions [13]. According to Huang et al. [14], it is better to consider evapotranspiration heat loss in a warm environment and non-uniform air movement. Furthermore, it is the foundation of a few adaptative Thermal Heat-balance model alternatives, especially the SET-based adaptive model from Parkison et al.'s work [8], based on ASHRAE Global Comfort Database II [15].

The characteristics of Gagge's SET (Standard Effective Temperature) index mentioned earlier present a promising opportunity for a Fan-First control application. However, the variability of environmental conditions raises questions about the applicability of this index to the MM Fan-First strategy. The primary inquiry is how Gagge's SET index responds to the range of tropical indoor conditions. When using the SET, are air velocity and clothing good alternatives to AC temperature setpoint? How can we quantify the variation in input variables and their impact on the model's output in hot and humid conditions? It is crucial to understand how relative humidity, particularly at higher levels, affects evapotranspiration heat loss and consequently influences the selection of one control action over another. Conducting a Sensitivity analysis (SA) of the SET can help to address these important questions.

Sensitivity Analyses assess the relative contribution of input variables to a model output. It has been widely used in the building industry for several decades using BEM simulation programs (Trnsys, EnergyPlus, DOE2) or ISO13790:2008 simplified models, especially for studying the influence of building design components or climates on energy consumption, space conditioning loads and thermal comfort objectives [16]. De Wit et al. [17] studied the impact of material uncertainty on HVAC sizing and energy use to improve the decision-making process. Bomptemps et al. [18] used an association of SA techniques to study the reliability of dynamic simulation models and presented a framework for parameter selection for high CPU-demanding models. Breesch et al. [19, 20] used SA techniques to study different kinds of natural ventilation design with the objective of thermal comfort in buildings. Tian et al. [16] presented a tenth of other application examples of sensitivity analysis in building energy simulation in their review.

However, research on Thermal Heat Balance comfort models' sensitivity for coupled systems control has been limited, even more so in hot and humid conditions. Moutela et al. [21] demonstrated that metabolism and radiant temperature parameters significantly influence Fanger's model over the entire PMV validity range. At the same time, relative humidity and air speed only played a secondary role in the PMV deviation. Hasan et al. [22] concentrated solely on the sensitivity of PMV to variation in metabolism within the same domain as Moutela

et al. Finally, Ji et al. [23] explored the Gagge's model and its sensitivity to various thermoregulation sub-models. They compared them to measured physiological temperature to propose an updated two-node model. Still, they did not investigate the Gagge's SET sensitivity to its inputs.

1.2. Aim of this work, general methodology and expected outcomes

This research aims to advocate the selection of the Gagge's Standard Effective Temperature and evaluate its sensitivity to variations in air velocity, clothing insulation and AC temperature setpoint. The focus is on ensuring its suitability for a Fan-First Mixed-mode cooling system control, particularly in hot and humid indoor conditions.

The proposed steps of this work are outlined as follows:

1. Justify the selection of Gagge's SET as the most appropriate candidate for implementing a MM *Fan-First* control algorithm in the Building Energy Model (BEM) for a tropical office application. This comfort-based algorithm will manage three parameters simultaneously: dry bulb temperature (T_{db}), air velocity *(v)*, and clothing *(clo)*.
2. Describe the field measurements taken from an MM building, which will serve as the basis for the environmental (T_{db}, T_r, *rh*, *v*) and individual variables (*met, clo*) used in the sensitivity analysis variation datasets.
3. Conduct the sensitivity analysis of the SET using various techniques. This includes comparing the latest Shapley Effect technique with the traditional Sobol indices and quantifying the contribution of simulating air velocity control (ceiling fan or openings) and clothing (occupant adaptive opportunity) against controlling AC setpoint temperature solely.

This study represents a preliminary step in defining the methodology designers, and researchers can use when selecting a comfort model for an MM Fan-First control application. Additionally, it provides insights into how Gagge's SET index model behaves quantitatively during the hottest periods in a typical tropical climate. It also emphasises the advantages of utilising advanced SA techniques for assessing comfort models based on an actual case study.

2. Selection of the Gagge's Standard Effective Temperature for MM control application

2.1. Background in comfort modelling and selection criteria

Various models exist to predict users' comfort in buildings. However, it can be challenging to select one of them outside of a normative framework for the MM cooling solution [7]. Standards and literature contrast naturally ventilated (NV) buildings (field measurement-based empirical approach modelling) with air-conditioned (AC) buildings (analytical approach modelling, known as Thermal Heat-balance Model or THM). In NV buildings, occupants are considered fully adaptable, i.e., they maintain their comfort by operating openings, solar shading devices, and ceiling fans. In AC buildings, they are supposed to be passive users. This dichotomy is reflected in standards with the comfort models dedicated to NV and AC buildings, respectively, the Adaptive Model (AM) and THM Fanger's PMV (Predicted Mean Vote) [24,25]. From 2010, the ASHRAE 55 standard includes another THM model, the Gagge two-node model [26], to calculate a cooling effect (CE) [24] further entered as input to the Fanger model (named PMV_{CE}). It aims to enhance air velocity's contribution over 1.0 $m.s^{-1}$, the normative limit of the PMV.

Building Energy Models (BEM) are widely used in the building industry to size AC systems appropriately. For coupled AC—Ceiling Fan systems, MEP engineers must simulate AC thermostat controls and a range of air velocities in BEM to estimate energy use and comfort performance accurately. Additionally, incorporating clothing flexibility into BEM can enhance comfort and energy efficiency. For instance, reducing clothing insulation by 0.1 clo (20 % of a summer average of 0.5 clo per ASHRAE 55:2023) equates to a 0.6 °C decrease in operative temperature [27]. However, this raises challenges for comfort models to integrate all three controllable parameters—temperature, air velocity, and clothing—within the MM cooling strategy for use in BEM.

The case of mixed-mode cooling adds an extra degree of complexity to the model selection process. Whereas air conditioning is available in such buildings, they offer total flexibility to occupants to be active in their comfort, mainly through solar shading, ventilation openings, ceiling fan use and flexible dress code. Hence, adaptive opportunities should be considered.

Furthermore, our problem must be solved in a critical hot and humid condition. The selected model should be adapted and the most reliable in that field.

To select the most appropriate comfort model for simulating MM Fan-First coupled system operation in BEM, we defined the criteria of selection as follows:

(1) The comfort model chosen should give the ability to adjust variables such as the clothing (clothing flexibility), the airspeed (ceiling fans, ventilation openings) and the setpoint temperature of air conditioners
(2) Its ambience validity domain should contain hot summer tropical indoor conditions, especially for Temperature and Air velocity. ($24 > T_{db} > 34$ °C, $0 > v > 2.5$ $m.s^{-1}$)
(3) It should be the most reliable in warm and hot conditions for office applications
(4) It should be the most reliable in humid conditions where heat loss by perspiration is critical

2.2. Questioning original adaptive models for MM application

Research has highlighted the strong similarities between naturally ventilated and MM-cooled buildings regarding user adaptation and, therefore, the use of the adaptive model (AM: Adaptive Models) for MM buildings [8]. AM, specific to naturally ventilated buildings (NV), transcribes adaptability in a linear model, which takes the form $T_{comfort} = a.\ T_{rm} + b$, where T_{rm} is the running mean outdoor temperature of the previous days [7]. Behind the concept of adaptability, three main components are considered: behavioural, physiological and psychological [28]. Adaptive model simplicity allows rapid implementation in a BEM for controlling the air conditioning setpoint [9,10]; they are well suited to buildings cooled by natural ventilation or in high humidity conditions [25], which are typical of a tropical climate [14]; they are dedicated to building in which individuals are predisposed to a greater capacity to adapt to their environment [29] (as opposed to air-conditioned buildings).

Unfortunately, Zhang et al. [30] mention that it neglects the effect of air movement and other factors influencing thermal comfort even if new versions integrating additional environmental parameters, such as relative humidity [31], are being developed. Finally, none of these models allows air speed and clothing to be considered controllable parameters like the setpoint temperature, excluding them from our study.

2.3. Questioning original Thermal Heat-balance models and their adaptive alternatives for MM application

Alternative solutions exist to bridge the gap between Adaptive Models (AM) and Thermal Heat-balance (THM) Models. This combinatorial approach was introduced after the AM became part of the standard and is referred to as the *adaptive heat balance approach* (further named Adaptative THM). It seeks to enhance THM models by better considering the three physiological, psychological, and behavioural adaptation factors, thereby rationalising the adaptive concept within a thermo-

physiological framework. This is based on the observation that the Fanger and Gagge THM models have been the subject of numerous reliability studies. As an example, following Humphreys's research in 2002 [21], Cheung et al. [22] showed, based on the worldwide ASHRAE Global Comfort Database, an accuracy of PMV ISO of only 34 % for all cooling modes [15]. Adaptive THM, which expresses comfort as a function of six environmental and individual variables, alongside the concept of adaptability *Comfort* = $f(T_{db}, T_r, RH, V, CLO, MET, adaptation)$, hold promise for comprehensive MM Fan-First cooling control.

Three primary Adaptive THM model types exist:

(1) **Output correction**: These models adjust THM outputs using a corrective factor k. Examples include Fanger and Toftum's ePMV [7,32,33], which use fixed *k*, or Yao et al.'s field-calibrated coefficients [32,35]. Zhang et al. proposed similar corrections for Gagge's SET [36]. The resulting model is of the following form: $THM_{corrected} = k.\ THM$
(2) **Input modification**: Schweiker et al. developed the Adaptive Thermal Heat-Balance Model (ATHM) by modifying inputs like metabolic rate and clothing insulation. This method applies to both PMV and SET [37,38]
(3) **Regression-based model**: Parkinson et al. [8] extended the adaptive theory with a SET-based regression model ($SET_{comfort} = a.\ T_{rm} + b$), highlighting that a third of the comfort effects must be attributed to the thermal balance influenced by the six individual and environmental parameters.

Despite these advancements, no consensus exists on the best model for MM-cooled buildings.

The MM control algorithm must assess comfort using a thermophysiological model (THM or Adaptive THM) to control multiple parameters. Currently, the available THM options are the Fanger one-node model (PMV indices) and the Gagge two-node model (SET indices), necessitating a choice between these two approaches. THMs evaluate the deviation from thermal neutrality. They carry out the thermal assessment of the occupant by establishing the difference between internal heat production and exchanges by conduction, convection, radiation, and respiration with the environment. The main advantage of Gagge's two-node model over Fanger's is the consideration of internal heat storage and transient thermoregulation systems. Two concentric cylindrical segments, called nodes, represent the skin and the human body's core. The exchanges occur between the ambience and the skin. The model evaluates the need to implement thermoregulation processes between the skin and the core body at each time step. Core and skin temperatures are then reassessed accordingly. Conversely, the more simplified Fanger's model only considers the exchanges between a single segment and node (the body) and the environment under steady-state conditions. [39]

The first aspect questioning the relevance of the PMV model is its validity domain. In a tropical climate, indoor ambient conditions which regularly reach $T_{db} > 30$ °C, RH > 60 %, 0 $m.s^{-1} < V < 2.5$ $m.s^{-1}$ go beyond the validity domain of Fanger's PMV ISO7730 (max 30 °C, 1.0 $m.s^{-1}$) [11]. This domain is extended (0.1 $m.s^{-1} < V < 2$ $m.s^{-1}$) by ASHRAE 55:2010 and later with the introduction of the cooling effect (CE) determined from the Gagge's SET. The CE is subtracted from the dry bulb and radiant temperature in the PMV formulation to calculate the PMV_{CE}. Tartarini et al. [40] found that neither PMV models (PMV or PMV_{CE}) could accurately predict thermal sensations on the warm side, and they should only be used in neutral conditions, i.e. $|PMV| \leq 1$. Aside from Fanger's model, the Gagge model has been the subject of multiple refinements since it was developed in 1971. Vellei et al. [28] mention the most up-to-date versions in their article and several research on the model's performance, namely good accuracy for neutral and hot or very hot conditions. In his book [24], Parsons mentions another advantage of Gagge's model over Fanger's steady-state equation. Thanks to its calculation procedure based on a time step of one minute, it is possible to conveniently determine the physiological constants over the chosen duration, making the model more dynamic.

The other aspect that questions the relevance of PMV in these conditions is the cursory consideration of evapotranspiration, especially in the presence of high air velocity. Huang et al. [14] showed in their experiment for evaluating thermal sensation in the case of a warm environment and non-uniform air movement that the PMV model does not take into account the cooling effect of airflow when the skin wettedness is over the 'dry' threshold of 0.06. The model only integrates evapotranspiration through metabolic activity [41]. Thus, this latter remains constant at a fixed metabolism regardless of the environmental conditions. This hypothesis appears counterintuitive in hot and humid conditions where the influence of heat losses by evapotranspiration depends strongly on temperature, relative humidity and air movement. With the Fanger model, in the case of office activity such as typing, which remains relatively constant at around 1.1 MET, the environmental conditions, even extreme, will not influence evapotranspiration, one of the main driving forces behind regulating the human body in tropical conditions. Gagge's model integrates this phenomenon more completely. It depends on the skin's wettedness and the difference in partial vapor pressure between the skin and the environment. It further demonstrates that skin wettedness, defined as the ratio of evaporation on the surface to the maximum evaporation capacity in the environment, is a good indicator of discomfort and thermal stress well beyond the sweating rate proposed by Fanger. This highlights some limits of Fanger's PMV in these conditions since it does not account for evaporative heat loss enhancement by elevated air velocity, as Gagge's does.

2.4. Gagge's SET index selection

In this study, we selected the Gagge two-node model due to its ability to dynamically account for internal heat storage, transient thermoregulation processes, and the detailed physiological response to environmental conditions. Its Standard Effective Temperature (SET) index provides a robust framework for assessing thermal comfort in mixed-mode cooling applications under hot and humid tropical conditions. Furthermore, the SET index can be adapted within an adaptive heat balance framework to integrate better adaptive opportunities and controllable parameters: temperature, air velocity, and clothing insulation.

We conducted a sensitivity analysis to evaluate its response to variations in critical indoor conditions to ensure the suitability and robustness of the Gagge's SET index for MM Fan-First control applications. SA results quantify SET's response to airspeed and clothing modulation against other parameters, explicitly in tropical indoor conditions.

3. Data collection: Reunion MM building case study

A field study was conducted in a mixed-mode office building (Fig. 2) for seven weeks in the summers of 2023 and 2024 in Saint-Pierre, Reunion Island, to contextualise the analysis with actual field measurements of a tropical case study. Reunion Island is a French outermost territory close to Madagascar and Mauritius islands in the Indian Ocean. The building is located at the border between the Aw and Am climate subzones of the A-Tropical köppen climate group. The average annual daytime temperatures [7 a.m. to 6 p.m.] do not drop below 23 °C for Saint-Pierre. During the hot season, the daily temperature is expected to range from 24 to 34 °Celsius, with an average summer relative humidity of about 65–75 %. The building is an old concrete structure, a two-floor house of approximately 150 square meters located by the sea. It has been renovated, enlarged and converted into an office building for an architectural agency. It is typical of many offices in Reunion Island for small companies under 30 employees. The main blind façades are NE and NW-oriented, not shaded or insulated. The main opened façades are S- SW-oriented, facing a green courtyard. Most ground-floor ceilings are



Fig. 2. Outdoor and indoor photographs of the case study building, "COArchitectes" Agency.

shaded from the sun (great tree) or do not get direct sunlight as they are not in contact with the outdoors (first floor, rooftop veranda). Since specific spaces are single-oriented, they do not have natural cross ventilation for users' comfort. These users have access to ceiling fans that can be combined with air conditioning for the hottest periods. There are four main spaces. A Mixed-Mode single office located on the first floor with double side openings, a Mixed Mode meeting room located on the ground floor with single side opening, a five desks NV fully cross-ventilated space (wood construction extension) and eight desks Mixed Mode office with single two side double door-windows openings (Fig. 2. All spaces have ceiling fans (brand: Hunter, model: Industrie II 132 cm). Mixed-mode spaces are also equipped with split air conditioner units (Fig. 3). Control of ceiling fans and AC thermostats is at the user's discretion.

The ceiling fans offer three different rotation speeds. The office administrator limits the thermostat threshold for the AC unit at 26 °C per the local Reunion Island Standard for offices and commercial buildings

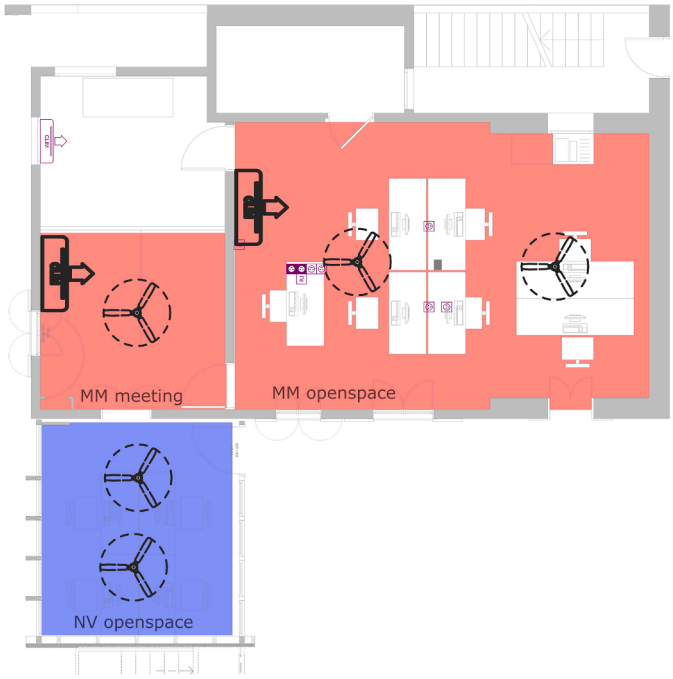

Fig. 3. Equipment location layout plan of the main floor of the study case building.

PERENE:2009 [42]. This setpoint is also recommended in Manzano-Agugliaro et al. [43] review of bioclimatic strategies for thermal comfort. Several field studies were done in the summers of 2023 and 2024. Environmental sensors (Dragino LHT65) recording dry bulb temperature and relative humidity were installed on all workstations. Each space was also equipped with a comfort station, detailed in Table 1, measuring air temperature, globe temperature, relative humidity, and air velocity. It was placed in the centre of the room, away from direct solar radiation and architectural masks or internal partitions. Mean radiant temperature is calculated from globe temperature, air velocity and dry bulb temperature according to ISO 7726:2023 [44]. Clothing garments for top, bottom, shoes and extra layers were recorded for each vote over 1400 votes and translated to clothing values according to ISO 9920:2009.

The indoor conditions extrema are determined from data averaged over 5 min with a confidence of 6 standard deviations (99.7 % of the measurement points). Mean and standard deviation are also computed and mentioned in Table 3.

4. Sensitivity analysis of Gagge's Standard Effective Temperature

4.1. Global sensitivity analysis: Sobols's indices for independent variables

Various SA methods exist for independent variables. Their choice depends on the objectives set and the constraints of the models [45]. Screening techniques such as One-factor-at-A-Time (OAT) discretisation and the Morris method are widely used in engineering because they are straightforward and computationally efficient. They are often used if the input parameter variability is close to its nominal value [46]. Nevertheless, they are limited to qualitative analysis, cannot assess parameter interactions and combined effects and may not fully explore the input space, leading to overemphasising trends when extreme values dominate. We did not select this method because running the Gagge two-node model costs very little on a desktop computer, and only five parameters are being tested. Nevertheless, for further details on the technique, the reader should refer to Machard et al. [47,48]. and Ioss and Lemaitre [45] and Tian et al. [16].

Global Sensitivity Analysis (GSA) based on the decomposition of the output variance, also called ANOVA (ANalysis Of VAriance), is more resource-intensive than the screening method. Still, they provide quantitative and valuable information. For example, Sobol's method can decompose all the output variance due to corresponding inputs and consider all interactions. The first-order Sobol indices S_i can be used to assess the variability of the output *(Y)* of a function *(f)*, knowing the

Table 1
List of environmental equipment and sensor types for registering indoor climatic conditions.

Supplier	Model	Probes	Measurements	Timestep
DeltaOhm	HD32.1 – Thermal Microclimate Data Logger	Combined temperature and relative humidity PT 100 probe. Globe temperature probe Ø 150mm Omnidirectional hot wire probe (0 °C…80 °C)	T_{db}, T_g, V, RH	*15* s
Testo	400	CO_2 probe with Temperature and relative humidity sensors Globe temperature probe Ø 150 mm TC type K Hotwire thermo-anemometer	T_{db}, T_g, V, RH	*15* s
Kimo	VT 110 / VT 115	Hotwire thermo-anemometer	V, T_{db}	*15* s
Campbell Scientific + Testo	CR1000	Combined temperature and relative humidity PT 100 probe. Globe temperature probe Ø 152mm Thermal anemometer	T_{db}, T_g, V, RH	*1* s

variability of the input parameters *(X_i)*, as shown in Eq. (1) representing the main effect. The second-order indices *Sij* can be used to assess the variability of the output *(Y)* of a function *(f)*, knowing the variability of the input parameters *(X_i)* and *(X_j)*, as shown in Eq. (2), representing the combined effects due to interactions. Finally, the sum of both represents the total effect as named total indices S_{Ti} (Eq. (3)). It includes the first order. It fully accounts for the higher-order effects due to interactions between inputs. With Sobol's indices, it is then possible to measure the relative importance of the contribution of all input variables in terms of the main effect and interactions of inputs [49]. The main property of Sobol S_i is its positiveness, and the sum of S_i is equal to 1 when there are no interactions, which makes Sobol indices very easy to interpret.

$$S_i = \frac{\mathrm{Var}[\mathbf{E}[Y|X_i]]}{\mathrm{Var}[Y]} \tag{1}$$

$$S_{ij} = \frac{\mathrm{Var}\left[\mathbf{E}\left[Y|X_iX_j\right]\right]}{\mathrm{Var}[Y]} \tag{2}$$

$$S_{Tj} = S_i + \sum_{i<j} S_{ij} + \sum_{j\neq i, k\neq ij<k} S_{ijk} + \ldots \tag{3}$$

Some methods exist to estimate those indices, such as Sobol and FAST (Fourier Amplitude Sensitivity Test). They all consider evaluating the model numerous times with different combinations of inputs; it becomes rapidly very computationally intensive. Typically, it could be counted on tens of thousands of evaluations. Monte Carlo sequences are well known but remain costly compared to their adaptation by Saltelli [45]. Multi-Fourier and coupled multi-Fourier transforms with random balance design (RBD) have been provided to lower the number of model evaluations [46]. These methods are well-suited to our case study, which involves rapid model evaluation and a small number of inputs, precisely five. Otherwise, they remain unstable and biased [45]. We used the GSA RBD-FAST method (Random Balance Design Fourier Amplitude Sensitivity Test [34,35]) associated with the method of generating samples by LHS permutation (Latin Hypercube Sampling) to determine the first-order Sobol indices. This method is as calculation time efficient as an OAT and has the advantage of quasi-random sampling across the whole range of variations. It is directly available in the *SAlib* Python library [50]. The Latin Hypercube sampling ensures a better homogenous exploration of the variation domain of parameters than traditional random sampling. The variation range is divided into N non-overlapping subranges with a probability of 1/N and is used for a random pickup process of values [19].

The variation range is based on actual building data, and the screening of the whole domain is bounded by the field study extrema in Table 2. The metabolism value is constant and equal to 1.1, the normative value of an office typing activity according to ISO7730. Unless metabolism is fixed at 1.1 MET, all variables are uniformly distributed. The choice of the uniform distribution is a strong hypothesis of variable independence. Furthermore, Haese et al. [51] described the detailed comfort field study in their article. Their analysis revealed a strong predominance of relative humidity regarding thermal sensations and user satisfaction. They [51] mentioned a shift at 68 % relative humidity for user satisfaction, independent of the other ambient conditions of the austral summer noted in the demonstrator building. Therefore, to evaluate small jumps in relative humidity, five series (i from 1 to 5) of sampling were executed using each time a different range of 10 relative humidity points, from 45 % to 95 %, called RH series (i) (see Table 2, note (1)). The LHS sampling technique mentioned above was used, and SET values were evaluated for all possible combinations. The five series of humidity ranges were plotted and compared.

4.2. The Shapley effects technique for dependent variables

All the methods mentioned above in Section 4.1 are well-suited for independent variables (uniform distribution with no correlation) but cannot handle correlated inputs. Nevertheless, in building engineering, Tian et al. [30] noted that it is common to work on building stock data that can have some form of correlation. Hence, the input space of parameter variation is not rectangular. For example, building age can be correlated to the building area of a city, or building geometry can be linked to a specific construction period or building stock [16]. As mentioned by Prieur et al. [52], *"When the inputs are described by an empirical distribution on observational data, it is extremely rare that the variables are statistically independent"*. Sobol's indices lose their interpretability in the presence of correlated inputs [52], they can become negative, and their sum does not necessarily equal 1. The relative importance of correlated inputs can be assessed by different methods like LMG (Lindeman Merand and Gold), PMVD (Proportional Marginal Variance Decomposition) or conditional variable importance from

Table 2
Variation ranges bounds of uniform distribution for the independent variable framework based on actual data from summer 2023.

	Relative Humidity (%)[1]	Dry Buld Temperature (°C)	Mean radiant temperature (°C)	Air Velocity (ms^{-1})	Metabolism (met)	Clothing (clo)
Lower bound (recorded min)	49	25.4	23.1	0.01	1.1[2]	0.29
Upper bound (recorded max)	88	32.1	31.2	2.2		0.79

[1] Field measurement for determination of humidity ranges series for Sobol's method (1) [45 %: 55 %], (2) [55 %: 65 %], (3) [65 %: 75 %], (4) [75 %: 85 %], (5) [85 %: 95 %].
[2] Typical fixed value for office activity sitting and typing as in ISO7730.

random forest, which are recommended and described in Tian's review of sensitivity analysis techniques for building energy analysis [16]. Those methods remain computationally intensive. To overcome this issue, Shapley values ϕ_i were introduced by Owen in 2014 [45] and are based on the coalitional game theory proposed by mathematician and economist Lloyd Shapley in his thesis back in 1951. It is recommended for dependent input variables. This concept aims to attribute the overall profit among players (or variables), given that they cooperate in a team (set of input variables). The marginal contribution of a player across all possible coalitions of players (also called permutations) defines the Shapley value. Shapley's value has four axioms: (1) Efficiency – The sum of all effects represents 100 % of the gain, (2) Symmetry – If two players contribute the same way, they get the same gain, (3) Dummy – if a coalition has the same gain with and without player X_i, then X_i gain should be zero, and (4) Additivity - When two models described by the prediction functions f and f' are combined, the prediction should correspond to the sum of the contributions derived from f and the contributions derived from f'. It stands right in between Sobol' S_i and S_{Ti}, and their sums remain equal to 1 ($0 < Si < \phi_i < S_{Ti} < 1$). Contrary to Sobol's total indice S_{Ti}, which fully accounts for higher-order interaction (interaction of X_{ij} is fully accounted in both S_{Ti} and S_{Tj}), Shapley value ϕ_i accounts for the main effect and only the part of higher order contribution X_{ij} of X_i interacting with Xj (with $j > i$). In other words, the interaction contribution is not counted twice like in the Sobol method. As mentioned by Prieur et al. [52], the first algorithms to calculate Shapley values were proposed in 2016 by Song et al. (Monte Carlo) and then in 2019 by Benoumechiara et al. (block bootstrap procedure). They are computationally intensive and impose an a priori knowledge of the conditional distribution. Broto et al. [53,54] introduced a subset aggregation method based on KNN metamodel (K-Nearest-Neighbors) that can solve this issue and be used for any dataset when a sample of the inputs is available and their distributions are unknown, which is our case in this study. This method is available in R sensitivity package 1.30.0 under the *shapleySubsetMc* function [55].

The parameter variation ranges are based on the actual building data distribution recorded during the summer working hours of the MM office in 2023 and 2024. Fig. 4 shows the distribution of actual data in solid colours, red and blue. Based on these two datasets' mean and standard deviation (Table 3), a normal distribution is fitted to better represent the on-site actual distributions. As mentioned above, distributions are non-rectangular and lose their independent feature. At this stage, it is impossible to subdivide by humidity ranges as in the previous section because fitted distributions are dependent on one another. As in the last section, the metabolism value will remain constant and equal to 1.1, the normative value of an office typing activity according to ISO7730. Clothing distribution will remain uniform between recorded extrema. Table 3 summarises all field measurements and distributions for the dependent framework.

5. Results and discussion

5.1. Contribution of parameters in the independent framework (Sobol indices)

Global sensitivity analyses are carried out across the entire variation domain for independent inputs and uniform distributions. After preliminary tests, it appeared that 10,000 draws were sufficient for converging the Sobol indices. SET is calculated using the two-node

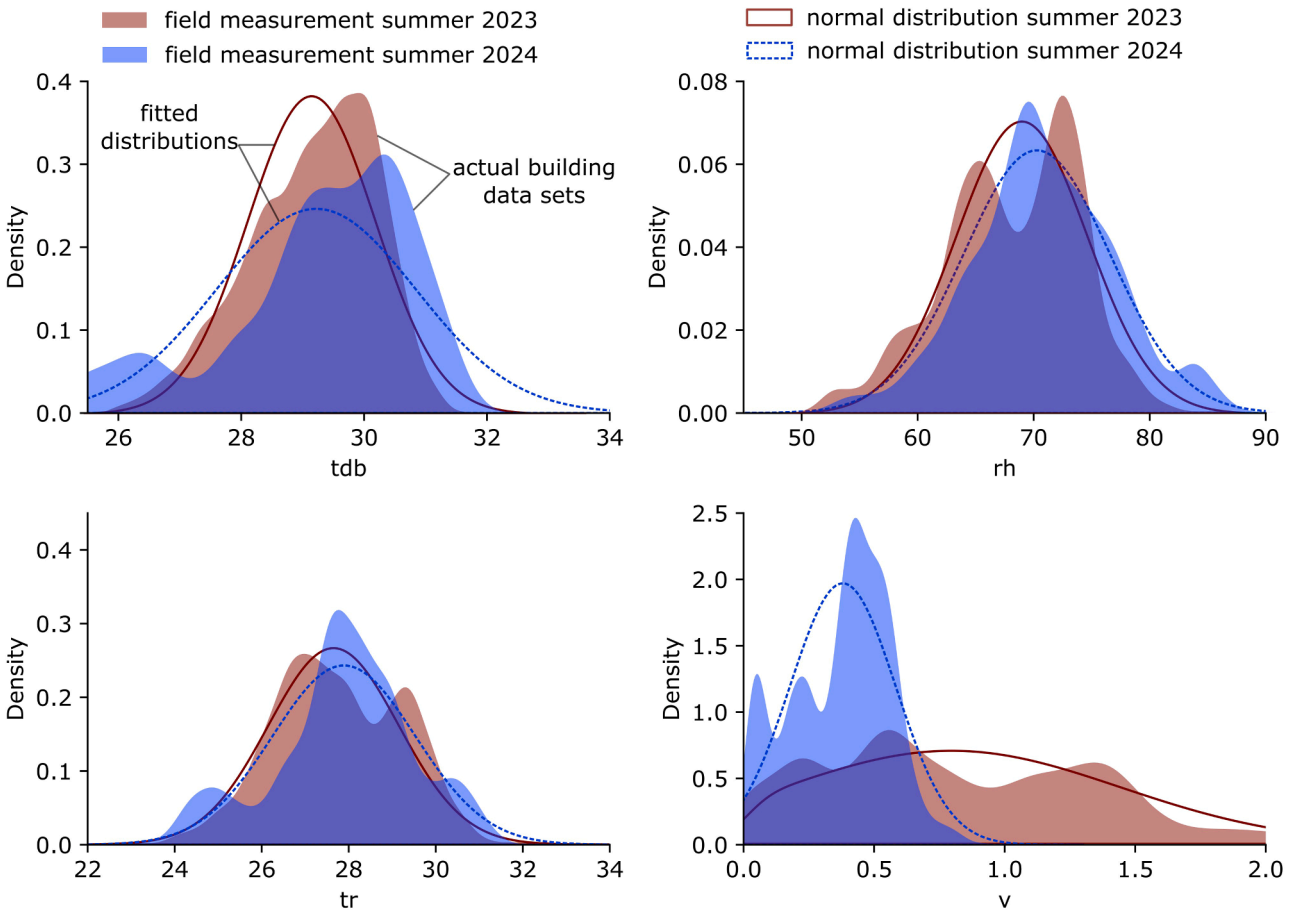

Fig. 4. Field measured environmental variables and their fitted normal distribution LHS sampling based on the mean and standard deviation for summers 2023 and 2024.

Table 3
Variation ranges and distribution types for the dependent variables framework based on actual data from summers 2023 and 2024.

Dataset		Relative Humidity (%)	Dry Buld Temperature (°C)	Mean radiant temperature (°C)	Air Velocity (ms^{-1})	Metabolism (MET)	Clothing (CLO)
Summer 2023	min	49	25.4	23.1	0.01	1.1	0.29
	max	88	32.1	31.2	2.2		0.79
	mean	68.9	29.2	27.7	0.83		
	standard deviation	5.9	1.1	1.5	0.54		
Summer 2024	min	51.7	23.2	21.1	0.01	1.1	0.29
	max	87	31.8	31.5	0.96		0.79
	mean	70.3	29.2	27.9	0.38		
	standard deviation	6.2	1.6	1.6	0.20		
	Distribution dependant framework	Normal	Normal	Normal	Normal truncated	Fixed	Uniform

model available in the *Pythermalcomfort v2.7* library [56] for each draw of the five RH series. Runtime is on the order of minutes on a desktop computer. For each series, the vertical extent of a violin diagram (Fig. 5) makes it possible to assess the dispersion of the output Y (SET index). The horizontal extent represents its probability density. The central bar corresponds to the interquartile range, representing 50 % of the data, centred on the median (white dot). The grey violins correspond to our reference case study in still air condition, whereas the blue ones represent our case study with real measured air velocities up to 2.2 ms^{-1} (Summer 2023). Median lines function of RH ranges are plotted in blue (actual case with measured air velocity) or dashed grey (actual case in still air conditions). The comfort and acceptability categories of the SET are represented in colours from (A) to "hot, very unacceptable" in red) to (F) "slightly cold, slightly unacceptable" in light blue, according to Parsons' correspondence table for SET [39]

Unsurprisingly, the probability of discomfort increases with relative humidity, as shown in Fig. 5. When in still air conditions, as shown in grey, for air velocities up to 0.15 ms^{-1}, the median of the SET increases by 1° to 2° SET for each series and by 5°SET from the RH series (1) to the RH series (5) as shown by the dashed line. The dispersion of the SET also doubles. In still air conditions, the SET index consistently trends toward uncomfortable levels, with 75 % of data points in very warm (Fig. 5 *cat. C*) and hot zones (Fig. 5 *cat. B*) at higher RH ranges. Conversely, the presence of higher air velocities (blue violin plots) mitigates potential discomfort, significantly shifting the SET distribution toward acceptable zones (Fig. 5 cat. *E and D, blue violins*). It is exacerbated at high RH, where having more than 10 % of points in the comfortable category (E) is difficult when in still air conditions (grey violins). With high air velocities (*blue violins*), it is possible to lower the overall dispersion of the SET for each RH series with an average median of 5°SET under the one for still air conditions (blue line). Below 70 % RH, it is possible to have at least 50 % of the output in the comfortable and acceptable (E) to cool (F) categories. The remaining 50 % are mainly in the slightly warm category (D). Only from the RH series (3) with high air velocities can one observe more than 25 % of the points in an unacceptable situation (orange gradient cat. B and C) when all RH series with still air (*grey violins)* showed a significant amount of uncomfortable SET.

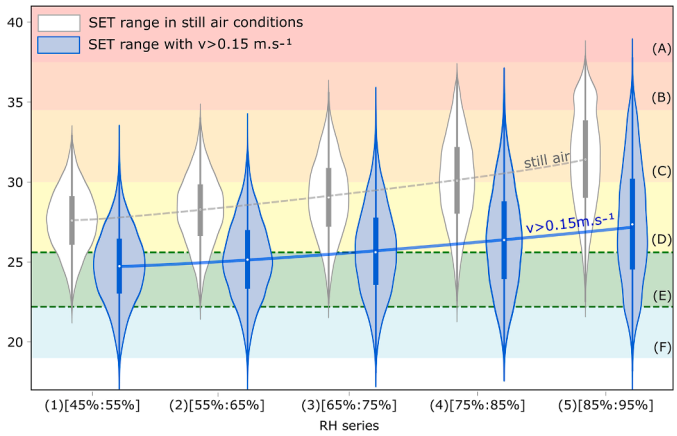

Fig. 5. Range of variability of the SET index as a function of relative humidity ranges with hypothetical low air speeds (still air) 0.01 to 0.15 ms-1(grey violins) and with air speeds representative of the case study from 0.01 to 2.2 ms-1 (blue violins) – (A) Hot, very uncomfortable, (B) Very Warm, very unacceptable, (C) Warm, uncomfortable, unacceptable, (D) Slightly warm, slightly unacceptable, (E) Comfortable, acceptable, (F) Slightly cold, slightly unacceptable.

The partial variances (Table 4) represent the absolute contribution of the parameters X_i on the output Y. They are expressed as a square of Y, i.e. SET^2. When comparing several sensitivity analyses, e.g. for several relative humidity ranges, it is necessary to validate that variance is not null, which could lead to a meaningless interpretation of first-order Sobol indices. All RH series show a total variance comprised between 4.8 and 13.4 SET^2. Fig. 6 presents the first-order sensitivity indices S_i for each input parameter of each series. The Sobol indice is the partial variance of Y knowing X_i, normalised by the total variance of Y (Eq. (1)). These Sobol indices represent a parameter's relative contribution to the output's variability. Within each series, we ensure that the sum of the Sobol indices is close to 1 and that the error bars are less than 5 % (Fig. 6). Then, we can confirm that there are no interactions of the input variables in the model evaluation. A parameter whose index is less than 0.1 can be considered to have a negligible influence on the output.

Fig. 6 shows that the relative contributions of the airspeed (v) and the clothing (clo) are of the same order of magnitude, whatever the relative humidity ranges. They are relatively constant at 0.25 from 45 % to 75 % RH and decrease slightly from 75 % RH. Their actual contribution (Table 4) increase with relative humidity to approximately double from the RH serie (1) range to the RH serie (5). In other words, the effect of a user action on one of these two parameters will have twice as much impact on the SET in conditions of high relative humidity than in dry conditions. At low relative humidity, the relative contribution (Fig. 6) of the two parameters (V) and (*CLO*) is slightly below (0.25) the contribution of temperature (T_{db}) (0.35). The more the relative humidity increases, the wider the gap becomes. It goes from 0.1-point difference in the RH serie (1) to the 0.15-point difference in the RH serie (3) to finally reach 0.35-point difference for the series RH serie (5). Thus, a user's

Table 4
Partial variance of the input parameters for a uniform distribution of independent inputs. Representation as a function of different relative humidity ranges for the tropical climate study case.

RH series-variables	(1) [45 %–55 %]	(2) [55 %–65 %]	(3) [65 %–75 %]	(4) [75 %–85 %]	(5) [85 %–95 %]
T_{db}	1.77	2.37	3.10	4.37	6.86
T_r	0.2	0.70	0.75	0.80	1.03
RH	0.01	0.02	0.02	0.06	0.10
V	1.33	1.54	1.89	2.10	2.65
CLO	1.46	1.60	1.96	2.23	2.73
Total	4.77	6.23	7.72	9.56	13.37

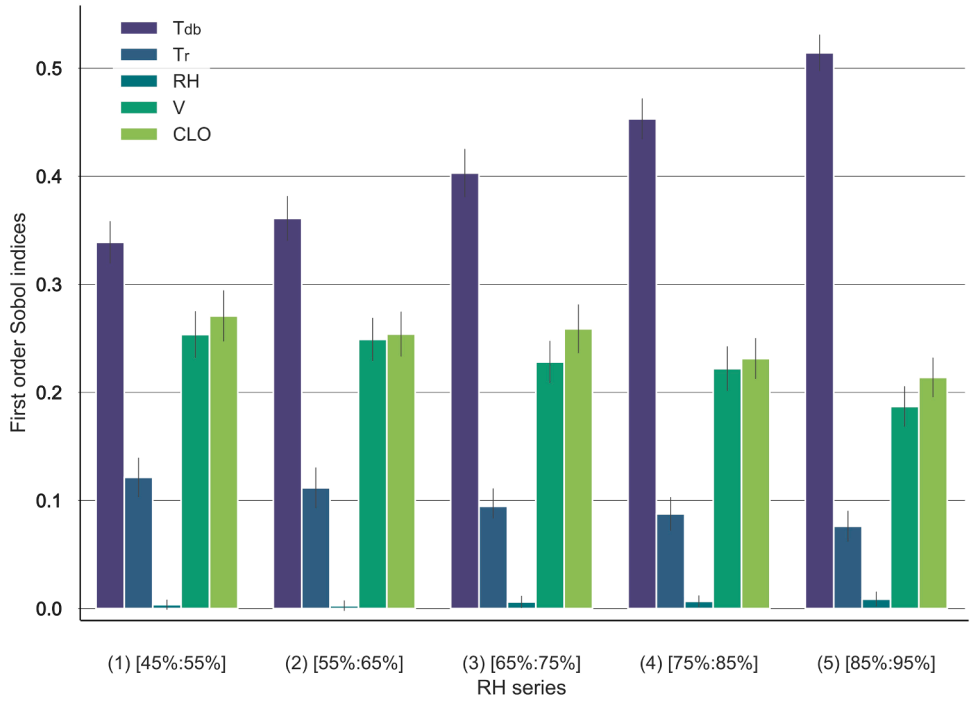

Fig. 6. Influence of control parameters on the SET. Representation of the first-order Sobol sensitivity indices of the input parameters for a uniform distribution of independent inputs. Representation as a function of different relative humidity ranges for the tropical climate study case.

action on the clothing and the airspeed will have the same impact as acting on the temperature setpoint at low relative humidity. However, the effect will be at least twice as low from 75 % relative humidity. This is explained by the higher the relative humidity in the environment, the more difficult it is for evaporative exchanges to restore body temperature. At this stage, it becomes necessary to act on the setpoint temperature (T_{db}) of an air conditioner to complete the effects of air velocity (V) and clothing (*CLO*). Finally, the contribution of the average radiant temperature of the walls and windows remains marginal in our case study, for which the building is well protected from solar stress, as is a slight variation (10 % max) in relative humidity.

5.2. *Contribution of parameters in the dependent framework (Shapley effects)*

The distributions of variables are constructed by fitting normal distributions from experimental datasets for summer 2023 and 2024. It is first to be noticed that the measured indoor conditions (Fig. 4) are similar in 2023 and 2024 for relative humidity and mean radiant temperature. Nevertheless, air temperature presents a more flattened normal due to a concentration measurement between 26 and 27 °C, resulting from more intensive use of the AC unit in 2024. Recorded air velocities are very different from the two datasets, with a mean of 0.83 $\pm$0.5 ms^{-1} in 2023 divided by 2 in 2024 (0.38$\pm$0.2 ms^{-1}). For the rest of the analysis, we will mention low air velocity range of [0: 1ms^{-1}] for 2024 and high air velocity range [0: 2ms^{-1}] for 2023, as recorded extrema in Table 3. Recorded meteorological data from the closest station (Pierrefond airport, 5 km from the building site) can partially explain this discrepancy; it presents almost the same outdoor wind intensity distribution with a mean of around 3 m.s-1 at 10 m high, but the wind directions differ. The southern façade of the building was far more exposed to strong winds (between 3 and 6 ms-1 and over 6 ms-1) in the summer of 2023 than in the summer of 2024. (30 % of S-facing winds in 2023 compared to 20 % in 2024, 24 % of W-SW winds in 2023 compared to 21 % in 2024). 2024′s strong winds exclusively come from the E-SE direction, and a construction mask highly protects the building's opened façade. Hence, it provides less wind access for the S-SW single-oriented opening spaces.

Fig. 7 presents the result of the Shapley values for both the dependent (dotted grey) and independent frameworks (coloured). The dotted barplot is the uniform distribution shown as a reference case from the independent framework Section 4.1. In a solid colour, the result of the Shapley method (Fig. 7) is similar to Sobol indices when compared with the average RH series (3) of [65 %: 75 %] (Fig. 6) because onsite measurement shows a normal distribution of RH centred on 70 % $\pm$ 6 %. Shapley effects are relevant to managing the independent framework. In this case of random draws in a rectangular space, the influence of temperature remains predominant (40 %), and airspeed and clothing make an equivalent contribution at $\pm$ 5 % for a total of 45 %. Those results align with Sobol's technique regarding trends, but one should remember that the absolute values of Sobol indices and Shapley values cannot be compared side by side.

According to the two datasets, Shapley values (Fig. 7) show different results. First, it is noted that, such as in the independent framework, one can reproduce the same trend concerning the influence of air velocity and clothing as for the independent framework. Their contribution to the SET remains equivalent at $\pm$ 5 %. It has been partially possible to reproduce the result sketched in Fig. 6 for the independent framework on two experimental datasets. Secondly, according to the average air velocity in the building, air temperature influence changes in front of clothing and air velocity. When mean air velocity is provided with a narrow range [0: 1 ms^{-1}], just like in the 2024 campaign (Table 3) (0.38 $\pm$0.2 ms^{-1}), the influence of air temperature is 70 % more influential than when air velocity is available for an extended range [0: 2 ms^{-1}] ((0.83$\pm$0.54 ms^{-1}) (2023). It is worth noting that with a higher range, airspeed and clothing combined are more influential than dry bulb temperature itself. Fig. 7 illustrates this with a Shapley value of 0.37 (T_{db}) in 2024 when *clo* and *v* are respectively 0.2 and 0.27. Conversely, in 2023, when a higher range or air velocity is available, the Shapley value of T_{db} drops to 0.22 when *clo* and *v* are 0.3 and 0.36, respectively. Combining these adaptive parameters can account for between 47 % and 66 % (Fig. 7) of the total output effect. Additionnaly, radiant temperature's contribution remains marginal in our two cases where it is close to air temperature, which is typical of NV buildings or conditioned

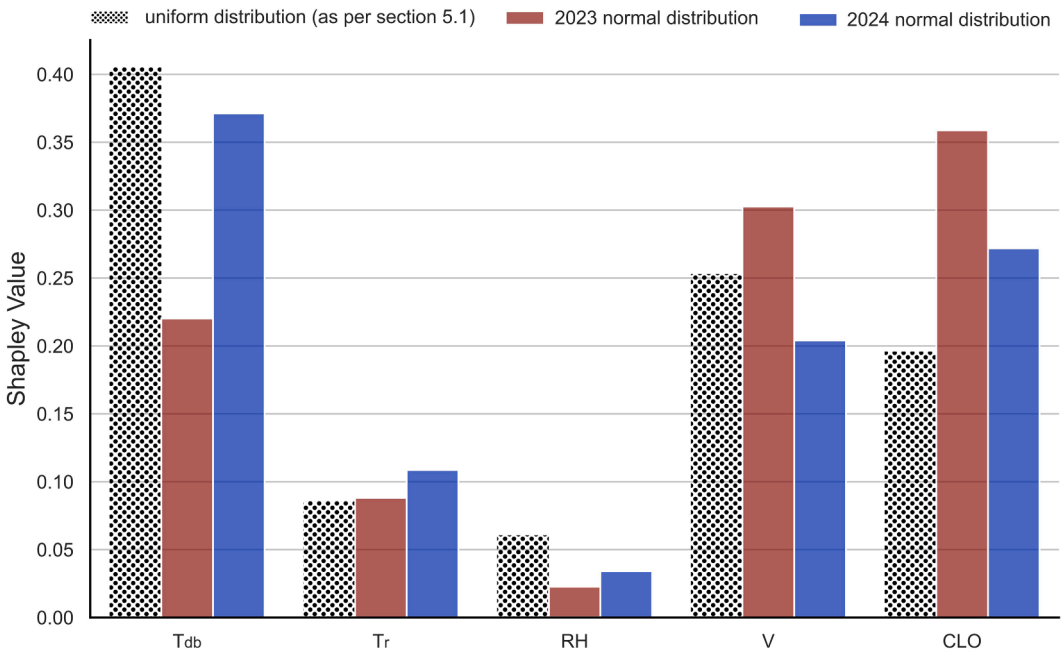

Fig. 7. Influence of control parameters on the SET. Representation of the Shapley values of the input parameters for a normal distribution of dependant inputs with uniform independent distribution as reference.

buildings with high setpoints. Relative humidity, centred for both datasets around 70 ± 5 %, does not influence the SET. More significant variations are needed to assess its influence, just like in Fig. 6, between the RH series (1) and the RH series (5).

To balance parameter's effect on SET and energy consumption, it is necessary to simulate the building energy model (BEM) with a selection of cooling system type, size and power (ceiling fans and air conditioning units). Energy use inherently depends on those three cooling system characteristics and the coupled systems' operation in given climatic conditions. SET is defined in the BEM control algorithm as the objective function to find the most energy-efficient path to comfort. Notably, unlike temperature setpoint, air velocity and clothing control parameters operate at a very low cost (ceiling fan) or no cost (clothing flexibility). These factors account for more than 60 % of SET variance. This insight offers a new perspective on reducing energy use by optimizing system sizing in MM buildings based on SET control, knowing that a traditional ceiling fan's maximum power use is around 50 W, while in comparison, even a small AC unit's power is around 1500 W.

6. Conclusions and perspectives

This study initially allowed us to raise the question of the relevance of comfort tools for managing mixed cooling systems in tropical conditions. Several lessons can be learned from it.

First, we showed that the Gagge model presents an advantage over others when considering the tropical climate. We highlighted that the historical AM models are not suited to multiple parameter control in building simulation, such as coupled temperature, air velocity and clothing. It also demonstrates that the PMV has limitations, such as its validity range well below the actual tropical conditions. While the PMV airspeed range can be modified by the Cooling Effect (CE), this presents no significant improvement for the warmest part of the sensation scale. Our analysis demonstrated, on the contrary, that Gagge's SET ticks all the boxes of MM *Fan-First* cooling control in tropical climates. It better considers the phenomenon of evapotranspiration, is more reliable in warm conditions, and has a dynamic nature that could be easily coupled with the dynamic of *Fan-First* cascade cooling systems in the BEM control algorithm. The SET index is promising as it is the base of the recent "nudged" adaptive model of Parkinson's [8] for all kinds of buildings or the ATHB framework of Schweiker [38].

The Sobol sensitivity analyses highlight critical insights into the dynamics of the SET index under various environmental and operational conditions. The studies confirm that the impact of parameters such as airspeed and clothing insulation is significant, regardless of the humidity range. Key findings reveal that at low to medium RH (45 %−70 %), airspeed and clothing collectively contribute about 50 % of the total variability in SET, matching the influence of air temperature. With increasing RH, the combined contribution lowers, highlighting the diminishing effectiveness of the body's evaporative heat loss, resulting in a need to adjust the AC setpoint. Under still air conditions, the SET index often reaches uncomfortable levels, with 75 % of data points falling in the very warm and hot categories at higher relative humidity (RH). However, increased air velocity reduces discomfort, shifting the SET distribution toward more comfortable zones.

Shapley effect analysis provides complementary results. When air velocities are limited [0: 1 m/s], Dry bulb temperature accounts for up to 35 % of the SET variance, and 47 % is accounted for clothing and air velocity. However, with a broader range of air velocities [0: 2 m/s], adaptive parameters (V and CLO) collectively influence the SET variability by 66 %, presenting a compelling case for their prioritisation in mixed-mode (MM) cooling strategies. In that case, temperature accounts for only 22 % of the total.

This study demonstrates that leveraging adaptive parameters like air velocity and clothing insulation using a SET-based control can substantially reduce energy use while maintaining comfort in MM buildings. Ceiling fans, with significantly lower power consumption (~50 W) compared to AC units (>1500 W), provide a sustainable pathway for optimising thermal comfort in tropical climates. The negligible influence of radiant temperature ($T_{db} \sim T_r$) and relative humidity variability within typical operating ranges (around 69 % ± 5 %) further simplifies MM control strategies.

This article presents a study with practical implications for selecting a comfort model for a MM Fan-First control objective. It introduces methods to investigate comfort models' behaviour, particularly emphasising the impact of the chosen distribution, variation range, and sensitivity analysis techniques. Its findings can have practical implications, as they help select SET and improve our understanding of its behaviour under the particular conditions of a tropical climate.

Nevertheless, defining the conditions that allow switching from one cooling mode to another remains an entire question. Indeed, as mentioned by Parkinson et al. [8], this remains a fertile area of research and will depend on many contextual factors for each building. The comparison between the model and actual data promises to be an essential second step for choosing the combined model based on SET. A technical solution must also be proposed to implement such a comfort-based control algorithm in BEM simulation tools to account for all three parameters and assess the energy use of both ceiling fans and air-conditioning units, thus linking SET and energy use.

Finally, this type of study could be an additional tool for comparing different comfort indices before implementing them in a control algorithm. This methodology could also be applied to various environmental conditions, such as the Continental and Mediterranean climates, which experience severe heatwaves during which fans could be beneficial in reducing energy use when coupled with AC.

Disclosure instructions

While preparing this work, the authors used the free Grammarly app to check grammar correctness and improve readability. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

CRediT authorship contribution statement

Maxime Boulinguez: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Aurélie Foucquier:** Writing – review & editing, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Jean Castaing-Lasvignottes:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] C.M. Rodriguez, M. D'Alessandro, Indoor thermal comfort review: the tropics as the next frontier, Urban Clim. 29 (Sep. 2019) 100488, https://doi.org/10.1016/j.uclim.2019.100488.

[2] S. Jim and Priyadarshi R Shukla, 'IPCC AR6 WGIII FullReport - Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'. Accessed: Apr. 19, 2022. [Online]. Available: https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.

[3] A. Malik, et al., The potential for indoor fans to change air conditioning use while maintaining human thermal comfort during hot weather: an analysis of energy demand and associated greenhouse gas emissions, Lancet Planet. Health 6 (4) (Apr. 2022) e301–e309, https://doi.org/10.1016/S2542-5196(22)00042-0.

[4] E. Arens, H. Zhang, W. Pasut, Y. Zhai, T. Hoyt, and L. Huang, 'Air movement as an energy efficient means toward occupant comfort', p. 127.

[5] M.G. Kent, et al., Energy savings and thermal comfort in a zero energy office building with fans in Singapore, Build. Environ. 243 (Sep. 2023) 110674, https://doi.org/10.1016/j.buildenv.2023.110674.

[6] S. Gokarakonda, C. Treeck, R. Rawal, Investigating optimum cooling set point temperature and air velocity for thermal comfort and energy conservation in mixed-mode buildings in India, Energies (Mar. 2022), https://doi.org/10.3390/en15062259.

[7] R. de Dear, J. Xiong, J. Kim, B. Cao, A review of adaptive thermal comfort research since 1998, Energy Build. 214 (May 2020) 109893, https://doi.org/10.1016/j.enbuild.2020.109893.

[8] T. Parkinson, R. de Dear, G. Brager, Nudging the adaptive thermal comfort model, Energy Build. 206 (Jan. 2020) 109559, https://doi.org/10.1016/j.enbuild.2019.109559.

[9] D. Sánchez-García, D. Bienvenido-Huertas, C. Rubio-Bellido, Computational approach to extend the air-conditioning usage to adaptive comfort: adaptive-Comfort-control-Implementation script, *Autom. Constr.* 131 (Nov. 2021) 103900, https://doi.org/10.1016/j.autcon.2021.103900.

[10] D. Sánchez-García, J. Martínez-Crespo, U.R.-R. Hernando, C. Alonso, A detailed view of the Adaptive-Comfort-Control-Implementation Script (ACCIS): the capabilities of the automation system for adaptive setpoint temperatures in building energy models, Energy Build. 288 (Jun. 2023) 113019, https://doi.org/10.1016/j.enbuild.2023.113019.

[11] EN ISO 7730:2005 - Ergonomics of the thermal environment - analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria (ISO 7730:2005), 2006.

[12] A.P. Gagge, A.P. Fobelets, L.G. Berglund, A standard predictive index of HUMAN response to the thermal environment, Ashrae Trans 92 (part 2B) (1986) 23.

[13] M. Vellei and J.L. Dréau, 'On the prediction of dynamic thermal comfort under uniform environments', p. 17, 2020.

[14] L. Huang, E. Arens, H. Zhang, Y. Zhu, Applicability of whole-body heat balance models for evaluating thermal sensation under non-uniform air movement in warm environments, Build. Environ. 75 (May 2014) 108–113, https://doi.org/10.1016/j.buildenv.2014.01.020.

[15] V.Földváry Ličina, et al., Development of the ASHRAE Global Thermal Comfort Database II, Build. Environ. 142 (Sep. 2018) 502–512, https://doi.org/10.1016/j.buildenv.2018.06.022.

[16] W. Tian, A review of sensitivity analysis methods in building energy analysis, Renew. Sustain. Energy Rev. 20 (Apr. 2013) 411–419, https://doi.org/10.1016/j.rser.2012.12.014.

[17] S. de Wit, G. Augenbroe, Analysis of uncertainty in building design evaluations and its implications, Energy and Buildings 34 (9) (2002) 951–958, https://doi.org/10.1016/S0378-7788(02)00070-1.

[18] S. Bontemps, L. Mora, blatman geraud, Reliability of dynamic simulation models for building energy in the context of low-energy buildings, in: 13th Conference of International Building Performance Simulation Association, Chambéry, France, 2013.

[19] Breesch, Hilde and Arnold Janssens, Uncertainty and sensitivity analysis of the performances of natural night ventilation, 2004.

[20] H. Breesch, 'Natural night ventilation in office buildings'.

[21] R. Moutela, J.D. Carrilho, and M.G.D. Silva, 'Sensitivity of the Pmv index to the thermal comfort parameters', 2015, doi:10.13140/RG.2.1.3936.1447.

[22] M.H. Hasan, F. Alsaleem, M. Rafaie, Sensitivity study for the PMV thermal comfort model and the use of wearable devices biometric data for metabolic rate estimation, Build. Environ. 110 (Dec. 2016) 173–183, https://doi.org/10.1016/j.buildenv.2016.10.007.

[23] L. Ji, A. Laouadi, C. Shu, L. Wang, M.A. Lacasse, Evaluation and improvement of the thermoregulatory system for the two-node bioheat model, Energy Build 249 (Oct. 2021) 111235, https://doi.org/10.1016/j.enbuild.2021.111235.

[24] *ANSI/ASHRAE standard 55-2023 – Thermal environmental conditions for Human occupancy*, 2023. Accessed: May 30, 2024. [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy.

[25] *EN/TR 16798-2:2019 energy performance of buildings - ventilation for buildings - part 2 : interpretation of the requirements in EN 16798-1 - indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Module M1-6)*, Aug. 2019.

[26] A.P. Gagge, Effect of energy conservation guidelines on comfort, acceptability and health. A Serie of Laboratory and Field Studies, John B. Pierce Foundation, 1976.

[27] S. Schiavon, K.H. Lee, Dynamic predictive clothing insulation models based on outdoor air and indoor operative temperatures, Build. Environ. 59 (Jan. 2013) 250–260, https://doi.org/10.1016/j.buildenv.2012.08.024.

[28] F.H. Mallick, 'Thermal comfort and building design in the tropical climates', p. 7, 1996.

[29] R.J. de Dear, G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55, Energy Build 34 (6) (Jul. 2002) 549–561, https://doi.org/10.1016/S0378-7788(02)00005-1.

[30] S. Zhang, Z. Lin, Adaptive-rational thermal comfort model: adaptive predicted mean vote with variable adaptive coefficient, Indoor Air 30 (5) (Sep. 2020) 1052–1062, https://doi.org/10.1111/ina.12665.

[31] M. Vellei, M. Herrera, D. Fosas, S. Natarajan, The influence of relative humidity on adaptive thermal comfort, Build. Environ. 124 (Nov. 2017) 171–185, https://doi.org/10.1016/j.buildenv.2017.08.005.
[32] R. Yao, et al., Evolution and performance analysis of adaptive thermal comfort models – A comprehensive literature review, Build. Environ. 217 (Jun. 2022) 109020, https://doi.org/10.1016/j.buildenv.2022.109020.
[33] P. Ole Fanger, J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates, Energy Build 34 (6) (Jul. 2002) 533–536, https://doi.org/10.1016/S0378-7788(02)00003-8.
[34] J. Gao, Y. Wang, P. Wargocki, Comparative analysis of modified PMV models and SET models to predict human thermal sensation in naturally ventilated buildings, Build. Environ. 92 (Oct. 2015) 200–208, https://doi.org/10.1016/j.buildenv.2015.04.030.
[35] R. Yao, B. Li, J. Liu, A theoretical adaptive model of thermal comfort – Adaptive predicted mean vote (aPMV), Build. Environ. 44 (10) (Oct. 2009) 2089–2096, https://doi.org/10.1016/j.buildenv.2009.02.014.
[36] S. Zhang, Z. Lin, Standard effective temperature based adaptive-rational thermal comfort model, Appl. Energy 264 (Apr. 2020) 114723, https://doi.org/10.1016/j.apenergy.2020.114723.
[37] M. Schweiker, Combining adaptive and heat balance models for thermal sensation prediction: a new approach towards a theory and data-driven adaptive thermal heat balance model, Indoor Air 32 (3) (Mar. 2022), https://doi.org/10.1111/ina.13018.
[38] M. Schweiker, A. Wagner, A framework for an adaptive thermal heat balance model (ATHB), Build. Environ. 94 (Dec. 2015) 252–262, https://doi.org/10.1016/j.buildenv.2015.08.018.
[39] K.C. Parsons, Human thermal comfort. CRC Focus, CRC Press/Taylor & Francis Group, Boca Raton London New York, 2020.
[40] F. Tartarini, T. Cheung, S. Schiavon, E. Arens, The prediction accuracy of different predicted mean vote (PMV) model formulations, in: L.L. Wang, H. Ge, Z.J. Zhai, D. Qi, M. Ouf, C. Sun, D. Wang (Eds.), Proceedings of the 5th International Conference On Building Energy and Environment, Springer Nature, Singapore, 2023, pp. 2363–2370, https://doi.org/10.1007/978-981-19-9822-5_255.
[41] P.O. FANGER, Thermal Comfort Analysis and Applications in Environmental Engineering, Danish technical Press Copenhaguen, 1970.
[42] 'PERENE Réunion, Mise à jour 2009. Règles de conception thermique et énergétique des bâtiments tertiaires et résidentiels adaptées aux zones climatiques de l'Ile de La Réunion'. 2009.
[43] F. Manzano-Agugliaro, F.G. Montoya, A. Sabio-Ortega, A. García-Cruz, Review of bioclimatic architecture strategies for achieving thermal comfort, Renew. Sustain. Energy Rev. 49 (Sep. 2015) 736–755, https://doi.org/10.1016/j.rser.2015.04.095.
[44] *ISO 7726:2021 ergonomics of the thermal environment - instruments for measuring and monitoring physical quantities*, 2023.
[45] B. Iooss and P. Lemaître, 'A review on global sensitivity analysis methods', Apr. 09, 2014, *arXiv*: arXiv:1404.2405. doi:10.48550/arXiv.1404.2405.
[46] J. Goffart, M. Woloszyn, EASI RBD-FAST: an efficient method of global sensitivity analysis for present and future challenges in building performance simulation, J. Build. Eng. 43 (Nov. 2021) 103129, https://doi.org/10.1016/j.jobe.2021.103129.
[47] A. Machard, C. Inard, J.-M. Alessandrini, C. Pelé, and J. Ribéron, 'Sensitivity analysis of the input parameters impacting summer thermal discomfort in buildings under future climate in Paris', presented at the IBPSA France 2020, Nov. 2020. Accessed: Jan. 22, 2024. [Online]. Available: https://cstb.hal.science/hal-04067828.
[48] A. Machard, 'Towards mitigation and adaptation to climate change : contribution to building design', phdthesis, Université de La Rochelle, 2021. Accessed: Mar. 11, 2024. [Online]. Available: https://theses.hal.science/tel-03675251.
[49] T.A. Mara, W.E. Becker, Polynomial chaos expansion for sensitivity analysis of model output with dependent inputs, *Reliab. Eng. Syst. Saf.* 214 (Oct. 2021) 107795, https://doi.org/10.1016/j.ress.2021.107795.
[50] J. Herman, W. Usher, SALib: an open-source Python library for Sensitivity Analysis, J. Open Source Softw. 2 (9) (Jan. 2017) 97, https://doi.org/10.21105/joss.00097.
[51] G. Haese, M. Boulinguez, P. Bernaud, A. Couzinet, An innovative approach to better understand hot discomfort, based on the measurement of global human responses, including physiological and sensory indicators - application to end users of mixed mode cooled buildings under tropical climate conditions. Ventilation, IEQ and Health in Sustainable Buildings, Aalborg University, Copenhagen, Denmark, 2023.
[52] B. Iooss and C. Prieur, 'Shapley effects for sensitivity analysis with correlated inputs: comparisons with Sobol' indices, numerical estimation and applications', Nov. 25, 2019, *arXiv*: arXiv:1707.01334. Accessed: Mar. 14, 2024. [Online]. Available: http://arxiv.org/abs/1707.01334.
[53] B. Broto, F. Bachoc, M. Depecker, Variance reduction for estimation of Shapley effects and adaptation to unknown input distribution, SIAMASA J. Uncertain. Quantif. 8 (2) (Jan. 2020) 693–716, https://doi.org/10.1137/18M1234631.
[54] M.B. Heredia, C. Prieur, N. Eckert, Global sensitivity analysis with aggregated Shapley effects, application to avalanche hazard assessment, *Reliab. Eng. Syst. Saf.* 222 (Jun. 2022) 108420, https://doi.org/10.1016/j.ress.2022.108420.
[55] B. Iooss, B. Broto, R sensitivity Package - Global sensitivity analysis of model outputs and importance measures, CRAN (2024).
[56] F. Tartarini, S. Schiavon, pythermalcomfort: a Python package for thermal comfort research, SoftwareX 12 (Jul. 2020) 100578, https://doi.org/10.1016/j.softx.2020.100578.