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Implementation of Desk Fans in Open Offices in Brazil: Proposition for Optimizing Thermal Comfort and Energy Consumption

(Implementação de ventiladores de mesa em escritórios compartilhados no Brasil: proposição da otimização do conforto térmico e consumo energético)

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Thesis submitted to the Graduate Program in Civil Engineering at the Federal University of Santa Catarina as a partial requirement for obtaining the title of Doctor in Civil Engineering.

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To my parents.

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ABSTRACT

The global warming scenario drives nations to adopt strategies to reduce greenhouse gas emissions and electricity demand. Buildings in Brazil account for more than 50% of the country's electricity consumption, and cooling is one of the main end-uses in commercial buildings. One way to reduce this consumption is to extend the setpoint temperature of cooling systems and use personal conditioning systems (PCS) to maintain occupants’ thermal comfort. In Brazil, the prevalence of high temperatures and preference for high air speed indicate that desk fans would be a good fit for office spaces. Despite numerous research in recent years, there is still a lot to be understood about the best way to implement PCS in buildings. One of the biggest challenges is defining setpoint temperature limits for achieving both comfort and energy savings. Considering these possibilities and issues, this thesis aims to evaluate the feasibility and best practice of applying desk fans into shared workspaces in Brazil. The thesis is structured in five articles: (1) literature review; (2) assessment of fans for equipment selection; (3) potential expansion of setpoint temperature for Brazilian climates with the use of desk fans; (4) current operation procedures in Brazil and a comparison to other countries; (5) guidelines for implementation based on a field study. The first article helped to understand the gaps in the topic and to define the methods of the thesis and the following papers. The second article is based on a controlled study with 40 people assessing 4 desk fans. Air flow sensation, the possibility of adjustment, noise, and cost are the most important aspects for selecting a device. Users preferred the evaporative cooling fan, however, considered its cost-benefit not worth it. Therefore, two other fans, with similar rates were selected for the field application presented in paper 5. The third article presents, through computer simulation, the potential extension of setpoint temperature when desk fans are associated with mixed-mode operation in offices in Brazilian cities. Results show that fans can expand up to 30 % comfortable occupancy hours in open offices and increase energy consumption by up to 1.5 %. The simulation and prediction models indicate 28 °C setpoint is applicable for Brasilia, Manaus, and Fortaleza, and 30 °C for Florianopolis with a low risk of overheating. However, the interviews with building operators carried out for paper 4 indicate the most common setpoint in Brazil is 23 °C in office spaces. This temperature is the most common also in Canada, while in Singapore and Italy, which have warmer summers, 26 °C is the main cooling setpoint. Therefore, there was not found a clear relation between setpoints and climate, which indicates the adaptive concept not to be applicable to setpoint selection. The fifth paper was based on a field implementation of desk fans with setpoint temperature increment from 23 °C up to 27 °C in Florianopolis. Occupants’ expectations was found to have a great impact on the applicable setpoint limits. Occupants felt more pleased with fans changing indoor temperature from 24 °C to 25 °C. However, many limitations hindered the experiment results and gradual changes are suggested for future implementation, associated with engaging operators and occupants, and monitoring thermal perception with timely surveys.

Keywords: thermal comfort; energy efficiency; personal conditioning systems; desk fans; office.

RESUMO

O cenário de aquecimento global tem levado as nações a adotarem estratégias para reduzir as emissões de gases de efeito estufa e a demanda de eletricidade. No Brasil, os edifícios são responsáveis por mais de 50% do consumo de eletricidade, e a refrigeração é um dos principais usos finais em edifícios comerciais. Uma forma de reduzir esse consumo é estender a temperatura de *setpoint* do ar-condicionado e adicionar sistemas de condicionamento pessoal (PCS) para manter o conforto térmico dos ocupantes. No Brasil, a predominância de altas temperaturas e a preferência por alta velocidade do ar apontam ventiladores de mesa como uma boa opção de PCS para espaços de escritório. Apesar de ser um equipamento acessível, a literatura apresenta desafios para implementação adequada desses equipamentos. Por conta disso, esta tese tem como objetivo avaliar a viabilidade e as melhor prática da aplicação de ventiladores de mesa em escritórios compartilhados no Brasil. A tese está estruturada em cinco artigos: (1) revisão bibliográfica; (2) avaliação de ventiladores para a seleção de equipamentos; (3) potencial de extensão da temperatura de *setpoint* nos climas brasileiros com o uso de ventiladores de mesa; (4) procedimentos atuais de operação de edifícios no Brasil e em outros países; (5) diretrizes de implementação de ventiladores com base em um estudo de campo. O primeiro artigo ajudou a entender as lacunas bibliográficas sobre este assunto e a definir os métodos da tese e dos artigos seguintes. O segundo artigo baseia-se em um estudo em câmara com 40 pessoas que avaliaram 4 ventiladores de mesa. Nesse estudo, a sensação do ar, a possibilidade de ajuste, o ruído e o custo foram identificados como os aspectos mais importantes para a seleção de um ventilador. O ventilador preferido pelos participantes foi o que proporcionava resfriamento evaporativo. Mas, seu custo foi considerado muito alto e por conta disso, outros dois outros ventiladores foram selecionados para a aplicação em campo do artigo 5. O terceiro artigo apresenta, por meio de simulação computacional, a extensão potencial da temperatura de setpoint quando ventiladores de mesa são associados ao modo-misto de operação em escritórios de 4 cidades brasileiras. Os resultados mostram que os ventiladores podem aumentar em até 30 pontos percentuais as horas de ocupação em conforto térmico e aumentar o consumo de energia em até 1,5 pontos percentuais. Os modelos de simulação e predição indicam que o *setpoint* máximo de 28 °C é aplicável em Brasília, Manaus e Fortaleza, e 30 °C em Florianópolis, com baixo risco de superaquecimento. No entanto, as entrevistas com operadores de edifícios apresentadas no artigo 4 indicam que o *setpoint* mais comum no Brasil é 23 °C em escritórios. A comparação com outros países mostrou que essa temperatura é também a mais comum no Canadá, que tem um clima mais ameno, enquanto em Cingapura e na Itália, que têm verões mais quentes, 26 °C é o principal *setpoint* de ar-condicionado. Portanto, não foi encontrada uma relação clara entre *setpoint* usado e o clima, o que indica que o modelo adaptativo não é aplicável à seleção de *setpoint*. O quinto artigo foi baseado em uma implementação de campo de ventiladores de mesa com incremento de temperatura de *setpoint* de 23 °C a 27 °C em Florianópolis. Esse estudo mostrou o impacto da expectativa térmica dos ocupantes sobre os possíveis limites de incremento do *setpoint*. Os ocupantes ficaram mais satisfeitos com ventiladores sob uma temperatura do ar 1 °C superior a inicial, indicando possibilidade de subir de 24 °C para 25 °C. Por outro lado, muitos fatores afetaram os resultados e pode-se concluir que uma intervenção mais gradual seria mais benéfica e poderia ter alcançado valores mais altos como os 26 °C identificados em estudos anteriores similares.

Palavras-chave: conforto térmico, sistemas pessoais de condicionamento, ventiladores de mesa, escritórios, Brasil.

RESUMO EXPANDIDO

Introdução

A perspectiva do aquecimento global leva as nações a adotarem estratégias para reduzir as emissões de gases de efeito estufa e a demanda de eletricidade. No Brasil, os edifícios são responsáveis por mais de 50 % do consumo de eletricidade do país, e a refrigeração é um dos principais usos finais em edifícios comerciais. Uma forma de reduzir esse consumo é ampliar a temperatura de acionamento dos sistemas de climatização. Caso isso seja feito, podem ser usados sistemas de condicionamento pessoal para manter o conforto dos ocupantes, pois eles permitem o ajuste local das variáveis ambientais com baixo consumo energético. Entretanto, a definição dos limites de temperatura deve considerar diferentes fatores, como preferências individuais, expectativas e o tipo de sistema pessoal que será usado. No Brasil, a predominância de altas temperaturas e a preferência por alta velocidade do ar indicam que os ventiladores de mesa teriam um bom potencial para uso em escritórios. Nessas condições, estudos realizados em câmaras climáticas indicam limites de aceitabilidade de até 30 °C. Porém, estudos de campo indicam preferência por 26 °C. Quando os ocupantes têm controle sobre os sistemas, eles podem privilegiar o alívio térmico imediato, preferindo diminuir a temperatura do ar-condicionado a usar o movimento do ar, o que resulta na redução do potencial de economia de energia dos ventiladores. Em espaços compartilhados, é mais difícil agradar a todos e chegar a um consenso sobre a temperatura de acionamento do ar-condicionado. Para resolver esses problemas, alguns estudos propõem o uso da automação, com base em modelos pessoais de conforto térmico. Esses modelos permitem o ajuste da temperatura com base nas demandas previstas dos ocupantes. Além disso, é possível integrá-los a algoritmos que considerem o consumo energético previsto para atingir a temperatura ideal. No entanto, esses algoritmos são complexos e exigem um alto nível de automação do sistema para serem aplicáveis que muitas vezes não está disponível nos edifícios brasileiros. Além deste caminho, ainda pouco aplicado, foi identificado que não há diretrizes claras para a implementação prática de sistemas de condicionamento pessoal.

Objetivos

Considerando as possibilidades e questões expostas, esta tese visa avaliar a viabilidade e as melhores práticas para aplicar ventiladores de mesa em espaços de trabalho compartilhados no Brasil. Para isso, a tese baseia-se em cinco artigos que cumprem cinco objetivos específicos: 1) identificar o estado da arte sobre a implementação de sistemas de condicionamento pessoal; 2) compreender quais os critérios principais para a seleção de ventiladores com bom desempenho para os usuários; 3) avaliar o potencial de expansão da temperatura do ar condicionado em escritórios nos climas brasileiros quando há ventiladores de mesa; 4) identificar os atuais procedimentos de operação no Brasil e comparar com outros países; 5) propor diretrizes para implementação com base em um estudo de campo.

Metodologia

O artigo 1 apresenta uma revisão de literatura sobre a implementação de sistema pessoais de condicionamento entre 2017 e 2019. O artigo 2 é baseado em um estudo controlado em uma sala de escritório que contou com a participação de 40 pessoas. Cada pessoa utilizou 4 tipos de ventiladores de mesa, para ao final comparar seu desempenho, selecionar o melhor equipamento e os avaliar os critérios de seleção. O artigo 3 apresenta uma análise realizada por simulação computacional em que foram testadas três alturas de um edifício padrão de planta aberta localizado em quatro cidades brasileiras. Foi comparado o consumo e conforto térmico previsto dos ocupantes em uma condição condicionada a 24 °C com uma estratégia que combina modo misto de operação (alternando ventilação natural e condicionamento) com o uso de ventiladores de mesa. Considerando esta estratégia, foram testadas três temperaturas de termostato: 26, 28 e 30 °C. O artigo 4 foi baseado em entrevistas estruturadas sobre perguntas abertas e de múltiplas respostas que foram aplicadas a 72 operadores e gestores de edifícios de 7 países. O roteiro de entrevistas foi desenvolvido pelos membros do Anexo 79 – Operação e projeto de edifícios focados nos ocupantes, que é um grupo de especialistas coordenado pela Agência Internacional de Energia. Por fim, o artigo 5 apresenta os resultados de um experimento de campo no qual foram disponibilizados ventiladores de mesa para 34 ocupantes em um escritório localizado em Florianópolis, no qual a temperatura de ar-condicionado foi aumentada a cada dia enquanto as variáveis do ambiente e percepção térmica dos ocupantes forem registradas. Com base nesta experiência foram sugeridas algumas diretrizes para futuras implementações.

Resultados e Discussão

A revisão apresentada no artigo 1 foi utilizada para identificar as lacunas sobre o tema e a definir a metodologia dos demais artigos e da tese como um todo. Foi identificado que muitos estudos relacionados à implementação de sistemas pessoais de condicionamento (do inglês, PCS) propõem o uso de modelos pessoais de conforto térmico, para que seja possível prever as preferências de cada ocupante. Entretanto há poucas informações disponíveis sobre como associar as predições individuais a uma resposta única que possa ser utilizada para controlar a temperatura de um ambiente com múltiplos ocupantes. Além disso, há um aumento de complexidade quando se busca atender tanto o conforto quanto a redução de consumo elétrico, pois os dois objetivos podem ser conflitantes. Esta revisão ressalta que há múltiplos aspectos que devem ser considerados e que não há uma solução única bem como diretrizes identificáveis na literatura para atingir maior eficiência. Uma das barreiras identificadas anteriormente para a implementação de ventiladores de mesa, havia sido as caraterísticas técnicas do produto. Por conta disso, o segundo artigo focou em uma comparação de produtos do ponto de visto de sua usabilidade, tendo pessoas como a principal fonte de informação e os produtos, quatro ventiladores disponíveis no mercado brasileiro. Os resultados indicaram que as pessoas consideraram a sensação do vento e ajuste são os aspectos mais importantes para a seleção de um dispositivo. Entretanto, o ruído e o custo também são importantes. Esta experiência indicou que os usuários preferiram, dentre as opções, um ventilador que promove resfriamento evaporativo, possuindo um filtro embebido em água, que auxilia a redução da temperatura do ar insuflado. No entanto, esse equipamento custa 40 vezes mais que os demais e por isso, os participantes, indicaram preferir outras opções, não considerando um bom custo-benefício. Portanto, dois outros ventiladores, com classificações semelhante, foram selecionados para a aplicação em campo apresentada no artigo 5. No artigo 3, foi considerado o ventilador de menor consumo dentre os dois selecionados no artigo 2, possuindo potência de 3W. As simulações indicaram que o uso de ventiladores (considerando o modelo adaptativo de conforto térmico), permite estender em 30 % a quantidade de horas de ocupação em conforto térmico. Por outro lado, no cenário mais crítico, em que o ar-condicionado teria menor consumo anual, ativado a 30 °C e os ventiladores precisariam ser utilizados mais frequentemente, o consumo dos ventiladores representaria menos de 2 % do consumo total da edificação. Isto é, a adição dos ventiladores tem impacto energético muito baixo, enquanto o impacto para maximizar o conforto é alto. Considerando seu uso, o ar-condicionado poderia ser operado a 28 °C em Manaus, Brasília e Fortaleza, e chegar a 30 °C em Florianópolis, onde as condições térmicas são mais amenas. Segundo os dados da simulação, essas temperaturas permitem manter o conforto sem gerar uma frequência crítica de ocorrência de superaquecimento. O que gera entre 20 % e 35 % de economia de energia se comparado ao cenário sem modo misto ou ventiladores e com temperatura de acionamento de 24 °C. Por outro lado, as entrevistas realizadas com operadores e gestores de edificações no artigo 4 indicaram que a temperatura de ativação do ar-condicionado mais comum no Brasil é 23 °C. Esse valor coincide com o mais praticado no Canadá, um país de clima predominantemente frio. Enquanto em Singapura, que possui clima mais cálido, é mais comum o uso de 26 °C. Dentre estes e os demais países (Itália, EUA, Alemanha e Polônia), os menores valores de ativação de ar-condicionado foram identificados no Brasil, indicando que há um grande potencial de ajuste para economia de energia, dado que pessoas em climas mais quentes como Singapura, se adaptaram a maiores temperaturas. No estudo de campo apresentado no artigo 5, a temperatura de ativação padrão era 23 °C, porém, verificou-se que de fato a temperaturas interna média era 24 °C. Após a disponibilização dos ventiladores, foi testado o aumento da temperatura de ativação a até 27 °C. Entretanto foram recebidas muitas queixas e foi necessário voltar à temperatura padrão por quatro dias antes que valores mais altos pudessem ser testados novamente. Após análise dos resultados, identificou-se que isso ocorreu por uma incapacidade do sistema de climatização em manter a temperatura definida, e grande influência da temperatura interna que aumento no período de intervenção. Ainda assim, os participantes gostaram dos ventiladores e o número de votos de preferência por não mudar a condição interna aumentou em 20 pontos percentuais com os ventiladores. Isso ocorreu a uma temperatura do ar interna média 1 °C acima do período sem ventiladores. Isso é, a pessoas preferiram 25 °C com ventiladores à 24 °C. Apesar disso, estudos anteriores indicaram 26 °C como valor limite, o que indica que talvez fosse possível atingir 2 °C sob outras circunstâncias. De todas as formas, estes valores encontrados em campo são inferiores aos limites indicados por simulação (30 °C). Com base neste experimento e estudos anteriores, as diretrizes propostas são: envolver os operadores no processo de intervenção; diagnosticar o funcionamento do sistema antes de qualquer intervenção; explicar aos ocupantes o benefício e como a intervenção será feita; após a disponibilização dos ventiladores, mudar a temperatura do ar-condicionado gradualmente, esperando mais de 2 semanas entre modificações. As análises indicaram que o limite de extensão aplicável pode ser definido pelo 90° percentil das temperaturas pré-intervenção, pois este é um limite a que os ocupantes estão acostumados. Será importante validar este conceito em estudos futuros de maior duração. Também é importante que trabalhos futuros tentem definir o intervalo mínimo de adaptação dos ocupantes a mudanças de temperatura para facilitar aplicações práticas.

Considerações Finais

Este trabalho abordou os potenciais e barreiras de uso dos PCS. Algumas barreiras podem ser superadas facilmente, como a falta de conhecimento sobre o potencial desses sistemas, que pode ser superada com a divulgação de estudos como este. Além disso, foi verificado que ao serem exposto à opção de usar ventiladores de mesa as pessoas tendem a apreciar seu efeito. Por isso, mais aplicações em campo podem ser vantajosas. Outra barreira se relaciona com a qualidade e custo dos ventiladores disponíveis no mercado. Seria benéfico que houvesse opções com resfriamento evaporativo a valores mais acessíveis. Porém, há produtos disponíveis no mercado, com preços e potência energética baixas que já seriam aplicáveis e vantajoso para ambientes de escritório existentes. Para auxiliar neste processo são necessárias diretrizes e normativas que auxiliem os operadores a incorporarem estas estratégias nas edificações. Algumas delas foram apresentadas neste trabalho, mas há demanda para mais estudos que se aprofundem na adaptação dos ocupantes a estas intervenções e delimitem melhor o tempo de cada processo.

Palavras-chave: conforto térmico, sistemas pessoais de condicionamento, ventiladores de mesa, escritórios, Brasil.

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ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers (in England)
HVAC	Heating, Ventilation and Air-Conditioning
NZEB	Near-Zero Energy Building
PCS	Personal Conditioning Systems

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1 INTRODUCTION

The perspective of global warming drives nations to adopt strategies to reduce greenhouse gas emissions and therefore energy demand, which is the main responsible for the emissions (IEA, 2019). Building in Brazil accounts for more than 50 % of electricity consumption (EPE, 2020), and in commercial buildings, most of this energy is used for cooling the spaces (ELETROBRAS; PROCEL, 2007). In addition to HVAC purchase growth, air conditioning demand is expected to increase as global temperatures increase (IEA, 2018). Therefore, innovative and intelligent solutions should be used to face upcoming events. The first possible modification is changing the assumption that indoor spaces need to be uniformly conditioned to a single temperature Melikov (2016). Great opportunities for energy savings are achieved by conditioning the occupancy zone while room temperature can be relaxed (SCHIAVON; MELIKOV; SEKHAR, 2010). As a consequence of the variation in preferences, a single temperature hardly pleases the majority of the occupants of an environment (ANTONIADOU; PAPADOPOULOS, 2017; DE DEAR *et al.*, 2013; VERHAART; LI; ZEILER, 2018). Thus, conditioning environments at very tight temperatures tend to waste energy and not satisfy occupants.

Hoyt et al. (2015) show that extending the setpoint temperature can generate up to 80 % energy savings depending on the local climate. To maintain occupants' thermal comfort, the authors suggest the use of personal conditioning systems (PCS). PCS generate a non-uniform environment in which, due to local control, each occupant can adjust their local thermal environment within a space (BRAGER; ZHANG; ARENS, 2015). In addition to meeting users' demands, PCS would allow the environment to be maintained at broader temperature ranges, as fine-tuning or intensification of cold/heat is locally available. The increased perception of control has also a psychological effect, intensifying occupants' thermal satisfaction (BOERSTRA *et al.*, 2015; LUO *et al.*, 2016). Besides, Sekhar et al. (2005) show that the workstation microclimate prevails over occupants' thermal comfort in comparison to room temperature. Therefore, PCS can maintain occupants' comfort under a non-optimal environment temperature.

Based on the alliesthesia principle the potential savings of PCS could be even greater. Alliesthesia shows thermal pleasure is only achieved by thermal variation close to the skin (DE DEAR, 2011). Therefore, the impulses produced by PCS should not be constant (PARKINSON; DE DEAR, 2016), and consequently supply power oscillation can be beneficial. Punctual stimuli have proven to effectively change the whole body's thermal sensation if applied in the right spots of the body (ZHANG, H. *et al.*, 2010a; ZHANG, Y.; ZHAO, 2008). Some points of the body have a higher concentration of cold or heat thermoreceptors, and when spotted by a stimulus transmit a message to the brain that generates a global effect (DE DEAR, 2011). Thus, it is possible to generate thermal comfort with low-power devices, as they do not need to affect the whole body, only a few strategic points. However, the application of these concepts is still incipient, and many PCS are developed by universities and are not market available. Individual fans, on the other hand, are one of the most efficient PCS for warm climates (WARTHMANN *et al.*, 2018) and are ready-to-use products. They are also easy to implement, showing low impact on workspace and building infrastructure.

Nevertheless, their use is still not common in office spaces in Brazil. One of the reasons may be the lack of knowledge about PCS potential. In addition, occupants' willingness to use them can be a barrier as air-conditioning is preferred. Although previous field studies indicate that Brazilian occupants tend to prefer higher air velocities regardless of the room conditioning mode (CANDIDO *et al.*, 2010a; DE VECCHI *et al.*, 2017). The availability of desk fans was found not to be enough to change users' behavior regarding the use of air-conditioning (ANDRÉ, 2019; ANDRÉ; DE VECCHI; LAMBERTS, 2020). In shared workspaces, occupants cannot easily adjust the cooling setpoint to their individual preferences as their colleagues are affected (HE, Y. *et al.*, 2018; LI; MENASSA; KAMAT, 2017b). To solve this problem, many studies suggest the temperature should be automatically controlled based on personal thermal comfort models (JIANG; YAO, 2016; KOSTIAINEN *et al.*, 2008; PANTELIC; RAPHAEL; THAM, 2012; WANG *et al.*, 2018; XU *et al.*, 2017). These models employ machine learning fed with a small set of occupants' votes to predict their preferences (KIM; SCHIAVON; BRAGER, 2018). Nevertheless, the development of these models is time-consuming, and their application depends on the available controls, technology, and further definition of algorithms that would correlate each personal model to define a unified temperature adjustment. This means that the application of these solutions is complex and depends on a technological development level that might not be the standard for Brazilian buildings.

Therefore, the definition of how much setpoint temperature could be extended and how to apply this extension is an important barrier to using PCS for increasing comfort and saving energy. Although the setpoint temperature extension depends on the local climate, the greater the dead band the greater the energy savings, regardless of the climate (HOYT; ARENS; ZHANG, 2015). Most studies with PCS are carried out in climate chambers and indicate the temperature extension for warm climate conditions to be between 30 °C and 35 °C (WARTHMANN *et al.*, 2018). However, studies in real office spaces show maximum acceptability with fans to be between 27 °C and 28 °C, while the preferred temperature is usually 26 °C (GOTO *et al.*, 2007; LIPCZYNSKA; SCHIAVON; GRAHAM, 2018; SHETTY *et al.*, 2016). That shows the real-life temperature limits are lower than the ones identified in controlled experiments, and other methods are needed to define these limits. The adaptive thermal comfort model is based on field data and includes the use of fans as an adaptive strategy (DE DEAR; BRAGER, 1998a; INDRAGANTI; OOKA; RIJAL, 2015) could be a suitable method. However, this model is mainly applicable to naturally ventilated spaces as in conditioned spaces a low correlation between indoor and outdoor conditions is observed (DE DEAR; BRAGER, 1998b). Therefore, more studies are needed to discuss occupants' acceptability, temperature limits, and procedures for PCS application.

For the exposed reasons, this thesis aims to identify best practices for implementing personal conditioning systems in open offices in Brazil. To achieve that, some objectives are defined:

a) Identify the main proposed methods and challenges in the literature for implementing personal conditioning systems.
b) Verify which characteristics users find important for selecting a personal fan and select the best available device.
c) Understand usual setpoint temperatures, control, and procedures used in buildings with central conditioning systems.
d) Identify the potential temperature extension in Brazilian climates when desk fans are available.
e) Implement desk fans in an open office to identify acceptable temperature extension in a real space.
f) Propose guidelines for optimal implementation of PCS in open offices to increase occupants' thermal comfort saving energy.

1.1 REPORT STRUCTURE

This thesis is structured around 5 papers published or that will be submitted to international journals. The correlation between the publications is depicted in Figure 1. Each paper presents a different aspect and meets one of the proposed objectives, except the fifth which meets the last two objectives (e and f). The fifth paper presents a tentative application of the knowledge gathered in the previous ones to finally fulfill the thesis aim.

Figure 1 – Relationship between the thesis' papers

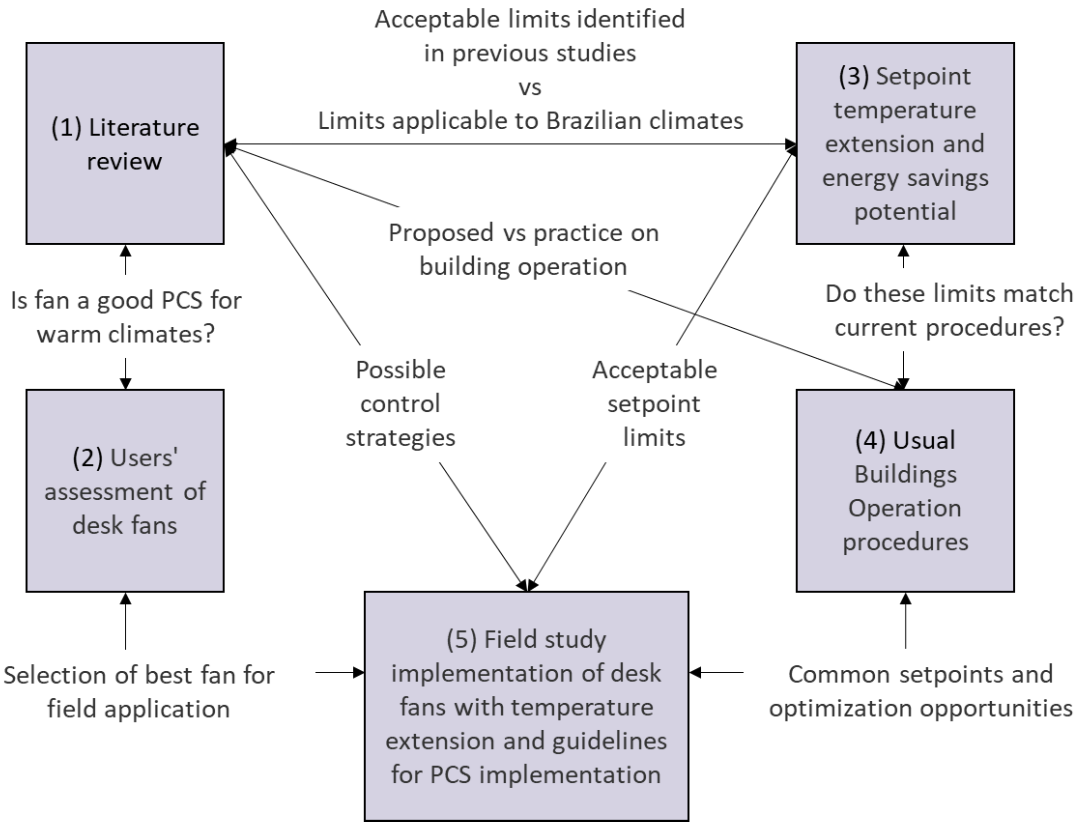


Figure 1 shows the five papers that compose this thesis and address the following topics: (1) literature review; (2) users' assessment of personal fans; (3) setpoint temperature extension and energy savings potential; (4) usual buildings operation procedures; and (5) field study implementation of desk fans with temperature extension and proposition of guidelines. The literature review (1) brings a state-of-the-art on personal conditioning systems (PCS) implementation based on articles published between 2017 and 2019. Paper (1) helped to understand the gaps in the topic and to define the method of the thesis and the following papers. One discussion topic of paper (1) was the selection of PCS, which confirmed fans would be an efficient option for Brazilian climates. Based on that, in paper (2) a human subject experiment was carried out to compare market available fans. The selected products were later used in the field application presented on paper (5). In addition to how to select the PCS, the other main question identified in the literature review relates to the definition of possible temperature extension. Therefore, paper (3) explores the climate adaptation point of view based on building performance simulation. Indoor temperatures were analyzed based on the adaptive model and overheating risk to identify suitable maximum temperatures for Florianopolis, Brasilia, Fortaleza, and Manaus. The simulations considered the use of low-power fans in office spaces associated with mixed-mode operation. The results were expected to be comparable to previous studies from paper (1), to usual values from paper (4), and applicable values from the field experiment of paper (5). In addition, by identifying common setpoints in real buildings in Brazil and other countries, paper (4) helped to verify the potential for real-life extension. Paper (4) also helped to identify the system’s controllability capacity for applying some control strategies identified in paper (1) and operators’ point of view about the use of PCS. These strategies were considered for field implementation on paper (5), to test the best approaches and equipment identified in previous papers. Finally, based on the field experience, paper (5) presents guidelines for the optimal implementation of PCS.

The next section presents each paper, indicating publication information, objective, method, and main results related to the thesis. The full papers are attached as appendices at the end of the thesis, as well as additional data. After presenting the papers, their outcomes are discussed in the discussion section and the main thesis results are synthesized in the conclusion. The conclusion also includes limitations and suggestions for future research.

2 ARTICLES PRESENTATION

This section presents each of the five articles included in this thesis.

2.1 LITERATURE REVIEW

This paper, entitled “User-centered environmental control: a review of current findings on personal conditioning systems and personal comfort models” aims at presenting a literature review of personal conditioning systems implementations. The review focuses on two main questions. How can the optimal temperature limits in an existing space be defined? Which would be the best type of PCS for a specific space? This paper was published in 2020 and its full version is presented in APPENDIX A. The following sections present the study method and main results relevant to this thesis.

2.1.1 Method

The search was performed on the Scopus platform using the following keywords: thermal AND comfort AND personal AND (system OR conditioning). The analysis period was limited between 2017 to 2019 (as the review was finished in early 2020) which showed an increase in the number of publications and included many reviews of papers from previous years. The publications in English, excluding book chapters and conference reviews, resulted in 398 papers. Those papers passed through a screening process resulting in the selection of 113 articles relevant to the subject. In addition to personal conditioning systems, personal comfort models were the second main theme of the publications. Therefore, the review was organized into three sections to synthesize the information about i) Association of personal conditioning systems to personal comfort models; ii) Personal Models and automation; iii) Selection of personal conditioning systems.

2.1.2 Main Results

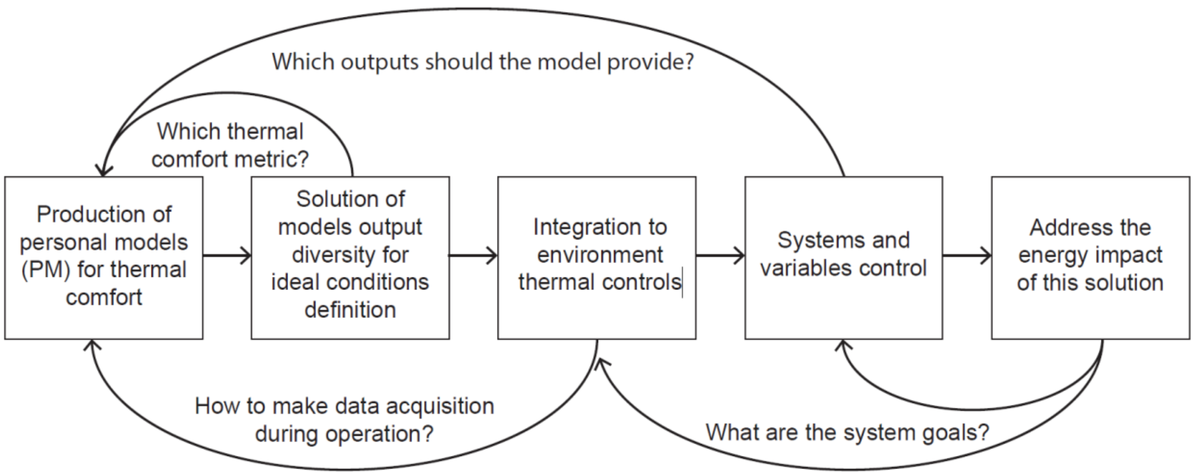
As mentioned before, there is a strong link between personal comfort models and personal conditioning systems (PCS). The main reason is that personal comfort models would be more suitable for predicting occupants’ thermal comfort in existing buildings, especially when PCS are available (KIM; SCHIAVON; BRAGER, 2018). Although the use of personal conditioning systems allows local and individual adjustment of environmental variables, PCS are more often used as a complementary system (MELIKOV, 2016), therefore the room temperature in shared spaces still needs to be defined. The room temperature extension can generate a great amount of energy savings (HOYT; ARENS; ZHANG, 2015) so defining the maximum extension is very important. However, occupants present great inter-individual (among occupants) and intra-individual (through time) thermal preference variations (WANG *et al.*, 2018), which generalized models like the adaptive and PMV-PPD cannot predict (HE, M. *et al.*, 2017; MISHRA; LOOMANS; HENSEN, 2016; SHETTY *et al.*, 2016). Personal comfort models, on the other hand, are developed based on feedback from one occupant's thermal perception associated with environmental variables, therefore can consider those variations (KIM; SCHIAVON; BRAGER, 2018). Initially gathered data is used to create prediction models applying machine learning technics. Therefore, these models could be used to automatically adjust the room setpoint temperature accurately, adjusted to a given group of occupants and varying through time and season (KIM; SCHIAVON; BRAGER, 2018). In addition, the use of PCS could be considered and included if available during the data-gathering phase, so broader setpoints would be applicable (DU *et al.*, 2019; SHETTY *et al.*, 2019; TANAKA *et al.*, 2019).

Although most of the reviewed studies indicate the goal of personal comfort model (PCM) development is HVAC control automation, few of them explain exactly how to achieve that. Fewer validate the strategy in an operating space. Figure 2 presents a flux of questions that need to be answered for applying PCM. The first point is on how to integrate the results from individual prediction models into a unified temperature. The main strategies consider is based on median votes with an adjustment interval (CHAUDHURI *et al.*, 2019; JIANG *et al.*, 2017; JUNG; JAZIZADEH, 2019; ZANG; XING; TAN, 2019). A tentative to reach consensus (KIM *et al.*, 2018) or majority (LI; MENASSA; KAMAT, 2017a, 2017b), but it is more time demanding and difficult to implement. The main controlled variable is the setpoint temperature, but some studies propose the automation of PCS to guarantee broader temperature conditions acceptance (KALAIMANI *et al.*, 2018; LIU *et al.*, 2018; SHETTY *et al.*, 2019; XU *et al.*, 2017). However, that can hinder occupants' perception of control (SHETTY *et al.*, 2016), which negatively affects their thermal satisfaction (BOERSTRA *et al.*, 2015). In addition, the system requirements, and features necessary to implement this type of automation, based on a prediction model, are not addressed in the reviewed articles. Some of them propose an additional prediction algorithm for energy consumption consideration

(CHAUDHURI *et al.*, 2019; KALAIMANI *et al.*, 2018; XU *et al.*, 2017). In this case, one algorithm would find a common setpoint among all occupants' personal models and consider the energy consumption prediction input. These layers increase the complexity of automation control and time demand for data collection and prediction.

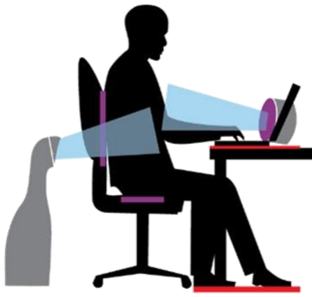
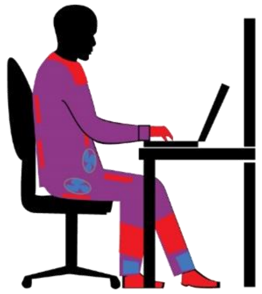
Another discussion presented in the review is about the thermal perception scales used in personal comfort models. A great variation was found in levels, terms, and distribution. However, 3-level preference scale is recommended for PCM (KIM; SCHIAVON; BRAGER, 2018).

Figure 2 – Application of personal comfort models for system automation



The limits of temperature extension vary by type of PCS as each type has a different potential to maintain or increase users' thermal comfort (ZHANG, H.; ARENS; ZHAI, 2015). Therefore, their selection can have a great impact on energy savings. Numerous types of PCS were found in the literature and a trend is observed going from fixed solutions to portables and wearables, as illustrated in Figure 2. Wearable solutions present great advantages in terms of reducing energy demand because they can be continuously and directly in contact with the skin, so they maintain the stimuli when a person is moving around. However, the challenges related to connecting wearables to room setpoint temperature control are greater. In a workspace where wearable PCS are part of the conditioning strategy, the employer or building owner would need to provide them to all employees and require their use all the time. On the other hand, portable equipment would not affect occupants' clothing and be easily connected physically to a network if necessary. The possibility to freely position portable PCS on a workstation is an advantage from a controllability point of view. Targeting specific points on the body with greater sensitivity to cold or heat can intensify the overall effect (ZHANG, H. *et al.*, 2010a, 2010b). However, the user will be responsible for choosing the affected area, therefore the effects are less predictable. Overall, if users are aware of the equipment's effect on multiple body parts, portable PCS can be easier to implement and more adjustable than wearable PCS.

Table 1 – Personal Conditioning Systems Classification - color scale: blue=cooling, red=heating, purple = both

Fixed	Portable	Wearables
		

Another benefit of portable PCS is that they have low impact on the building infrastructure. Convective PCS are predominant among the reviewed articles. Desk fans are a portable version of convection equipment, allowing the control of air movement with low energy demand. Desk fans can produce up to 2.3 m/s with 2 W, being considered the most efficient cooling PCS (HE, M. *et al.*, 2017; LUO *et al.*, 2018a; WARTHMANN *et al.*, 2018). This indicates this type of PCS would be a good fit for Brazilian warm climates, especially at workspaces, where occupants tend to stay at their workstations most of the time.

2.2 USERS' ASSESSMENT OF DESK FANS

This paper, entitled "Users' Assessment of Personal Fans in a Warm Office Space in Brazil" aimed at identifying the aspect users find most relevant for selecting fans. In addition, user ranking of some Brazilian available equipment was used to select the best fans for the field implementation. This paper was published in 2021 and its full version is included in APPENDIX B.

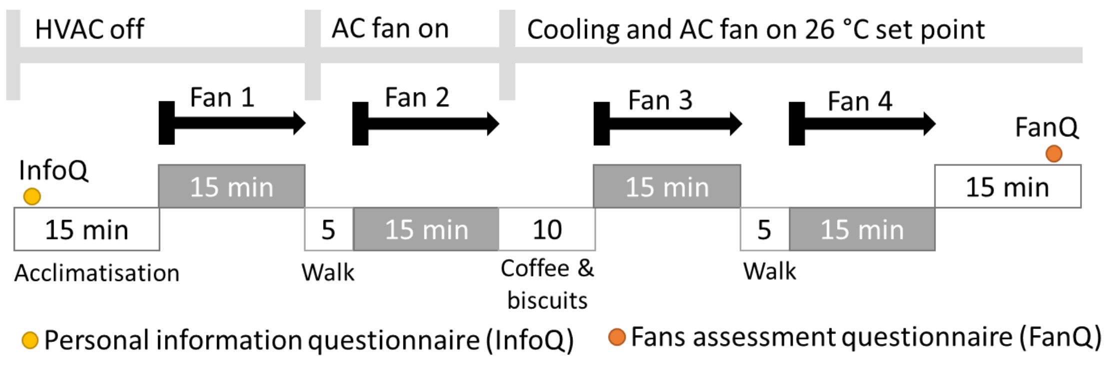
The following sections present the study method and main results relevant to this thesis.

2.2.1 Method

This study is based on a human subject experiment carried out in the Laboratory for Energy Efficiency in Buildings of the University of Santa Catarina, in Florianopolis. The city is in the southeast of Brazil with a climate classified as subtropical by Köppen-Geiger (PEEL; FINLAYSON; MCMAHON, 2007) and as 2A by ASHRAE 169 (2020a). The experiment was conducted between late February and early March 2020, to include higher outdoor air temperatures. In this period, 10 sections were performed with 40 participants. The room layout was set so four people could work at the same time using laptops.

Figure 3 summarizes the procedures in each section. The experiment started with participants entering the room, opening the laptops, and answering the personal information questionnaire (InfoQ in Figure 3). While acclimatizing to a warm environment, participants received instructions on the experiment procedure. After 15 minutes they received the first fan and tested it for 15 minutes. There was an interval of 5 or 10 minutes between testing each fan, to reduce the influence of continuous use. During this interval, participants walked through the building or stayed outside the test room having coffee and food. After testing all four fans, they filled in the assessment questionnaire (FanQ in Figure 3) to rank fans' characteristics and indicate which device they prefer. The preferred fan was asked three times, at the beginning of the questionnaire, and at the end before and after disclosing their prices. The four equipment tested presented different aesthetics, control capabilities, sizes, and power. One of them, option d, had a water tank providing evaporative cooling. All questionnaires' questions are presented in APPENDIX C.

Figure 3 - Experiment procedure



To reduce bias, each section included men and women under different age groups and a random order of fans. All participants tested the fan at the time. The sections happened in the morning and afternoon. The cooling system (HVAC) was used with different settings to account for its influence on fan use, simulating a dead band (HVAC off), outdoor air circulation (AC fan on), and cooling activation with extended setpoint (AC on at 26 °C). Indoor air temperature varied from 26.9 °C to 29.3 °C and relative humidity from 60 % to 70 % among all sections, the average condition was 28 °C and 70 %.

2.2.2 Main Results

This experiment brings three important outcomes to this thesis. The first is identifying the most important aspect of fan selection. Figure 4 shows how users ranked aspects for a purchase selection. Thermal and acoustical aspects are the most important. However, the maximum speed the fan can reach was considered secondary and ranked below the financial and functional aspects.

Figure 4 – Aspect raking for desk fans purchase selection

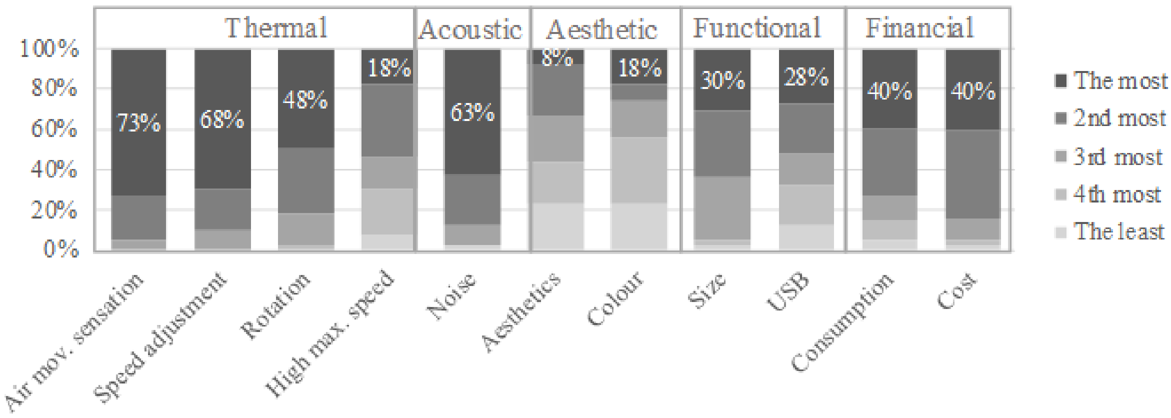
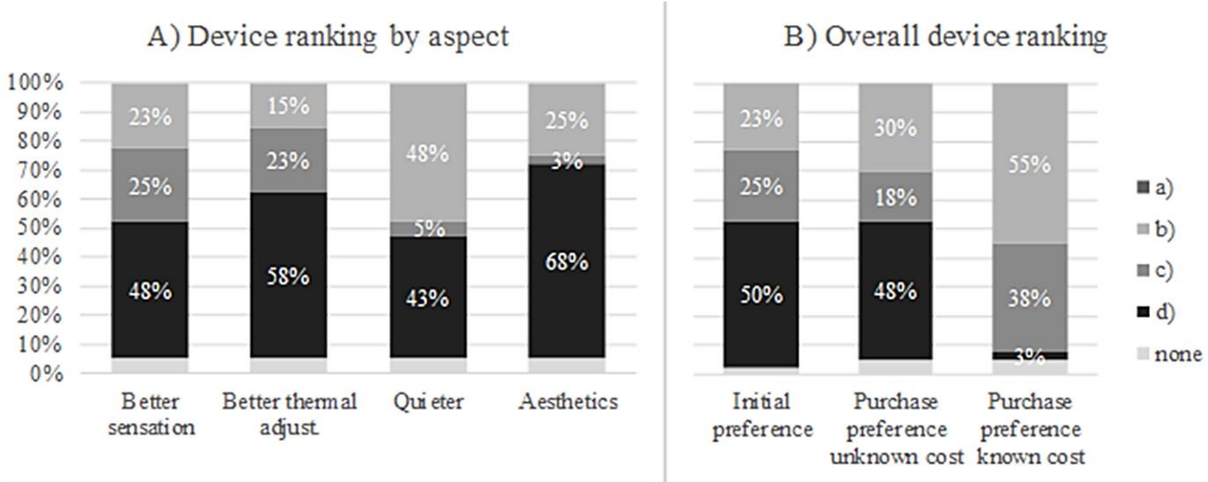


Figure 4 shows the most important aspect is the air movement sensation. Figure 5A shows the evaporative cooler – option d – was perceived as the best regarding this aspect. Some participants commented that they felt option d had smoother air flow. In addition, option d was rated to have greater adjustability, probably because it includes 23 air speed levels. Option d has also the best aesthetics, but this is a less important selection factor (see Figure 4).

Figure 5 – Equipment ranking



Therefore, option d was preferred by 50 % of participants initially and before price discloser. After disclosing the costs, only one person was willing to purchase option d. Table 2 shows the price of each option and that option d was 40 times more expensive than option b. Option b received more votes and c got second place. Although these two options were ranked similarly at the beginning (23 % and 25 %), more participants would buy option b than option c at the end (55 % and 38 %, respectively). This means participants found option d was not cost-effective. Further analysis of the votes showed younger people (20-30 years old) and women preferred option b while older people (older than 50) preferred option c and men in general had split opinions about options b and c. Therefore, both are good options depending on the user characteristics.

Table 2 – Assessed equipment cost in dollars

			
a) $ 6.12	b) $ 8.45	c) $ 11.00	d) $ 367.33

Regarding participants' willingness to use a desk fan in workspaces, an interesting result was found comparing the pre- and post-preferences to this experiment. Before the experiment, 45 % of participants indicated preferring to work in a conditioned environment while 23 % indicated preferring to work in a naturally ventilated space with desk fans. However, after the experiment, 25 % of participants indicated to prefer working in a cooled space with desk fans and 38 % indicated preferring a naturally ventilated space with desk fans. Therefore, most participants (63 %) after this experiment would like to have a desk fan in their workspace. This result indicates that the opportunity to use a desk fan in the office environment may motivate occupants to use it, even if they initially indicate a low predisposition.

2.3 SETPOINT TEMPERATURE EXTENSION AND ENERGY SAVINGS POTENTIAL

This paper, entitled “Achieving mid-rise NZEB offices in Brazilian urban centers: a control strategy with desk fans and extension of set point temperature” aimed at identifying the energy savings potential of associating mixed mode to desk fans in office buildings located in different Brazilian climates. The impact of this strategy on the classification of near-zero building and energy-positive energy were also assessed but will not be addressed in this thesis as they are less relevant. For this thesis, the most relevant results are the setpoint extension limits and fans’ impact on thermal comfort and building consumption. This paper was published in 2022 and its full version is available in APPENDIX D. The following sections present the study method and the most relevant results.

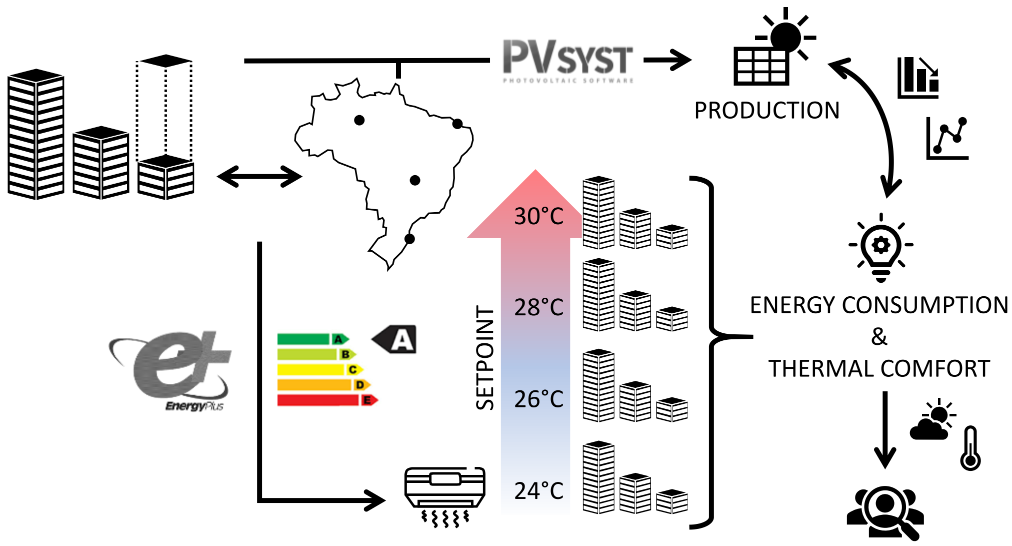
2.3.1 Method

This study is based on building performance simulation and the procedures are synthesized in 6. The reference buildings have open plans, 3 heights, and are in four Brazilian cities. The simulation baseline mode is fully conditioned with a 24 °C setpoint. The tested strategy was mixed mode, which means alternating between natural ventilation and air-conditioning according to the setpoint, and that was associated with the use of one desk fan per person. Desk fans had 3 W each. The mixed mode setpoint – cooling activation and windows closing – was 26 °C, 28 °C, and 30 °C. In all scenarios, desk fans activated when the indoor operative temperature exceeded 26 °C.

The simulation outputs were the building energy consumption, total and by end-uses, and indoor operative temperatures, used to predict occupants’ thermal comfort. The adaptive model (ASHRAE, 2020b) was applied to predict thermal comfort. In addition, the overheating risk was assessed by applying a method proposed by CIBSE (2013), which suggests that temperatures 1 °C above the adaptive model limit should occur in less than 3 % of occupancy hours.

The simulated buildings' envelope and systems had high efficiency based on the Brazilian building energy labeling system. The conditioning system was split with inverter, which is more common in Brazil in small to mid-size offices. The selected cities were Florianopolis and Brasilia in climate 2A; and, Manaus and Fortaleza, in 0A climate (ASHRAE, 2020a).

6 – Method overview



2.3.2 Main Results

Initial comparison between buildings with different heights indicated small differences in energy consumption by square meter, therefore, the average values were used for further analysis. Figure 7 shows the average annual energy savings related to the baseline – fully conditioned building at 24 °C. Figure 7 compares the total building energy consumption and shows the buildings located in cities in the same climate zone achieve similar savings. Manaus and Fortaleza under climate 0A achieve 20 % to 40 %, while Florianopolis and Brasilia under climate 2A achieve 15 % to 25 % energy savings.

Figure 7 – Total energy saving compared to baseline by setpoint and city

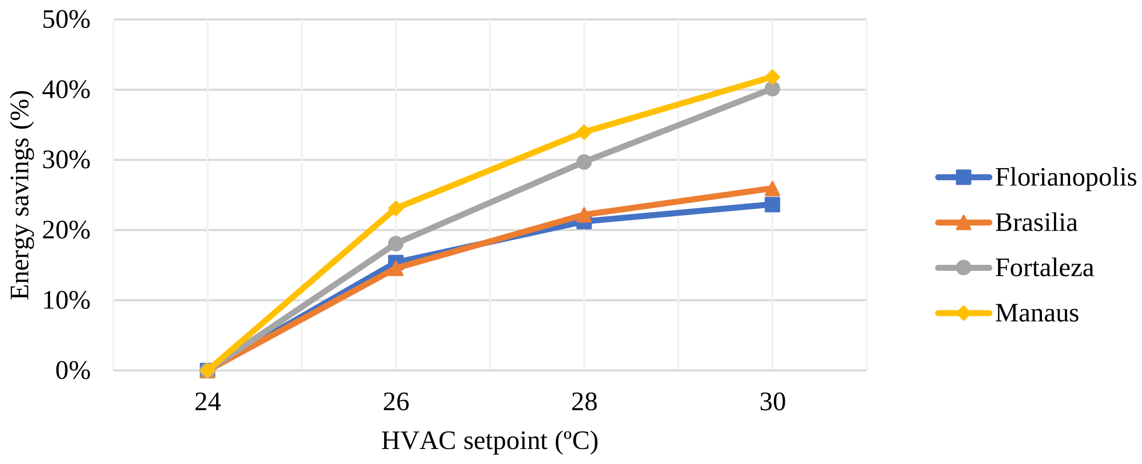
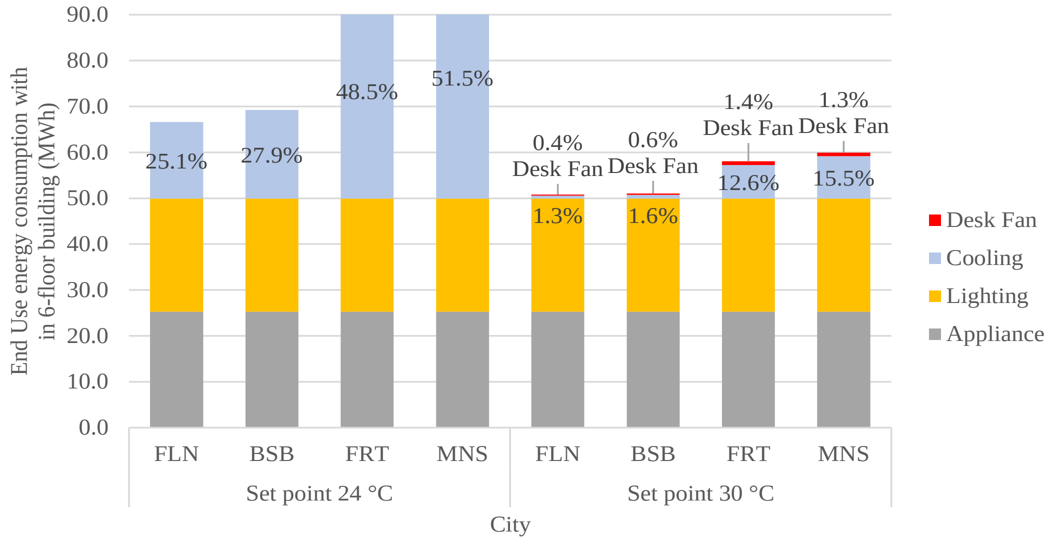


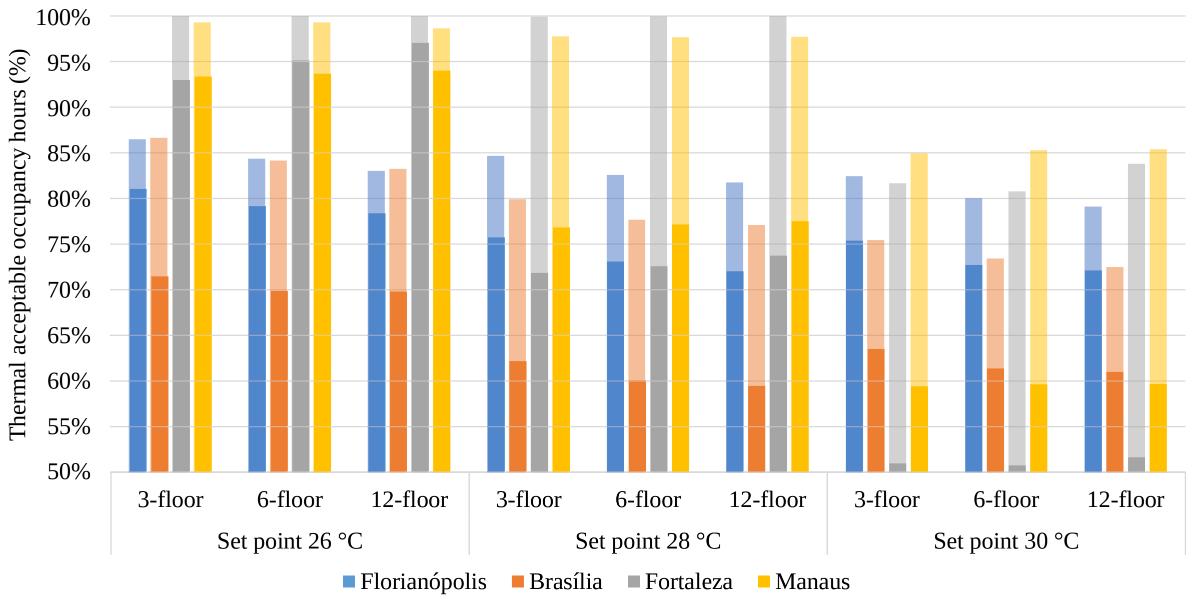
Figure 8 shows these savings are produced by the reduction of cooling (and ventilation) energy consumption. This stems from the cooling being activated in a shorter period because of the alternation to natural ventilation and the increase of the setpoint temperature. With 30 °C the cooling consumption in Florianopolis (FLN) and Brasilia (BSB) is minimum – 1.3 % and 1.6 % of total consumption, respectively. This setpoint results in greater activation of desk fans as indoor temperature is higher than 26 °C for a longer period. Nevertheless, even in this case, Figure 8 shows fans' energy consumption would represent a small proportion of total energy consumption, up to 1.4 %.

Figure 8 – 6-floor building annual energy consumption by end-use with 24 °C and 30 °C setpoint in Florianopolis (FLN), Brasilia (BSB), Fortaleza (FRT), and Manaus (MNS)



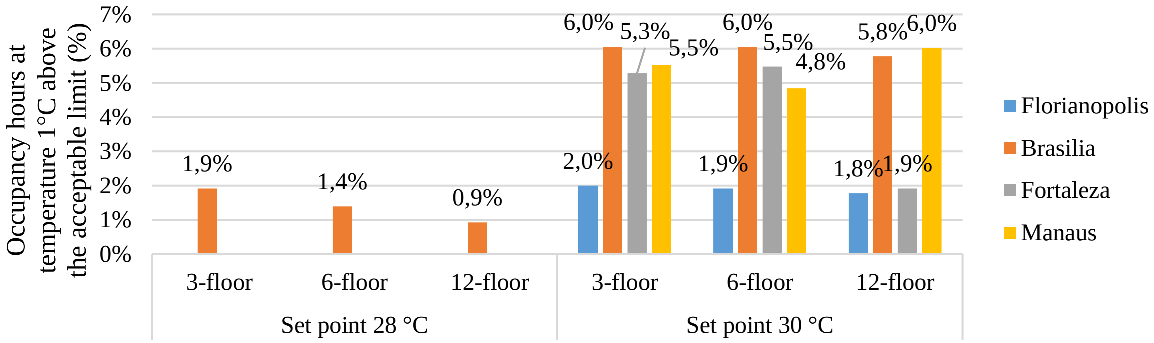
Although the small consumption, desk fans produced a big increase in the percentile of comfortable hours. Figure 9 shows in lighter colors, fans increased by 3 % to 32 % the percentile of acceptable hours depending on the climate and building height. The greatest and lowest increments are observed in Fortaleza. Buildings located in Brasilia are the only ones with annual percentages below 75 % considering fan use. Therefore, fans maintained thermal comfort most of the time in all cities and buildings.

Figure 9 – Percentage of comfortable occupancy – lighter colors indicate the increase generated by fans



In addition, Figure 9 indicates 30 °C setpoint temperature applies to most of the cities and buildings' heights when fans are available. However, Figure 9 does not indicate critical the high temperatures are at times of discomfort. Figure 10 shows adopting a 30 °C setpoint temperature results in more than 3 % of occurrence high temperatures for most of the buildings, therefore, the risk of overheating is high. The exceptions are the buildings located in Florianopolis, that do not achieve the 3 % threshold, as 2 % is the highest value. Additionally, Figure 10 shows 28 °C could generate a low frequency of high temperatures for buildings located in Brasilia. The setpoint of 26 °C does not generate any occurrence of high temperatures at any of the buildings and cities.

Figure 10 – Overheating assessment



Therefore, based on Figure 10 up to 28 °C setpoint applies for Brasilia, Fortaleza, and Manaus, and up to 30 °C applies for Florianopolis in the simulated buildings with mixed mode and desk fans.

2.4 STANDARD BUILDING OPERATION PROCEDURES

This paper, entitled “Practical differences in operating buildings across countries and climate zones: Perspectives of building managers/operators” aimed at identifying regional differences in operators’ decision-making, procedures, and available building control technologies. For this thesis, three topics are the most relevant, especially the information from Brazilian interviewees. The first one is the setpoint temperatures used in buildings, the second is the use of personal conditioning systems in real buildings and the third is the control strategies commonly used. This paper was published in 2023 and its full version is available in APPENDIX E. The following sections present the study method and main results relevant to this thesis.

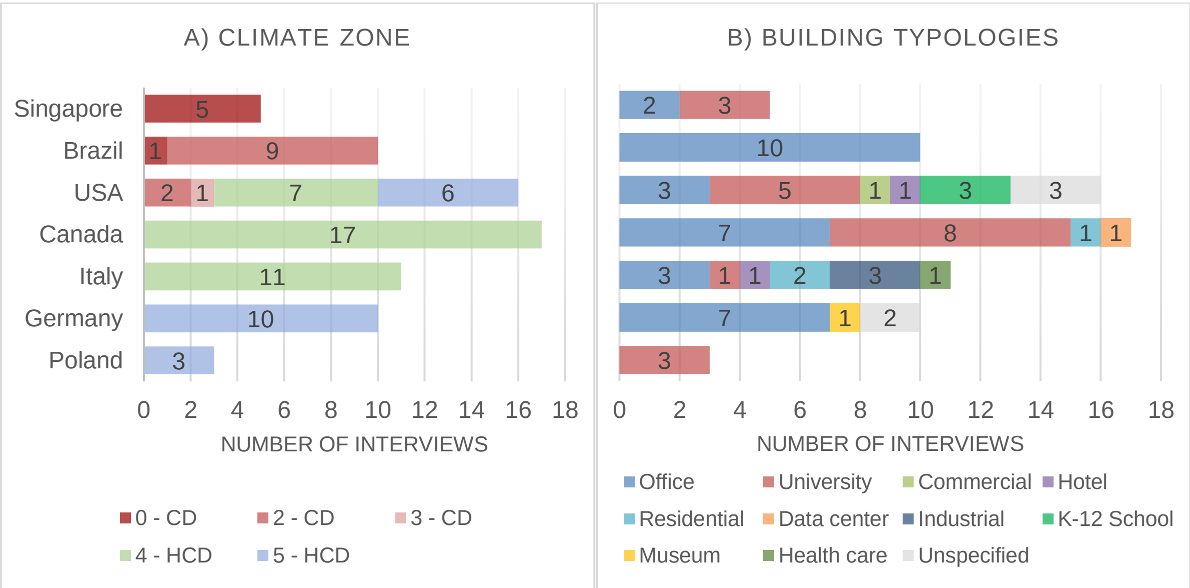
2.4.1 Method

This study is based on interviews with building managers and operators from 7 countries, Germany, Italy, Singapore, Canada, USA, Poland, and Brazil. The interviews were proposed by Professor Michael Kane as an activity of Annex 79 - Occupant-Centric Building Design and Operation of the International Energy Agency. Therefore, the specialist participating in this activity developed the interview script, presented in ANNEX A. The interview script was translated and applied by native-speaker researchers from each country. The answers were recorded and transcribed back into English in a spreadsheet. The data was analyzed in NVivo® software. This software allows categorizing the information into themes by grouping parts of the text. Therefore, the analysis method was thematic analysis associated with cross-case comparison methodology (SOVACOOL; AXSEN; SORRELL, 2018) to understand the influence of climate-related and country-related differences on multiple aspects of building operation procedures and systems.

2.4.2 Main Results

Figure 11 shows the distribution of the 72 interviews by country, climate, and typologies. To answer more specific questions about daily operation procedures we asked the operators to focus on one of the buildings they manage, and those buildings were categorized by typology as indicated in Figure 11B. The climates were classified based on ASHRAE 169 (2020a) and grouped by the predominance of cooling or heating demands. The warmest is 0 and the coolest in the sample is 5. Warmer climates with prevalent cooling-degree days and low heating-degree days (≤ 2000) were classified as "cooling-dominated (CD)", while those with similar heating and cooling-degree days as "heating and cooling dominated" (HCD) (CORY *et al.*, 2011). There are no interviews from heating-dominated climate locations which would be indicated by 6 to 8 climates. Figure 11A shows HCD predominates in the sample and 75 % of the interviews relate to climate 4. Almost half of the interviewees are from Canada and the USA. Most operators and managers gave details about office and university buildings. There are 10 Brazilian responses, and all of them are on office buildings located in climates 0 and 2.

Figure 11 – Sample overview



One of the main aspects expected to be related to climate characteristics in the operation procedures was the cooling and heating setpoint temperatures. The correlation would stem from a climate adaptation, so higher cooling and heating setpoints were expected under warmer climates, while lower cooling and heating setpoints were expected under colder climates. However, Figure 12 shows the opposite for heating setpoints, the most frequent setpoint in climate 4 is lower than the one in climate 5 – 21 °C and 22 °C, respectively. In addition, the cooling range in climates 0 and 4 is the same, while the most recurrent temperature of climate 4 is the same as in climate 2 – 23 °C. On the other hand, Figure 13 shows that countries in the same climates indicate very different setpoints like Italy and Canada. Another important difference is the use of heating in climate 2 in the USA and not in Brazil. Therefore, country-related aspects like economics are suggested to affect the setpoint definition, as energy/cost savings were indicated as one of the operators' main goals. Some operators also indicate these setpoints suited most occupants' comfort, meeting their other main goal, occupants' thermal comfort.

Figure 12 - Setpoint temperature ranges mentioned by operators by climate zone

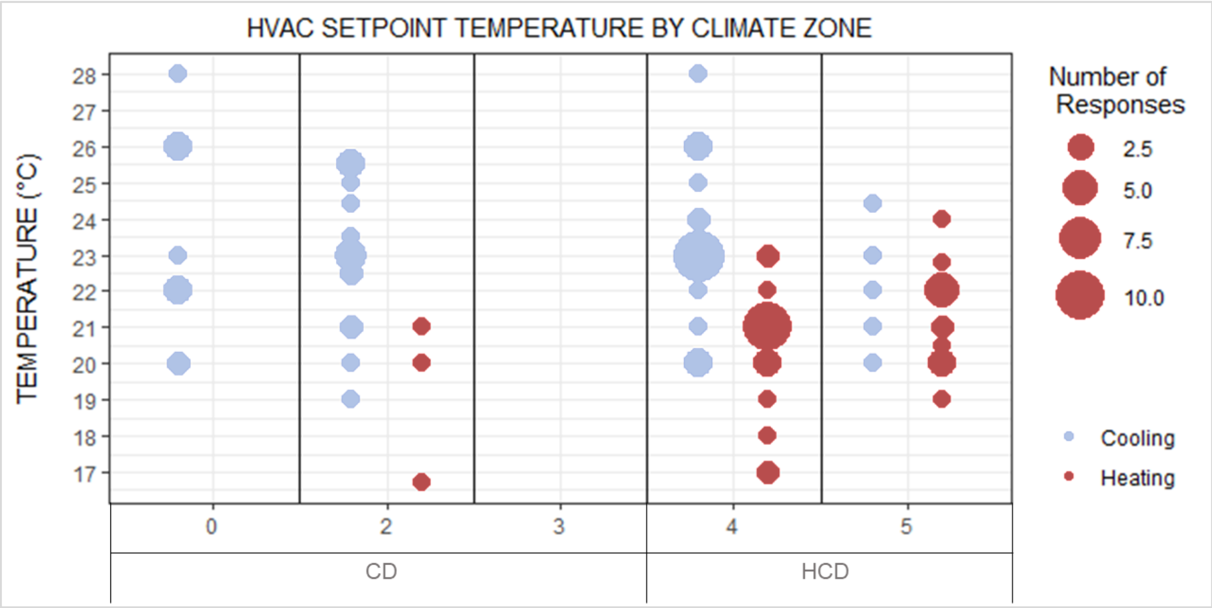


Figure 13 - Setpoint temperature ranges mentioned by operators by country

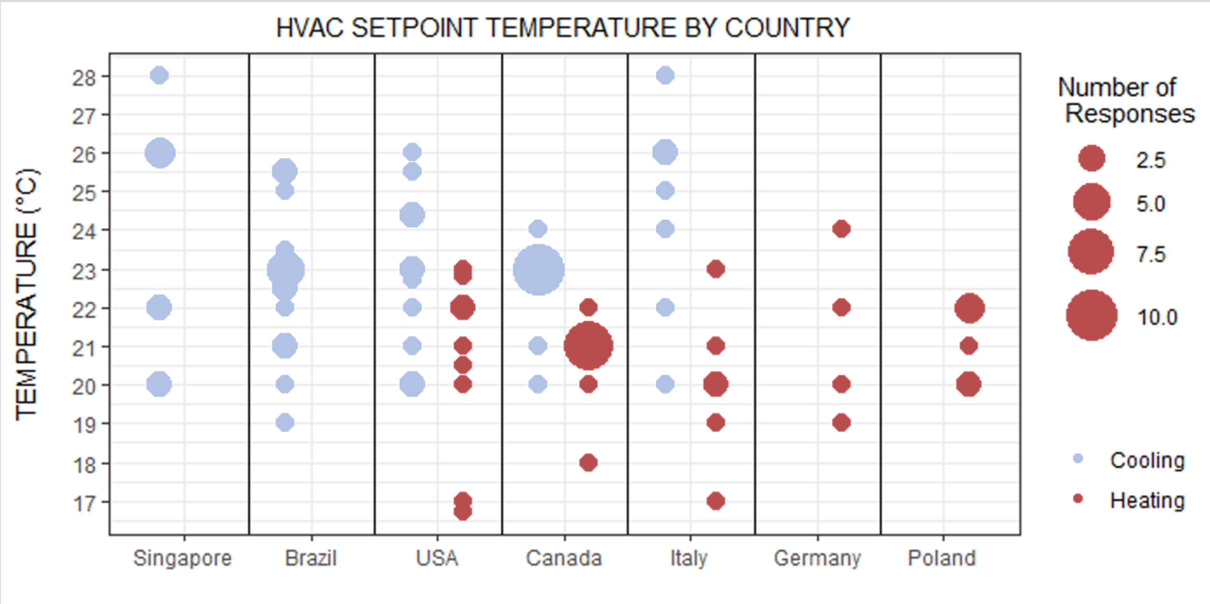
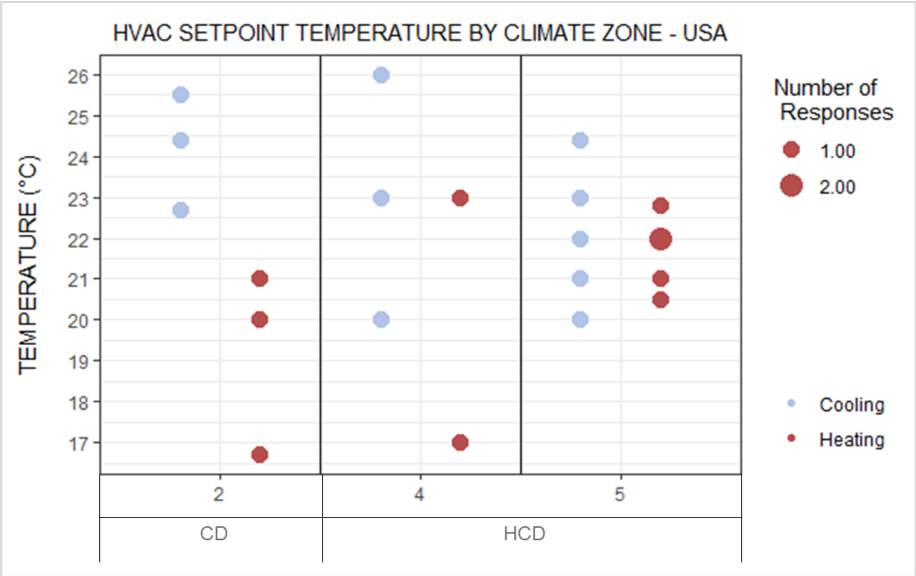


Figure 13 shows the lowest cooling setpoint was indicated in Brazil and the most frequent cooling setpoint was 23 °C, the same as Canada, although the big climatic difference. Conversely, in Italy and Singapore, the most frequent setpoint is 26 °C, which indicates a potential for increasing the Brazilian commonly used setpoints. The analysis of local standards also indicated these values are greatly influenced by regulations. Brazilian standards (ABNT, 2008; ANVISA, 2003) present the lowest cooling temperature range compared to other countries, from 21.5 °C to 25 °C, and the most frequent setpoint is the average of this range. In Italy and Singapore, in contrast, the most indicated setpoint is the upper standard limit (DPR 412/93, 1993; UNI/TS 11300-1, 2014; SINGAPORE STANDARDS COUNCIL, 2016).

Therefore, regulatory, and probably economic factors influence the setpoint differences affecting the expected trend. Even within the same country, which would present more uniform economic and regulatory aspects, setpoints definition do not follow climatic opportunities. Figure 14 shows that in the USA setpoint ranges become closer and overlap in climate 5. This indicates occupants in colder climates have lower adaptability, as heating and cooling are used to maintain a similar temperature range.

Figure 14 - Setpoint temperature ranges mentioned by operators by climate in the USA



Some operators did not indicate any setpoint, mentioning indoor temperatures were automatically controlled based on outdoor conditions. This was most frequent in Germany and the USA. In Brazil, the most frequent control type was the use of fixed setpoints without any or low occupant adjustment opportunities. This fixed control was mainly mentioned in Brazil, although thermostat and setpoint control limitation was predominant in most countries. In other countries, the limitation consists in defining a range within which occupants can vary the temperature. Operators indicated the main reason to restrict occupants' control was the disagreements among occupants.

Operators also indicated restricting the use of personal conditioning systems (PCS), especially heaters. They considered the heater could present safety risks and malfunctioning of the air conditioner. An operator mentioned the use of personal heaters during winter could trigger the cooling setpoint causing energy waste. Both issues are not generated by fans, as they only recirculate air and do not produce cold. This with personal heaters indicates system interconnection limitations.

Around 74 % of sampled buildings included Building Management System (BMS), which could include different controls, sensors, and automation software. The main function mentioned was the automatic control of the central HVAC setpoint and schedule. However, the use of additional sensors like CO_2 and occupancy sensors was more frequent in USA and Canada and not frequent in Brazil. The use of occupancy sensors for HVAC systems control was mentioned in the USA, Canada, and Singapore, but in most cases, they were not connected to the BMS and were used only for lighting automatic activation. That indicates most buildings would not be ready for an implementation of PCS that includes interconnection to the central setpoint definition, as few of them include room sensors for occupancy and additional appliances.

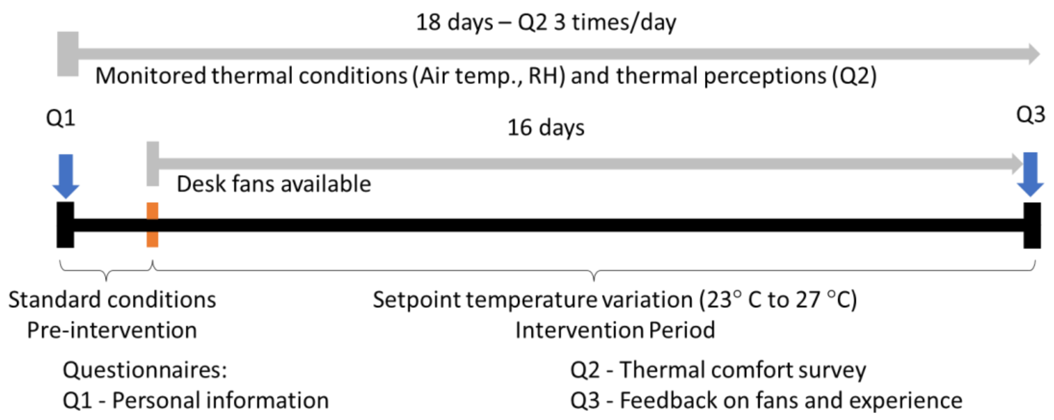
2.5 LESSONS LEARNED AND GUIDELINES FROM AN IMPLEMENTATION OF DESK FANS WITH SETPOINT EXTENSION

This paper, entitled “PCS implementation in open office: guidelines from a field study with desk fans” aimed at presenting the results of field implementation of desk fans in an open office with increment of setpoint and based on the lessons learned to proposed guidelines for PCS implementation. This paper was not published yet but is intended to be submitted in 2023 and its full version is available in APPENDIX F. The following sections present the study method and main results relevant to this thesis. The proposed guidelines are presented in the thesis discussion section.

2.5.1 Method

This study is based on the field implementation of desk fans in an open office located in Florianopolis – climate 2A (ASHRAE, 2020a). The implementation included 34 participants from two areas of the building. The building is fully conditioned by a central chilled water system and each area had a fan coil unit (FCU), although the areas were not enclosed, allowing air exchange. Figure 15 shows a synthesis of the experiment procedures. For 18 days the air temperature and relative humidity (RH) were recorded. Occupants filled out a personal information questionnaire (Q1) on the first day and started filling out the thermal perception questionnaire (Q2) 3 times a day. The first two days were a pre-intervention period; therefore, occupants’ perception was registered under standard operation. On the third day, occupants received desk fans and on the fourth day, the setpoint temperature started to increase. Participants chose fans option b or c tested in the experiment of paper 2 (see Table 2) and two of them received option d. During the intervention period, the setpoint changed from the default 23 °C up to 27 °C. After enough votes were collected, occupants answered the feedback questionnaire (Q3). All questionnaires’ questions are presented in APPENDIX G.

Figure 15 – Experiment procedures



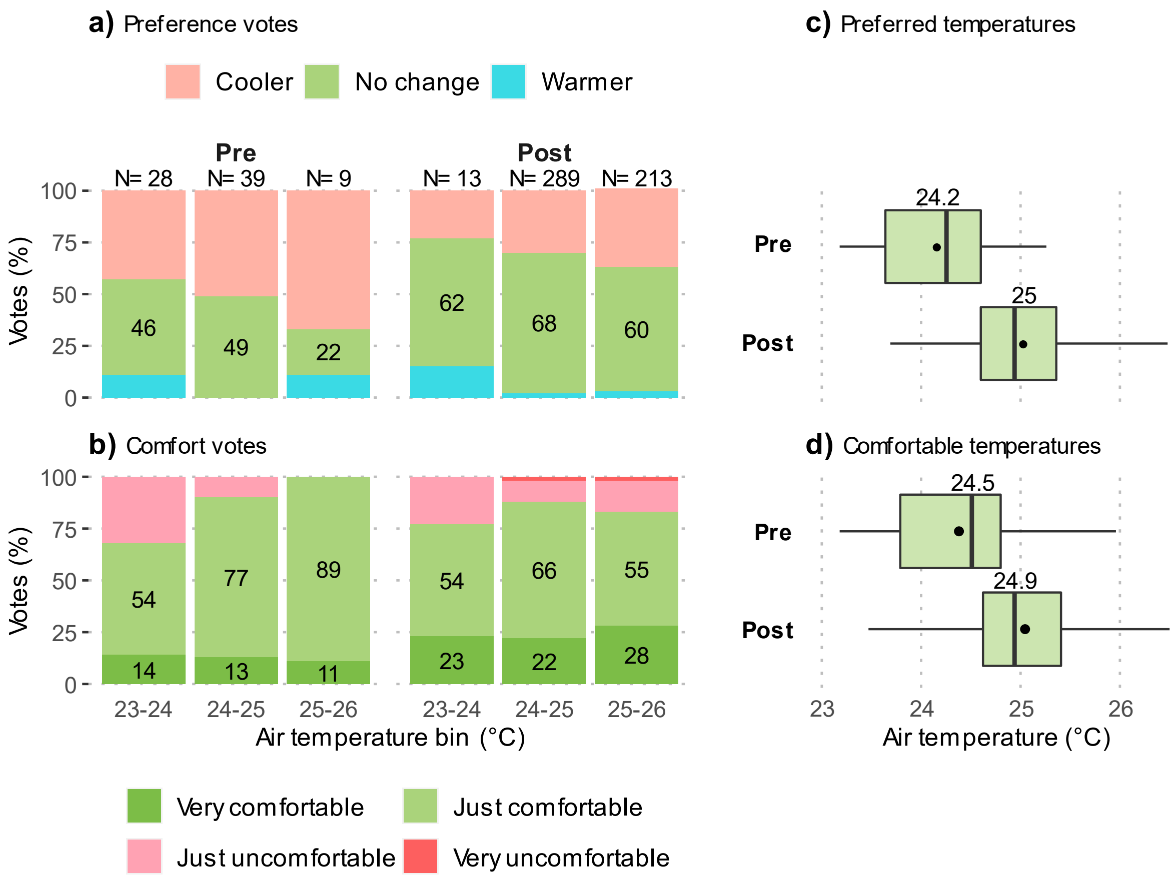
The gathered data was then processed into tables, using Excel and RStudio. Statistical analysis were deployed to evaluate the significance of differences (t-test and multiple regression analysis). The threshold for statistical significance was p-value<0.05. To verify the effect size over the results the Spearman coefficient (rho) was calculated and to compare probabilities size difference, Cliff's delta test was applied.

2.5.2 Main Results

During the experiment, there was a great mismatch between setpoint and indoor air temperature. Although the default setpoint before the intervention was 23 °C, the mean indoor temperature in this period was 24 °C. There was a significant correlation between indoor and outdoor air temperature when outdoor temperature exceeded 24 °C, which was not expected for a conditioned environment. Therefore, the indoor air temperature during the intervention could not be precisely controlled and tended to be higher than the setpoint, especially in the afternoon. The setpoint increased progressively up to 27 °C during the intervention, the mean indoor temperature was 25.2 °C, with 0.8 standard deviation and the maximum temperature was 28.9 °C. The outdoor temperature in the second week of the experiment increased dramatically, causing a greater-than-desired impact on indoor temperature. Consequently, a few occupants indicated to be very uncomfortable and the setpoint temperature returned to default. Further extension was possible after four days when "very uncomfortable votes" disappeared. After that, we tested higher setpoints in the morning when temperature control was more efficient.

Despite this limitation, Figure 16 shows the percentage of “no change” votes increased with desk fans under all indoor temperature bins. In both periods the higher percentage of satisfaction occurs between 24 °C and 25 °C, and fans increased 20% of “no change” votes in this temperature bin. A significant difference is found between mean pre-post preferred temperatures, which were respectively 24.2 °C and 25 °C. The preferred interval (between 25-75%) was 1 °C higher when fans were available. The percentage of very comfortable votes also increased for all temperature bins. However, during the period with fans the percentage of just uncomfortable votes increased for some interval and 2-3 people felt very uncomfortable between 24 °C and 26 °C air temperature. The mean comfortable temperature is significantly different, but the Cliff’s delta indicated the percentage of “no change” shows a large difference (delta=-48) while comfortable votes difference is negligible (delta=-5). Nevertheless, in the last week of the study, the mean indoor temperature was 1 °C higher than the pre-intervention period – 24 °C and 25.2 °C, respectively – and the percentage of comfort was almost the same (~75%). Corroborating the possibility of increasing 1 °C air temperature when desk fans are available.

Figure 16 – Thermal Perception by indoor temperature bin in pre (without fans) and post (with fans) intervention



Different variables were analyzed to identify the main factors that influenced the results. The multiple regression probability analysis indicated mean outdoor air temperature significantly influenced occupants' comfort but was not their thermal preference. In contrast, indoor air temperature was found to influence significantly thermal preference but not thermal comfort. The experiment period (pre or post intervention) was a significant factor to preference and comfort, while fan status (on/off) at answering time was not significant to either. Another important topic is the granularity of control. Although occupants showed varying preferences, individual identifier (ID) did not significantly influenced the probability of preference or comfort. The same was found for the system identifier, FCU1 and 2. Therefore, the same temperature could be applied to both studied areas.

To further understand how discomfort could be avoided in future studies different indicators from the literature related to adaptation and expectation were tested. Table 3 shows all tested indexes and correlation coefficients calculated.

Prevailing mean outdoor air temperature (T_{pma}) is based on the adaptive model (ASHRAE, 2020b). The 80th and 90th upper percentile (Q80, Q90) temperature of the pre-intervention period derive from Peixian et al. (2019) who identified occupants' comfort votes as mainly correlated to the 80th percentile (Q80) of indoor temperature. This means, a broader temperature than the usual range that occurs 80 % of the time, can lead to discomfort. The Q80-2 and Q90-2 are a moving percentile, considering that along the week there could be some adaptation, causing people to accept a new reference value. The D indexes are associated to the magnitude of the change, verifying how the delta temperature from one day impacted the next.

Table 3 – Linear correlation to percentile of comfort and preference votes. The * indicates significant values ($p<0.05$).

Name	Meaning	Correlation to (rho)	
		Comfort	Preference
T_{pma}	Prevailing mean outdoor air temperature	0.48	-0.39
Q80	Freq. T_a higher than 80th value of pre-int.	0.32	-0.27
Q90	Freq. T_a higher than 90th value of pre-int.	0.79*	-0.75*
Q80-2	Freq. T_a higher than 80th value of 2-3 prev. days	-0.4	-0.39
Q90-2	Freq. T_a higher than 90th value of 2-3 prev. days	0.58*	-0.52
D80	Delta 80th T_a of the day before	0.26	-0.13
D_{mean}	Delta mean T_a of the day before	0.19	0.008
D_{max}	Delta maximum T_a of the day before	0.11	-0.11

Table 3 shows that, different from , Peixian et al. (2019), only the 90th percentile (Q90) of the pre-intervention period is significantly correlated to both comfort and preference votes. The Q90-2 is also significant for comfort votes but with a smaller effect size (0.58 in comparison to 0.79). T_{pma} correlation is not significant. The 90th percentile temperature was 25.2 °C, 1.2 °C higher than the mean pre-intervention temperature, which occupants were used to. Therefore, when this usual upper limit was exceeded, occupants' thermal satisfaction decreased significantly. Although the 90th percentile of a pre-intervention period needs further validation, it could be used to limit the temperature extension to avoid occupants' discomfort in future interventions. This result highlights gradual change is beneficial to account for occupants' adaptation period.

Another important outcome relates to the feedback given by participants at the end of the experiment. Before the intervention (in Q1), only 3 participants out of 25 – who answered Q1 and Q3 questionnaires – indicated preferring air conditioning (AC) with fans on hot days. Most of them (13 people) preferred AC without fans. However, after the experiment, 12 people indicated to prefer AC with fans. Similarly to a previous study (ANDRÉ; DE VECCHI; LAMBERTS, 2020), initially occupants did not consider having fans an advantage, but that changed after the experiment. This highlights not only the effectiveness of desk fans as a PCS to meet occupants' demands but also the positive impact of increasing occupants' controllability. Moreover, this pre and post comparison indicates that all occupants should receive a PCS in an intervention because having the opportunity to use the PCS motivated users with low predisposition.

3 DISCUSSION

In this thesis, each of the presented papers addressed a different aspect related to the implementation of personal conditioning systems in shared spaces for optimal thermal comfort and energy efficiency performance. In this section three main aspects are discussed, PCS selection, setpoint temperature limits identification, and the guidelines.

3.1 PCS SELECTION

The review paper (1) presented the multiple types of existing PCS. For better effect, in warm and cold climates, the target body parts, and most effective physical principles are different. For heating, radiant equipment are more common, while for warm environments convective devices are more common (RAWAL *et al.*, 2020; WARTHMANN *et al.*, 2018). For cooling-dominant climates, small fans are the most efficient PCS as they produced high heat loss with low energy demand (HE, M. *et al.*, 2017; LUO *et al.*, 2018b; WARTHMANN *et al.*, 2018). The review (1) discussed the most effective body parts to direct PCS stimuli, however, for portable systems, like desk fans, that is secondary because users can direct it according to their preferences. Portable devices have the advantages of being adjustable and being close to users without restricting their dress code. They can be connected to a building management system (BMS) for consideration in defining setpoint temperature. However, based on the results from paper (4) this is mainly necessary for PCS that produce heating and/or cooling. For convective devices like desk fans, conflicting activation with the central system and energy waste is less likely. Nevertheless, automatic activation based on occupancy would be beneficial to overcome the users' difficulty to remember to activate the fans (ANDRÉ; DE VECCHI; LAMBERTS, 2020), although that needs to include automation overwriting opportunities. The disadvantage of portable PCS is that they are not close to users all the time as wearables can be. Therefore, they are recommended for stationary activities like offices in which occupants do not move around so often.

Regarding the equipment selection process, paper (2) experiment showed users have different priorities and taste. Therefore, allowing occupants to choose from more than one good quality product with different capabilities can help meet their demands and facilitate the implementation. There are good ready-to-use desk fans and using them is a way to promote occupant-centric building operation and energy savings as these devices are still underused in open office spaces. Nevertheless, product quality and aspects greatly affect usability

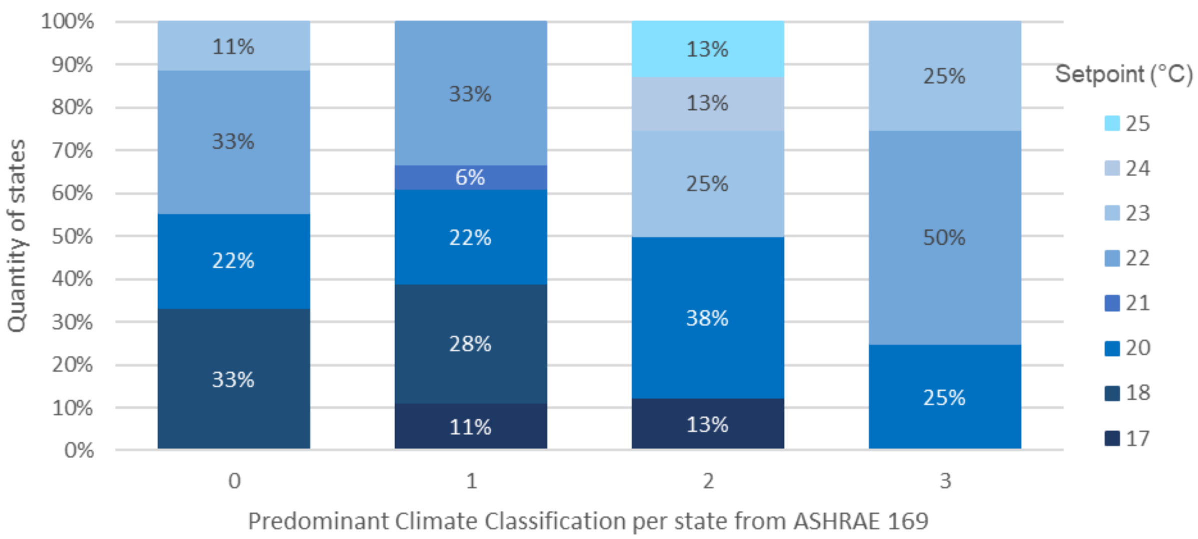
(ANDRÉ; DE VECCHI; LAMBERTS, 2020; KNECHT; BRYAN-KINNS; SHOOP, 2016). The experiment from paper (2) indicated none of the participants chose the noisiest fan – option a – and most of them found the cost of option d unfeasible. Therefore, despite air flow sensation and adjustability being indicated as the most important selection criteria, noise, and cost were exclusion criteria. In addition, the preference for the evaporative cooling fan was a surprise, as indoor relative humidity was high (70 %) during most of the experiment and the evaporative cooling effect under this condition tends to be low. Therefore, this equipment showed great potential and should be further exploited. There are few studies about personal evaporative coolers in the literature (TEJERO-GONZÁLEZ; ESQUIVIAS, 2019). A review on evaporative cooling indicates most personal devices are attached to garments (YANG; CUI; LAN, 2019), showing a gap related to portable devices.

3.2 SETPOINT TEMPERATURE LIMITS

The main point that needs to be addressed for optimal implementation and control is the definition of the room setpoint temperature. The higher the cooling temperature the higher the energy savings, however, this maximum limit cannot exceed occupants' satisfaction limits. In the review (paper 1) we identified the maximum acceptable temperature in chamber experiments with desk fans is 30 °C (BRAGER; ZHANG; ARENS, 2015; WARTHMANN *et al.*, 2018; ZHANG, H.; ARENS; ZHAI, 2015). However, in real spaces, studies indicate a preference for 26 °C instead (LIPCZYNSKA; SCHIAVON; GRAHAM, 2018; SHETTY *et al.*, 2019). One hypothesis was that this limit could be influenced by local climate, especially when the building runs with mixed-mode operation. This hypothesis was tested with building performance simulation in paper (3) applying the adaptive model (DE DEAR; BRAGER, 1998b) to predict thermal comfort in mixed-mode environments (RUPP; GHISI, 2014). Results indicated 30 °C would apply only to Florianopolis which has a milder climate than Brasilia, Fortaleza, and Manaus. In those other cities, 28 °C was the highest limit to restrain overheating risk.

By applying the adaptive model without overheating risk analysis would lead to very wrong indications of applicable setpoint temperatures. The adaptive model indicates higher setpoints apply to warmer climates but that would result in higher occurrence of critical temperatures indoors. This indicates the adaptive model alone should not be used to define setpoint temperature limits for mixed-mode and naturally ventilated spaces. For fully conditioned spaces, paper (4) addressed the relation between setpoint selection and climate potential. However, we found overlapping cooling and heating setpoints in colder climates and no clear trend between variables. Economical differences and regulatory values influence setpoint definitions in real spaces. This result could be explained by thermal expectation and “the addiction” to HVAC identified in previous studies in Brazil. In these studies, the authors identified that occupants more exposed to air-conditioning (AC) tend to prefer cooler environments (CANDIDO *et al.*, 2010b; DE VECCHI; CANDIDO; LAMBERTS, 2012). Consequently, the selection of setpoint temperature tends to contradict the adaptive model. Figure 17 corroborates this affirmation showing lower setpoint temperatures are more frequently mentioned by households from states in warmer climates in Brazil. Figure 17 is based on governmental census research on assets and occupants’ behavior in residential buildings (PROCEL, 2019).

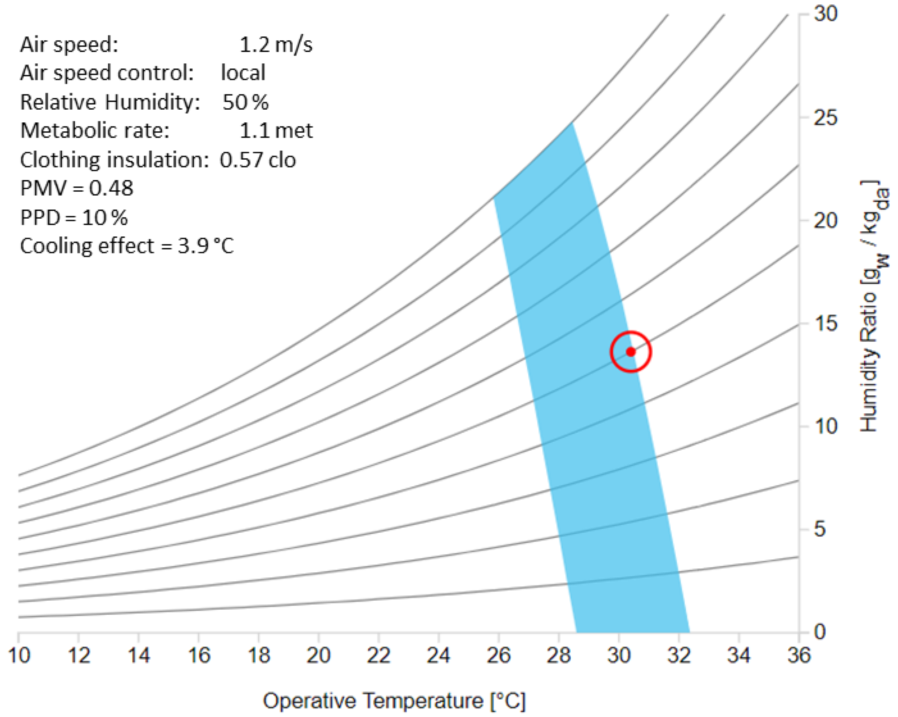
Figure 17 – Main setpoint temperatures used in residential buildings in Brazil by climate. Based on (PROCEL, 2019)



This assumption that under higher outdoor temperatures occupants would accept higher indoor temperatures was also rejected by the results of the field experiment presented in paper (5). Occupants’ thermal expectations affected temperature acceptance. When indoor air temperature exceeded the usual upper limit, characterized by the 90th percentile of pre-intervention period, occupants felt uncomfortable. As a result of this breach of expectations, discomfort persisted for four days. Occupants took one month to adapt to 1 °C temperature increment, from 24 °C to 25 °C. Previous studies showed a higher temperature limit, around 26 °C (KENT *et al.*, 2023; LIPCZYNSKA; SCHIAVON; GRAHAM, 2018; MILLER *et al.*, 2021; SHETTY *et al.*, 2019), indicating that the multiple limitations faced in this study might have hindered the results. Nevertheless, these values between 25-26 °C are much lower than the limits found in paper (3). The simulation indicated a low risk of overheating at the 30 °C setpoint in Florianopolis, which is 4 °C higher than the best-case implementation scenario.

Figure 18 shows the maximum limits indicated by the other main international thermal comfort model, PMV-PPD (FANGER, 1967; TARTARINI *et al.*, 2020), is also similar to the simulation value for Florianopolis, 30.4 °C.

Figure 18 – PMV-PPD maximum acceptable limit for office space with individual fans



Therefore, the main thermal comfort prediction models – the adaptive and PMV-PPD – are not consistent to what was observed in the field in this and previous studies. Indicating higher than applicable maximum setpoint temperatures. However, more studies are needed to validate the applicability or inapplicability of these models for defining setpoint temperature.

3.3 GUIDELINES FOR IMPLEMENTING PCS

Based on all papers, and especially the experiment presented in paper (5) we defined some guidelines for implementing desk fans in open office spaces with central systems. Most of them are also applicable to other types of PCS with some considerations.

The first step would be to select the appropriate PCS based on local cooling and heating demand. This thesis focused on warm climates, not addressing heating demand and the necessary procedures to implement heating PCS as the Brazilian climates have in general warmer temperatures. For those climates, fans can be a good PCS when the equipment is energy efficiency (low power and high/controllable air speed). Additionally, fans are ready-to-use personal equipment, there are good products available on the market and they are easy to implement in existing spaces, needing little infrastructure adaptation and occupying a small space in the workspace. They are especially fitted for office spaces where occupants do not move around a lot.

The second step would be to understand the HVAC system, its capability, and plan the intervention with the operators' support. As identified in paper (4), the operator or facility managers usually have a big knowledge and experience of how to deal with the building system and how its settings affect occupants throughout the year. Therefore, they should be engaged to participate in the implementation by receiving all necessary information about the procedures and the goals of the implementation. The implementation procedures should be discussed and adapted according to the operators' suggestions. Understanding how the setpoint modification affects the system and which control mechanisms are available is crucial for a successful implementation. Finally, for equipment such as desk fans the integration to the central HVAC control is not essential, but for other types of cooling and heating PCS that can affect room setpoint and thermostat.

Occupants should be instructed and aware of the procedures and the goals of the intervention as they have a key role in its success. Their opinions should be recorded before any intervention and after each step. The surveys used to do that should be short and based mainly on a 3-level preference scale. Therefore, the third step would be presenting the procedures and the survey to occupants. Indoor thermal variables should be recorded simultaneously with occupants' thermal perception. This process should be initiated before any intervention.

The fourth step is to provide PCS to occupants. All occupants should receive a PCS because the setpoint increment can increase the cooling/heating demand and the availability motivate users (as observed in papers 2 and 5). One to three days of adaptation to the use of PCSs can be planned before the room temperature is changed. As mentioned before, the modifications should be gradual, and it is estimated that any temperature change needs to be maintained during at least 2 weeks for physiological, psychological, and behavioral adaptation. The temperature extension limit of the first modification could be determined by the 90th percentile of the pre-intervention period. However, this application should also be gradual, especially when the limit is higher than 1 °C. For example, if the 90th percentile is 1.5 °C, temperature can be raised by 0.5 °C every 2 weeks and surveying occupants at each step. If occupants accept the 1.5 °C limit after 2 weeks, another increment can be calculated and tested the same way. Going above 26 °C might be possible only in locations where occupants are already used to this temperature. Small changes, like 1 °C can produce 5-10 % savings depending on the local climate (HOYT; ARENS; ZHANG, 2015). Besides, efficient desk fans will represent a very small energy consumption increment, <1.5 % of total consumption. Therefore, small changes can save energy and are preferred to avoid discomfort.

4 CONCLUSION

This thesis aimed at identifying the best practices for applying personal conditioning systems (PCS) in open offices in Brazil. That topic was investigated from different points of view in five papers. The first paper presented a literature review on PCS implementation. Data indicated desk fans as a suitable option for Brazilian climates. The second paper explored desk fans' selection criteria and selected good available products. The third paper presented an analysis of the maximum temperature extension potential for Brazilian climates when desk fans are provided and the resulting energy consumption. The fourth paper discussed common setpoints, control strategies, and PCS use in Brazil and other six countries. The fifth paper presented an implementation of desk fans in an open office and based on the lessons learned, reached the main purpose of this thesis, proposing guidelines for optimal implementation of PCS. Therefore, the thesis achieved all its objectives, and they can be synthesized in the following items:

- Many studies propose the implementation of PCS using personal comfort models to predict individual preferences more accurately. However, applying these models is very complex and more studies should demonstrate their application in the field. Two questions are common to any implementation of PCS. The first one is how to select the PCS and the second is how to define the room setpoint for optimal thermal comfort and energy efficiency. The literature includes enough information for the selection of the PCS type. However, the second does not have a clear answer and therefore, was exploited in this thesis.

- Although desk fans are known to be very efficient cooling PCS, products can have different efficiency, and their characteristics can affect usability. The experiment from paper (2) showed the ideal device needs to be silent, produce a smooth air flow, have numerous speed levels, have angular adjustment, and be cheap. In addition, personal evaporative cooling fans have great potential and are worth more studies.
- Building performance simulation shows great energy savings potential from the use of desk fans, especially associated to mixed mode operation. Small setpoint extensions can produce up to 20 % energy savings and desk fans, even when used constantly, will represent up to 1.5 % of annual consumption.
- The analysis of simulation data (paper 3) based on the adaptive model and overheating risk indicated 30 °C is an applicable setpoint for offices in Florianopolis. However, that is far from the applicable limits in the field (paper 5). In the field, it was possible to change the mean indoor temperature from 24 °C to 25 °C. Occupants' expectations affect temperature acceptance.
- The adaptive and PMV-PPD models indicate extension limits higher than verified in the field. In addition, paper (4) showed in real buildings the setpoint selection shows contradictory trends to what would be expected from the adaptive theory. Expectation, regulatory values, and economic aspects play an important role that is often disregarded.
- Greater temperature extension generates greater savings but can easily negatively impact occupants' thermal comfort. Trying to reach the maximum possible temperature extension is not the best approach. Gradual temperature changes from 1-2 °C can be more effective and lead to better results from occupants' satisfaction point of view their adaptation period is respected.
- Guidelines for optimal implementation are proposed based on this thesis experience: i) select a PCS suitable for the space/building, ii) plan the intervention with building managers' support considering he building HVAC system capabilities; iii) explain the procedures to occupants, start measuring environmental variables simultaneously to occupants' thermal perception; iv) provide PCS for all occupants, v) make a small temperature change (< 90^{th} percentile of the pre-intervention period); vi) after two weeks, evaluate applicability of further extension based on occupants' survey results.

4.1 LIMITATIONS

This work faced many constraints and limitations, the most important are the following described:

- The review paper (1) presents an state-of-art published in 2020, therefore an update could be proposed.
- Air quality was not assessed directly in any part of this thesis, although participants of the experiment presented in paper 2 complained about stuffiness. Desk fans can help to dilute pollution's concentration and increase perceived air quality, but CO_2 concentration and other pollutants especially in the breathing zone. These measurements would have been beneficial to show the additional advantages of desk fans.
- Building geometry and systems affect a lot the energy savings prediction. Therefore, paper (3) results are not generalizable for all Brazilian buildings. That would require a more extensive models database and simulations. In addition, a big part of the achieved savings in this paper came from changing the operation from fully conditioned to mixed mode and cannot be used to estimate the savings in fully conditioned buildings like the one in paper 5, for example.
- The sample of interviews from paper (4) is small and cannot be extrapolated to represent the common practices of each country. They were used to find trends and contradictions to the initial hypothesis.
- The field experiment presented in paper (5) faced numerous limitations. The main ones relate to poor temperature control, abrupt outdoor temperature increment that affected the indoor air temperature and the experiment design that did not account for those condition or the need for repeating the intervention and enlarging the sample sizes. Some data gaps were also related to occupants' strike and vacation periods. Additionally, because of technical constraints measuring energy savings was not possible.

4.2 SUGGESTIONS FOR FUTURE RESEARCH

Based on this work and the encountered limitations, here are some suggestions for future research:

- A long-term intervention experiment to an entire building, providing desk fans to all occupants and gradually increasing the setpoint temperature. This study would be important to identify what is the annual setpoint variation needed in an office building, how the fans would be used in other seasons, and the impact in a year round timelapse regarding thermal comfort and energy consumption compared to the previous condition.
- Determining minimum adaptation period for temperature change and the magnitude limits. This adaptation period is a major gap in the literature for long-term exposure under steady-state and a specific experiment design is needed to assess this information and verify the 90th percentile limit suggested in paper (5).
- Test the acceptability of the adaptive model and PV-PPD upper limits in real spaces with a gradual temperature change with and without PCS. In this study, we showed some evidence that the upper limits might not be applicable to define setpoints to existing spaces. But it is possible that with longer adaptation periods these limits can be achieved. Therefore, more experiments are needed to prove or reject their applicability.
- More studies with evaporative cooling fans in different climates – under high and low relative humidity. There are cheaper versions of evaporative coolers available in the market but few studies about them. Studies are needed to compare product characteristics, quality, use limitations, and even implementation potential. A long-term implementation experiment, similar to what was proposed for fans, could be carried out with evaporative cooling fans, allowing the comparison of pre-post results and proportional impact to desk fans.
- More studies comparing PCS quality, features, and impact are necessary to develop product regulations. This would be helpful for quality control and increase energy efficiency and usability.

- More field studies are needed to discuss and indicate guidelines for other types of PCS and discuss the differences to what was proposed in this study.
- Other studies about setpoint temperature could be carried out based on census data to further analyze the relationship between setpoint, climate and economic aspects of different countries.
- Open-source materials and guidelines for control implementation of HVAC automation considering cooling and heating PCS with would be very useful for pushing the implementation of these technologies.

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APPENDIX A – PAPER 1

TITLE

User-centered environmental control: a review of current findings on personal conditioning systems and personal comfort models

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ABSTRACT

Personal conditioning systems (PCS) enable increased thermal comfort and acceptability conditions in a wider temperature range, resulting in energy savings. Many studies analysed the thermal effect and energy efficiency of these systems, although the association between these two goals in practice is not that simple. In order to identify possible answers to understand what remains to be discussed on this subject, a review of recent publications on PCS was carried out, mainly focused on its implementation in shared office spaces. The reviewed publications shed some light on the use of personal comfort models associated with environmental control for system automation, as well as the development of new technologies that facilitate data acquisition and the proposition of new personal conditioning systems. The application and proposition of wearable systems and the development of textiles for smart clothing is an identified trend seeking greater mobility and flexibility of PCS use, although its integration to environmental management systems is challenging. Thus, this review discloses some questions that should be considered for the implementation of PCS and personal comfort models in real environments, including some insights based on current publications on the subject.

Keywords:

Thermal comfort; User-centric control; personal conditioning system; personal comfort model;

energy efficiency.

1. Introduction

The prospects for global warming [1] indicate a strong growing trend in the use of air conditioning systems in the world, which significantly increases energy demand in a scenario where buildings accounts for 55% of world energy demand [2]. As a large amount of this energy is used to condition large environments, the expansion of set point temperatures could generate from 30 to 70% in energy savings [3]. To enable this expansion, it is necessary to ensure that users remain in thermal comfort, which is possible through the use of personal conditioning systems (PCS) [3]. From an energy standpoint, the main advantage of PCS is to allow the expansion of environment set point, while local stimuli maintain users' thermal comfort with lower energy consumption [4–7]. Producing a more restricted thermal condition to the occupancy zone when required demands far less energy than maintaining the same condition in the overall environment, which makes PCS more efficient to use. They can be activated only when needed and at an intensity deemed appropriate by the user, so as to adjust the condition to users' preferences [7,8]. This on-demand activation helps to reduce energy consumption, but it is crucial to increase thermal comfort, since there is great variation between users' thermal preferences in the same environment [5,9–11]. Some studies verified that maintaining a single temperature in a collective use environment does not provide thermal comfort to the majority (80%) of the occupants. [9,10]. In general, buildings operate in low temperature ranges, generating overcooling and cold discomfort even during the summer [4,12]. Thus, besides not meeting the variation of personal preferences, the choice of set point temperature is inadequate, generating energy waste and thermal discomfort. This emphasizes the need to rethink the way in which environments are being conditioned [7].

According to De Dear [13], in order to please users, the important thing is to avoid thermal boredom. The author indicates that the transitory conditions created by occasional stimuli allow the production of positive alliesthesia - a kind of relief generated by the body returning to its point of equilibrium after an extreme thermal sensation, which is identified as thermal pleasure. Moreover, the further away from the point of equilibrium the body is, the greater the pleasure generated when there is a return to equilibrium; that is, the greater the variation, the greater the thermal pleasure generated [13]. Thus, the local and variable stimuli generated by PCS can provide improvements beyond thermal comfort by reaching thermal pleasure, which would not be generated in a uniform and constant condition. In order to produce these stimuli, several types of personal systems are proposed, with different effects and solutions [4,6]. Studies involving alliesthesia also indicate that it is not necessary to reach a large body surface to generate a global effect of comfort and thermal pleasure [13–15], so new technologies aim to take advantage of this ability by proposing more efficient and portable systems.

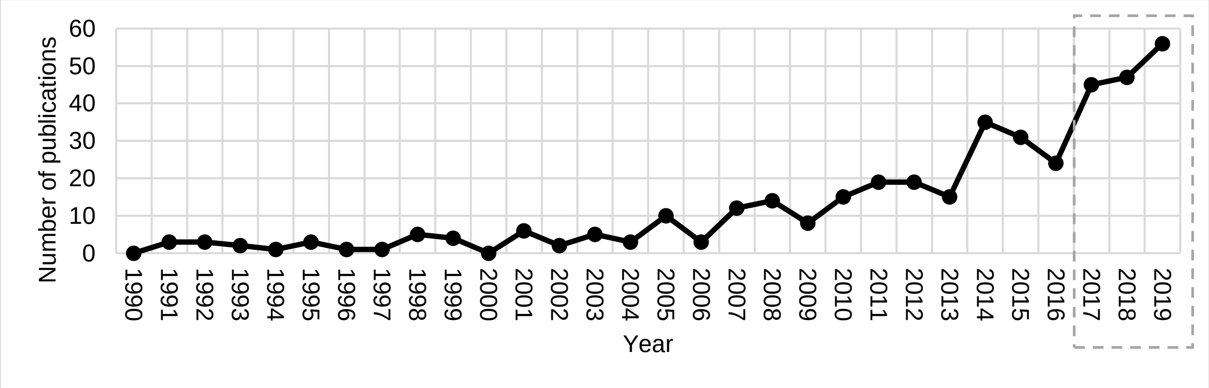
There is a growing number of publications on personal conditioning systems (PCS), which are sustained as a solution to reduce energy consumption in buildings and, at the same time, increase the thermal comfort of users [6,7,9,10,16]. Many studies analyse the thermal effect and energy efficiency of systems separately, which makes it difficult to understand the best solutions for both aspects. For example, Hoyt et al [3] defined the energy savings percentages produced by set point temperature expansion based on building simulation analysis, while Zhang et al [4] indicated thermal acceptability temperature ranges of different types of PCS based on users' feedback. However, Schiavon and Melikov [17] show that system efficiency also depends on the PCS consumption itself, since the highest percentage of savings is not necessarily achieved using any type of PCS with the broadest set point temperature. In some cases, changing the ambient set point will consume less energy than activating a great number of PCS in a multi-occupant space. In addition, most of the studies to define users' thermal acceptability limits with personalized systems are conducted in climate chambers which may not correspond to the accepted limits in real context.[18]. So how to define the optimal limits in an existing space? Which would be the best type of PCS for a specific space to achieve maximum thermal comfort and minimum energy consumption? The answer lies on comprehending individual users' needs better and predicting their preferences to associate these with suitable personal equipment and environmental controls. Solutions can involve new technologies for real-time data acquisition and personal comfort models that allow users' preferences to be considered for system automation [19]. In order to identify these possible solutions and understand what remains to be discussed on this subject, this paper aims to review recent publications on personal conditioning systems focusing on its implementation in multiuser office spaces. The main contribution of this work is to present a review that highlights questions and some insights for the implementation of PCS achieving their full potential.

2. Method and bibliometric analysis

To find the most recent articles on personal conditioning systems and identify the main issues involved in the subject, a research was conducted on Scopus platform. This platform was chosen because it allows the use of filters to facilitate the search and because it also includes a comprehensive number of journals and conference publications. The search was performed using the following keywords: thermal AND comfort AND personal AND (system OR conditioning). The first research including all publications until the end of 2019 resulted in 398 publications in English, excluding book chapters and conference reviews. As Figure 1 shows, the initial survey indicates that this subject has gained notoriety in the last 10 years.

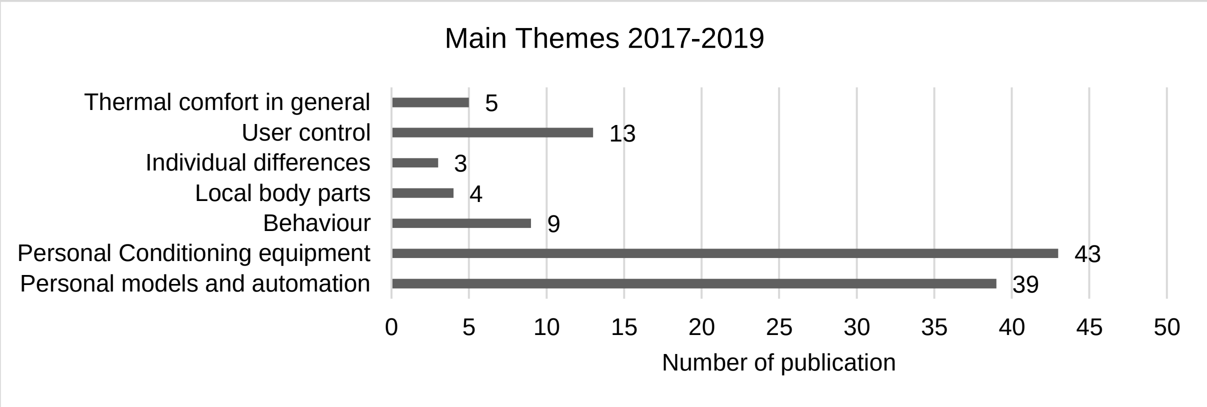
However, the biggest growth in number of publications can be seen more recently as of 2014, when the number of publications increased from 15 to 35 and it has not gone back to less than 24 per year since then. There was a decrease in 2016, which was offset by a growth in 2017, with 45 publications along the year - a number practically kept in 2018. In the last year this number increased to 56 publications, confirming this issue as a current research trend. Among all publications from the initial research, 14 reviews [9,11,27–30,16,20–26] were identified; 8 of which (more than half) were published as of 2017 [11,21–26,31]. Thus, the period selected for analysis was from 2017 onwards, as this will enable the identification of the current state of research on the subject, in addition to encompassing the knowledge acquired from the main studies of previous periods.

Figure 1. NUMBER OF PUBLICATIONS PER YEAR FROM THE SEARCH RESULT ON THERMAL COMFORT AND PERSONAL (SYSTEM OR CONDITIONING). THE HIGHLIGHTED INTERVAL BY DOTTED LINES (2017 - 2019) REPRESENTS THE OUTLINE OF THIS RESEARCH.



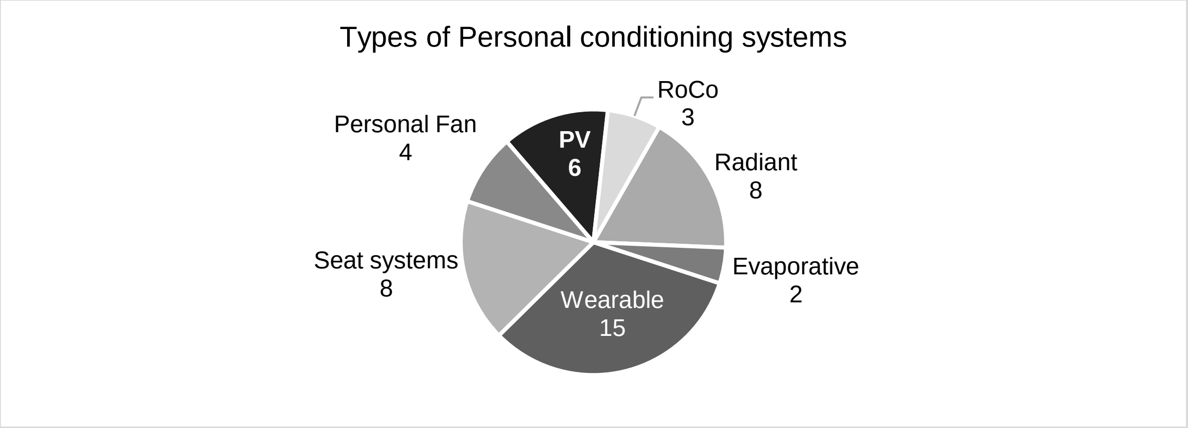
In the selected period, 148 publications were found and analysed. A selection of those especially relevant to the subject resulted in 113 publications. From there, main topics addressed in publications and their relevance were identified and listed according to Figure 2: 1) Personal conditioning equipment; 2) Personal models and automation; 3) Behaviour; 4) Local body parts; 5) Individual differences; 6) User control; and 7) Thermal comfort in general. Figure 2 shows that the "Personal conditioning equipment" topic has the highest number of publications, which includes studies proposing the development or evaluation of one or more personal conditioning systems. It can be observed that the second most discussed subject has a similar number of publications in the period, dealing with personal thermal comfort models used in automation of conditioning systems. User behaviour, as well as issues related to the control of systems without automation, are also relevant. This review was organized in three main sections, which integrates all the topics from Figure 2, especially the predominant ones: i) Association of personal conditioning systems to personal comfort models ; ii) Personal Models and automation; iii) Selection of personal conditioning systems.

Figure 2. NUMBER OF PUBLICATIONS PER MAIN THEMES DISCUSSED IN REVIEWED PUBLICATIONS



Considering that most publications deal with office spaces (71%), and a lower percentage covers the residential sector (13%) and vehicles (11%), i.e. automobiles, aircrafts and trains, the focus of this review is the office spaces. There is a predominance (33%) of studies on wearable PCS such as garments, textiles and conditioning accessories in the personal conditioning systems studies, as shown in FIGURE 3, which highlights that this is a current trending topic. However, it must be considered that among these 15 publications, three are related to the development of the same garment with attached fans and phase change material pockets [31–33]. In the case of personal ventilation systems (PV), a recurrence is also verified: four out of five publications deal with air cooling nozzles in aircraft cabins [34–37], and only one addresses office PV [38]. Studies on revolving comforter (RoCo) [39–41] have also been categorized, as this mobile system does not fit into the other classifications. All other systems involve more diversified equipment: connected to seats [23,42–48], radiant heating or cooling systems [42,49–55], evaporative cooling systems [56,57], desk fans [42,49,53] and a stand fan [58].

FIGURE 3. NUMBER OF TYPES OF PERSONAL SYSTEMS ADDRESSED IN REVIEWED PUBLICATIONS



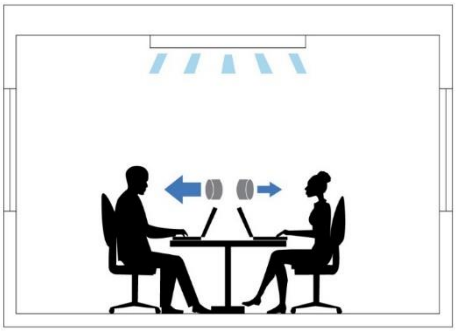
It is important to mention that, among the publications evaluating and proposing personal systems, only 18% involved field surveys; the majority (58%) was carried out in climatic chambers or controlled environments and 16% were based on laboratory experiments (mainly those dealing with textile development). Despite the low representativeness of fans and personal ventilation systems (PV) among the studies on PCS, the overall majority of publications (45%) focus on cooling or hot periods of the year. Nevertheless, a significant part (29%) addresses systems or conditions that include both heating and cooling, and a smaller part studies heating conditioning only.

The review was also complemented with other articles selected by the snowballing technique with information on important topics such as wearable systems and the development of some personal models from the initial selection.

3. Association of personal conditioning systems to personal comfort models

Personal systems are equipment that can complement the environment conditioning system or work autonomously, allowing each user to customize their microclimate to personal demands [5,6], as shown in the example of Figure 4. In this example, the environment is conditioned to a given temperature while the local systems are regulated to more or less air flow, or distinct inlet air temperatures, considering each user has a personal ventilation system (PV). This personal adjustment is very important so that variations in preferences between users in a multi-occupant environment are met. For this likely reason, most of the studies address office environments, as identified in section 2, because many are configured in shared spaces such as open offices.

Figure 4. ILLUSTRATION SHOWING AN EXAMPLE OF PCS USE IN A CONDITIONED ENVIRONMENT WITH DIFFERENT INDIVIDUAL ADJUSTMENTS



Individual preferences also tend to vary throughout the day [59] depending on environmental conditions and other factors such as the circadian cycle and psychological issues. These variations are known as intra-individual differences [20]. On the other hand, variations in preference among users are known as inter-individual, and can be generated by sociocultural and economical differences, as well as physiological and anthropometric factors, being the latter the most studied [11,20]. Even if the thermal comfort questionnaires include anthropometric questions in a general context, few studies focus on their impact on inter-individual differences [11,20]. Among existing studies, it can be seen that gender and age are indicated as the main factors influencing variation of thermal perception between users. Although there is much divergence on the statistical significance among studies, there is a consensus that the elderly and women are more sensitive [20]. Aging degrades body's thermal regulation systems, making the elderly more vulnerable to environmental variations and, at the same time, less aware of them [20]. On the other hand, women are more sensitive than men to thermal variations, especially under low temperatures, and tend to indicate greater dissatisfaction with the environment [20,60]. Due to this female sensitivity, some studies evaluating and proposing personalized systems [61,62] have started to carry out experiments with women only, since they provide more restrictive inputs to thermal conditions. The greater dissatisfaction by women may also come from sociocultural issues that reduce their ability to access controls [60,63], reducing their adaptation options mainly to clothing adjustment [52]. This difference between genders is recurrent in shared workspaces and can even affect productivity, which might generate economic impacts for a company [64,65]. Female productivity may be impaired due to cold discomfort generated by overcooling. On the other hand, the increase in ambient temperature has no significant impact on male productivity, indicating that raising the temperature to 26 °C may be favourable for the productivity of both genders [64]. This result highlights the need to identify an optimal point of operation of the system in shared spaces, and the one possible impact of neglecting inter-individual variations.

As mentioned, inter-individual and intra-individual variations can be solved by providing personalized systems to users, so that they can adjust their occupancy zone according to their preferences [11,20,59]. In the example shown in Figure 4, women could select lower air flow than men, allowing both to be comfortable in the same environment [38]. Even with local adjustment, it is necessary to define the ambient set point temperature for system activation. Since a wider activation interval between heating and cooling systems generates greater energy savings, the aim is to select the widest possible range that does not compromise the thermal comfort [3,4]. In general, this range is related to thermal acceptability, and studies indicate that it is possible to reach a limit of 16 °C and 30 °C [4,5,66] with personal systems, reaching up to 35 °C with a personal ventilation system (PV) air flow at 22 °C [24]. Thus, acceptability limits depend on the type of personal system adopted [4,24], making system selection important. Many studies with personal systems, as identified in section 2, are performed in climatic chambers, which may present different results from those found in the field. These may occur due to variations of metabolic rate, clothing and other user adaptation opportunities, which are restricted in controlled experiments [20]. In the field study conducted by Shetty et al [67] in offices with desk fans, for example, the highest temperatures that could be tested were 26 °C in an office and 27 °C in the other, because temperatures above these generated complaints. These values are much lower than the maximum acceptable limit of 30 °C identified in studies with individual fan in climatic chamber [4,49,68,69]. Kim et al [59] also verified thermal preference for environment temperatures around 23 °C, while previous studies in climatic chambers indicated the lower limit of acceptability at 18 °C with the use of the same equipment - a cooling and heating chair system. To reach broader limits of acceptable set point temperature, many studies propose the use of PCS with fixed settings [24,53], imposing its use at a limited condition, e. g. high airflow or radiant temperature. This solution helps to increase energy savings, but can compromise thermal comfort, as it eliminates the possibility of personal adjustment. The comfort limits for each user tend to vary throughout the day and year, due to climatic variations, physical activities, and other intra-personal variations, making this strategy work for a limited period and not on daily office routine.

Alternatively, thermal comfort prediction models included in international standards, such as the predicted mean vote model (PMV) or adaptive model, could be used as references [70–72] for defining the comfortable set point temperature and PCS settings. However, the PMV model is not suitable for predicting thermal comfort at the condition generated by PCS, since this model is indicated to uniform and constant environments, while PCS generate transient and non-uniform conditions [5,9,10]. Even the SET model [70] for high air speeds environment has been found to be incompatible with conditions accepted or preferred by users with personal systems [4,69,73,74]. This may result from matching comfort limits of SET model to PMV model, which is also referred to as PMV-SET model [75]. Alliesthesia theory [13,14] would be the best to explain the relationship between local and overall thermal comfort according to local stimuli, but there is no predictive model that applies it directly. The most suitable models for the study of transient and non-uniform conditions are the physiological multi-node models [6,9,16,66]. These models make calculations of heat exchange between the skin, bloodstream, body core and environment more accurate because they account for variations in surface conditions at up to 24 different body spots [76–78]. Thus, the physical effects and the relationships between global and local effects can be better understood [15,18,79]. However, these models, as well as the other models from international standards [70,71], are defined by the generalization of the users' thermal perception votes. Therefore, it is not possible to consider inter-individual variations of preferences by applying these models, because they are based on the generalization of data by means of averages [5,6,9,11].

As a counterpoint to these models' limitations, personal comfort models are proposed. These models are generated through machine learning based on individual user feedback. This way, models learn the preferences of each user in a real environment and allow the prediction of individual or group preferences [19]. In addition, users' feedback used to set prediction models are given at their actual everyday condition, which may include different types of personal conditioning systems or no PCS [80–82], consisting of a uniform or non-uniform space. Unlike other models, these variations do not limit this type of comfort model; it can be applied to different circumstance, as long as a sufficient number of variables are included in its definition to allow the prediction of such variations. For this purpose, data collection should include different moments along the year, during which all types of available conditioning systems are used together or independently – different types of PCS, central conditioning systems with different set points and natural ventilation. Thereby, individual prediction models can be generated based on personal preferences including hour, seasonal and intra-personal variations [19].

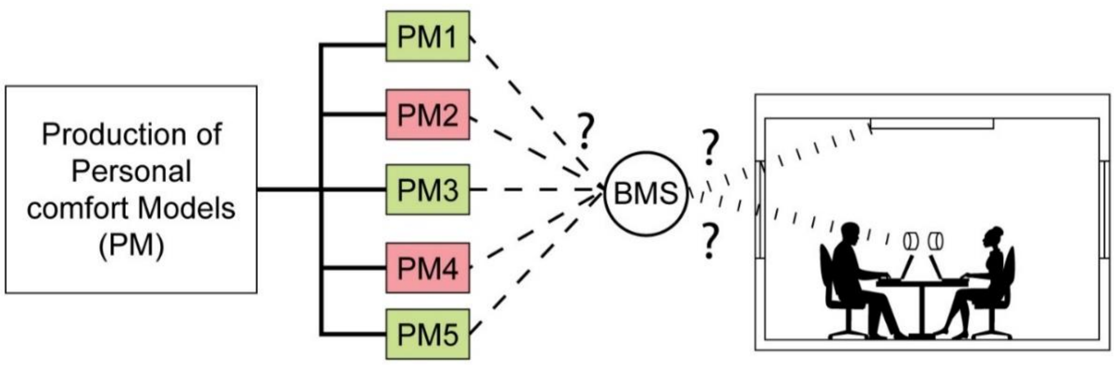
Due to this flexibility and the possibility of considering inter- and intra-personal variations, the application of personal models is highly recommended for predicting thermal comfort in existing environments [19], and would be even more recommendable for those with personal systems. In addition, since these models are built based on existing spaces and occupants' feedback, they are mainly used to generate outputs for automation of conditioning systems to meet individual thermal demands [19]. Thus, instead of defining a fixed thermal condition for the environment and PCS settings, by applying these models, it is possible to define variable limits throughout the year. These models can be used to automatically control the ambient conditioning systems and/or personal conditioning equipment. Using a personal comfort model to define the central conditioning set point temperature may allow systems to operate with broader values, adjusted to occupants' preferences, as well as increase thermal comfort and reduce energy consumption [80,81,83,84]. Also, the consideration of PCS local effect enables setting the whole ambient at even broader thermal conditions, increasing energy savings, because only local microclimate needs to meet user's demand [17]. Thus, comfortable conditions can be achieved by a wider ambient temperature associated to different local conditions, which may be more restricted. In this way, personal models allow to reach the maximum potential of PCS, making its implementation reach higher thermal comfort and lower energy consumption.

However, to achieve maximum performance, it is necessary to understand ways of applying these models associated with environmental control. Section 4 discusses the issues involving this association and the propositions presented in reviewed articles. For environmental control to achieve optimal performance, in addition to the proper use and configuration of predictive models, it is necessary to choose the best equipment for local demands. There is a wide variety of equipment on the market and under development, making the selection more challenging. Therefore, section 5 is dedicated to this issue, and shed some light about which criteria and indexes can be used for comparison and which product development trends are observed in recent literature.

4. Personal Models and automation

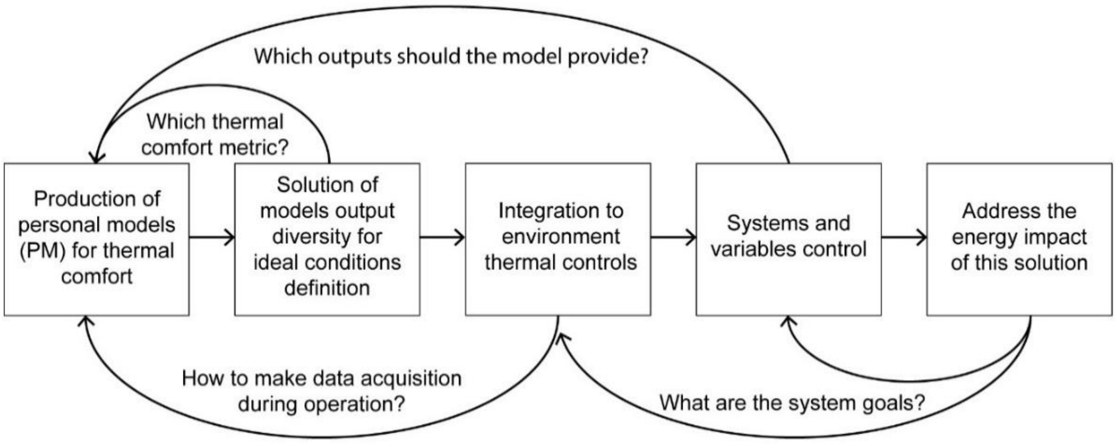
As previously presented, the personal comfort models are more appropriate to predict individual thermal comfort in existing environments. This section will address its application and link to the control of variables and environment systems, like personal conditioning systems. The first part of this process is the production of models, addressed by Kim et al [19], who present a framework consisting of the following steps: data collection; data cleaning and process; selection of modelling method and model construction; model error/adjustment calculation; and continuous update. The final result of these steps is the production of a personal comfort model for each occupant of a given space, which then needs to be integrated to environment controls. To discuss the issues involved in this integration, an expanded version of the example of Figure 4 will be used: an office with multiple users where there is a central conditioning system, in addition to openings for natural ventilation, and all users have the same PCS (which type is irrelevant at the moment). After defining and applying personal thermal comfort models, it could be found a result like Figure 5, in which the model output of two (PM2 and PM4) out of five users indicate thermal discomfort [85].

Figure 5. Application of personal models – How to deal with divergent results like illustrated below? (only PM2 and PM4 are uncomfortable). based on [85].



In this case, the first point that needs to be discussed is how to solve the diversity of preferences among users. If the majority of occupants – users 1, 3 and 5 – are comfortable, would this mean no changes are needed? These three people would represent 60% of occupants which is less than the minimum percentage criteria to comply with ASHRAE 55 [70], i.e. 80%. In a space with personal conditioning systems a higher percentage could be pursued since personal adjustment is possible [9]. In order to increase this number an action should be taken, which can include the adjustment of environment or local conditions, i.e. adjusting central or personal conditioning system settings. To adjust the environment condition, it is necessary to find a way to associate the model results to define how to achieve comfort for all users. In a space without PCS this is usually done by looking for optimal matching values across the models. Once this ideal condition is found, it can be transmitted to the building management system (BMS) for automatic or manual adjustment of the central conditioning systems. In the case of spaces with PCS, an overall condition could be defined for the environment and different local conditions. To do this, it would be necessary to establish which variables should be modified to meet individual demands and which systems - central or personal - should be controlled. Finally, the proposed system will have an impact on building energy consumption, so this impact should also be considered in the definition of environmental management. These were some of the main points identified for the implementation of personal comfort models for environmental control, which are summarized in Figure 6.

Figure 6. STEPS AND POSSIBLE QUESTIONS INVOLVED IN THE APPLICATION OF PERSONAL COMFORT MODELS FOR THE CONFIGURATION OF A MULTI-USER ENVIRONMENT CONTROL SYSTEM.



The following subsections will address the questions and steps presented in this figure, as follows: 4.1. Environmental control system goals; 4.2. Thermal comfort scales and index; 4.3. Models output diversity solution; and, 4.4. Real-time personal data acquisition technologies. Table 1 summarizes the data on personal comfort models and automation that will be discussed in those subsections. Studies involving other control options for offices, residences and vehicles will be addressed in subsection: 4.5. Alternatives to system automation and other spaces. This last subsection also includes considerations on the best control strategies for each type of space.

Table 1. Personal comfort model and automation studies summary data

Reference		Model production			Environment management system			Application				Validation with users?	
Authors	Year	Collected data	Thermal comfort scale/ Index	Model method	Goal	PCS type Control variable	HVAC Control variable	Real-time data acquisition during operation	Diversity solution	Adjust. Freq.	Adjust. interval	Number of people/ method	Model output
Liu et al [86]	2017	ta; rh; vel; met; clo; trm	PMV-SET-simplified	Decision tree	Optimize TC; consider EE	Fan Auto vel	Fixed Set point	ta; RH; user position	individual fan speed and maximal mean Tset-poitn	-	-	no	fan vel; rotation
Xu et al [80]	2017	ta; Tsup; ts-wall; solrad, Text; TS (5); TC (7); AMA	PMV-SET-personal; energy cost	LR	Optimize TC & EE	Fan Auto vel	Auto Set point autom.	ta; Tsup; ts-wall; solrad, text	PMV-SET-personal interval + max accept air speed	30 min	any	4/ climate chamber	ta; fan vel; Tset point; energy consumption
Li et al [87,88]	2017/ 2017	TS (5); TP (3); HR; activity; Tskin-wrist; clo; ta, rh; Text; RHext; window on/off; CO2	TS (5); TP (3)	Linear regression VN and logistic regression AC/ RF	optimize TC; consider EE	-	Auto activation set point	HR; activity; Tskin-wrist; clo; ta, rh; Text; Rhext; window on/off; Co2	50%+1= TS (+/-2) calculate Tset point adjust recheck votes: 2/3 of people = TP (0) change is made	30 min	1 or 2 °C	3/ field	TS (5); TP (3)
Laftchiev and Nikovski [83]	2017	ta; rh; vel; occupancy; HR, Tskin-wrist; met; TS (7)	TS (7)	SMV	predict TC	-	-	ta; rh; vel; occupancy; HR, Tskin-wrist; met	-	-	-	no	TS continuous scale
Kim et al [81]	2018	TP (3); clo; PCS control data; ta; To; rh; Text; sky cover; Tmpa; prec; Tset point; vel; occupancy; daytime; day week	TP (3)	RF	predict TP	Manual chair	User feedback (comfy) set point	ta; rh; chair operation	consensus	-	-	no	TP (3)
Ghahramani et al [89]	2018	TC (7); Tskin-face	TC (3)	Bayesian	predict discomfort	-	Auto Set point	Tskin-face	-	-	-	10/ climate chamber	TC discomfort
Cosma and Simha [90]	2019	TC (5); TS; Tskin-8upperBody	TC (5)	RF /SVM	predict TC; mean time to warm discomfort	-	Auto Set point	Tskin-upperbody one side	-	-	-	20/ field	TC (5); mean time to discomfort
Cosma and Simha [91]	2019	TC (5); TS; Tskin-face	TC (5)	RF	predict TC; mean time to warm discomfort	-	Auto Set point	Tskin-face	-	-	-	33/climate chamber	TC (5); mean time to discomfort

Kruusimägi et al [92,93]	2017/ 2018	occupancy; ta; Tsup; TS(7); TP(7); TsupChange	TS (7); TP (7)	Exponent. weighted running mean; Griffiths method	optimize TC; consider EE	-	Auto Set point	occupancy; ta; Tsup; (optional TS; TP; TsupChange)	TS neutral and TP - 1	10 min	1°C each 0.5 TS	5/ field	occupancy; TS(7); TP (7); Tset point
Pazhoohesh and Zhang [84,94]	2018/ 2018	TP (100); occupancy; ta; rh	TS (5)	fuzzy logic; CFD simulation	optimize TC; consider EE	-	Auto Set point	ta; occupancy	maximal or minimal TS neutral of the group	30 min	any	9/ field	occupancy; TS (5)
Kalaimani et al [95]	2018	ta; occupancy	PMV-simplified	SNOPT; simulation	optimize TC & EE	Fan / heater Auto vel/ Tsup	Auto Set point	ta; occupancy	individual regulation of PCS; Tset point to equal discomfort	30 s	any	no	fan vel; heater Tsup; Tset point
Jiang et al. [96]	2017	TS (7); ta; rh; tg; vel; clo; met	TS (7)	C-SVC	optimize TC; consider EE	-	Auto Set point	ta;RH; tg; vel; clo; met; HVAC energy consumption	mean TS (with group adjust)	-	0.5 °C	no	TS (7); Tset point; clothing adjustment
Guenther and Sawodny [97]	2019	ta; Tsup; fan level; Radext; Text; daytime; TC(7) ; dayweek	TC (7)	linear quadratic equation	predict TC	Ceiling fan Manual (1 fan / 2 people)	Auto Set point	ta; Tsup; fan level; Radext; Text; daytime	-	10 min	-	no	TC (7)
Liu et al [75]	2018	ta; rh; fan level; AMP (3); TS (7); AMA (7); TA (7)	PMV-SET or AMP (3)	generic optimizatio n algorithm	optimize TC and AMA	Fan Auto vel (1 fan/ 4 people)	-	AMP (3) when in discomfort	minimum deviation air speed preference	2 min	0.15 m/s	40/ field	fan vel
Salamone et al [98]	2018	TS (7); HR; EDA; T-skin-wrist; ta; rh; vel; tg; clo; met	TS (7)	Regression tree	optimize TC	-	Auto Set point	To; EDA; Tskin-wrist; rh	intersection between individual TC conditions (majority)	-	-	no	TS (7)
Aguilera et al [99]	2019	ta; TP (18)	TP (7)	Fuzzy logic	optimize TC; consider EE	-	Auto Set point	ta	global mean TP (18) = 9	-	-	16/ field	TP (7); Tset point
Chaudhuri et al [100]	2019	ta; HVAC frequency of use (f); TS (7);	TS (7)	SVC	optimize TC & EE	-	Auto set point	ta	mean optimal Ta	-	0.1 °C	no	TS (7); energy consumption; Tset point; f
Zang et al [101]	2019	ta; rh; vel; camera images;	PMV	SVM; Cuckoo search algorithm	optimize TC	-	Auto Set point	ta; rh; vel; camera images	mean of individuals PMV	-	-	no	ta; vel
Jung and Jazizadeh [102]	2019	ta; TC (100)	TC (3)	Bayesian	optimize TC; consider EE	-	Auto Set point	ta	mean TC + sensitivity interval	-	1 °C	no	probability of TC (3)
Du et al [82]	2019	ta; rh; vel; Tsup; affectedBP; Tskin-	TS (7)	Regression tree	predict TC; consider EE	PV; Fan Fixed	Auto Set point	Tskin-chest; Tsup; Tskin-upperbody-	-	-	-	no	TS (7)

		upperbody-8; TS(7) overall; TS (7) local; gender; AD; BMI				vel and Tsup		9; ta; rh; vel; gender; BMI; AD					
Cheng et al [103]	2019	ta; rh; camera images; Tskin-backhand	skin sensitivity index	Deep learning	predict Tskin-hand	-	Auto Set point	ta; rh; camera images			-	no	Tskin-backhand
Li et al [104,105]	2018/ 2019	ta; rh; thermo images-face	TP (3)	RF	predict TP	-	Auto Set point	thermo images-face	-	-	-	no	TP (3)
Warthmann et al [24] Metzmacher et al [106,107]	2018/ 2017	ta; Tskin-forehead;	Local TC (5)	Thermal physiological model	predict local TC	-	Auto Set point	Tskin-face	-	-	-	no	Local mean vote TC (5)
Shetty et al [67]	2019	ta; rh; CO2; occupancy; Text; RHext; rainfall	Manual PCS operation	Decision tree; RF	optimize TC; consider EE	Desk fan Auto vel activation	Fixed Set point	ta; rh; CO2; occupancy; Text; RHext; rainfall	set a high set point and activate fan automatically	-	-	no	fan activation; vel
Tanaka et al [108]	2019	ta; rh; trm; vel fan; met; clo; TS (7); Tsat (7); Product (7)	PMV-PPD-personal	Least-square	optimize TC; consider EE	fan speed/ activation	fixed set point	ta; rh; trm; vel fan; met; clo	set a high setpoint and activate fan automatically	-	-	37/field	fan activation; vel
Patil and Mudholkar [109]	2019	rh; trm; vel; met; clo	PMV	Fuzzy logic; GA	optimize TC	-	set point	rh; trm; vel; met; clo;	-	500 s	-	no	Tset point
Liu et al [110]	2019	Tskin-wrist; Tskin-ankle; wrist-Acc; HR; TS (7); TP (3); ta; Text; RHext; SolRad; Velext	TP (3)	RF / Extra Trees / C5.0 / GBM	predict TC	-	set point	Tskin-wrist; Tskin-ankle; HR; wrist accelerometry	-	-	-	no	TP (3)
Jung et al [111]	2019	Tskin-wrist; Tskin-chick; heat flux-wrist; heat flux-cheek; ta; rh	TP (3)	RF	predict TC	-	fixed set point	Tskin-wrist; Tskin-chick; heat flux-wrist; heat flux-cheek; ta	-	-	-	no	TP (3)
Kobiela et al. [112]	2019	TS (9); TC (9); ECG; Tskin-finger; Tskin-chest; ta; rh; trm; vel; clo; met; gender; age; height; weight; HR; HRV	cTSC (3)	Extra Trees	predict TC	-	set point	ECG; Tskin-finger; Tskin-chest; gender; age; height; weight	-	-	-	no	cTSC (3)

ta – air temperature
rh – relative humidity
Text – Outdoor air temperature
RHext – Outdoor relative humidity

vel – air velocity
trm – mean radiant temperature
tg – globe temperature
To – operative temperature
Ts-wall – wall superficial temperature
clo – clothing insulation rate
met – metabolic rate
EDA – electrodermal activity
ECG - electrocardiography
Wrist-Acc – wrist accelerometry
HR(V) – heart rate or heart rate variability
BMI – Body mass index
AD - body surface area
Tskin-(body part) – Skin temperature of an specific body part
CO2 – Carbon dioxide concentration
Tsup – Supply temperature
TsupChange - Supply temperature change
Tset point – Set point temperature
affectedBP – affected Body Parts

Solrad – Solar radiation
Velext – Wind speed
RF – Random Forest
LR – Langranian algorithm
SVM – Support Vector Machine
SVC – Support Vector Clustering
GBM – Stochastic Gradient Boosting
TC (n) – Thermal Comfort vote with "n" values scale
TS (n) – Thermal Sensation vote with "n" values scale
TP (n) – Thermal Preference vote with "n" values scale
TA (n) – Thermal acceptability with "n" values scale
Tsat (n) - Thermal satisfaction with "n" values scale
Product (n) – self-assessment productivity with "n" values scale
cTSC (n) - Combined thermal sensation and thermal comfort with "n" values scale
AMP – Air movement preference vote (3 values scale)
AMA – Air movement acceptability
TC – Thermal Comfort
EE – energy efficiency

4.1. Environmental control system goals

The discussion on the application of personal comfort models for environmental control starts with system goals, which are crucial to guide the following steps for system definition. The main goal of environmental control systems is to set a comfortable thermal condition. However, for achieving higher performance it could also include energy efficiency as another goal. That way the system could find an optimal point of operation considering both goals. To understand how to do that, it is necessary to consider how thermal comfort and energy efficiency relate to each other and how controllability might influence them.

Increasing the controllability of systems increases the satisfaction of users because it allows greater adjustment of environmental conditions, in addition to having a positive psychological effect generated by the increased perception of control [6,113]. On the other hand, the availability of system control can lead to increased energy consumption. Shahzad et al [114] verified simultaneous activation of cooling and heating systems, and simultaneous activation of cooling and window opening, in a building where users had full control over systems. Thus, the energy consumption of this building was higher than of a similar building with automated central air conditioning. He et al [53] found that if environment temperatures are controlled considering the preferences of the most sensitive users, the selected values will be more restricted than the acceptable limits, generating higher energy consumption than expected even when personal systems are provided to users. This indicates that the presence of personal systems may not lead to energy savings or extension of the set point conditioning systems temperature by itself. Warthmann et al [24] use the results of the study of Boerstra et al [115] to argue that users would feel the same satisfaction with automated systems and manually controlled ones if these systems could accurately predict their preferences. In the study by Boerstra et al [115], users felt comfortable when the system was automatically set to the same settings they had manually defined as ideal. On the other hand, an identified disadvantage of manual control was the reduction in productivity due to the time spent adjusting the system. However, at that time, the authors [115] concluded that no system would be as accurate in predicting the user preference as manual adjustment, so the result found was not to be considered as an incentive to automation. Within the reviewed articles, it is noted that new technologies and prediction models are proposed to enable the reduction of the need for user interaction with the systems. However, it appears that few conduct a system validation in the field to verify the acceptability of users and the system daily impact. Personal comfort models are often submitted to some process of accuracy verification, but each study employs a different metric, which makes it difficult to compare the results [19,110]. This validation is usually done between parts of the data collected without the application of the proposed automation system, which does not enable the verification of its impact during regular operation.

As shown, user controllability can increase thermal comfort, but also increase energy consumption. Most studies mention automation as a way to solve this conflict, as both goals can be included in an automate control system to find an optimal operation point. However, few studies on personal comfort models propose a way of integration between these goals and an optimization system that covers them both. A great part of them (see Table 1) only includes the first stage of the process shown in Figure 6 - the production of prediction models. It does not cover the next step - proposition of a method to associate the personal models - so that, in case of divergent results, it would be possible to optimizing thermal conditions for the comfort of the group (optimize TC). After determining this optimized condition, the next step to set an environmental control would be the integration of this solution with the ambient conditioning systems, defining which settings or variables should be controlled. The systems included in studies were divided into two groups in Table 1: heating, ventilation and air conditioning systems (HVAC) that correspond to environment systems, and the local personalized conditioning systems (PCS). Table 1 shows that, despite the search terms used, less than one third of the reviewed studies included PCS. Most of them propose optimizing environment conditions by just controlling central systems (HVAC), mainly through automated set point temperature adjustment. On the other hand, as indicated in column “Goals” of Table 1, only three studies proposed automation systems to define the environment settings by aiming at both optimization of thermal comfort and energy efficiency (optimize TC & EE).

Some studies consider the energy impact, but do not include it as a system goal, proposing a simplified way to restrict energy consumption. In studies [67,86,108], consumption is not directly addressed but it is proposed the raise of environment temperature to the maximum acceptable (29-26°C) while the personal fans are automatically controlled to maintain local comfort, which helps reducing energy consumption of central systems. Du et al [82] consider a similar condition, studying the prediction of thermal comfort in a high-temperature environment (28-32°C) with three types of personal ventilation systems: a fan, a personal ventilation (PV) with cold air jet and another PV without cold air. The authors do not suggest how to optimize the ambient condition, but how to predict the thermal comfort intervals varying the settings of each system, which would enable an automation. Other studies without PCS set a limit range for set point temperature so the definition of comfortable conditions does not have a negative impact from an energy standpoint - one study defines the range of 20-26 °C [99] and the other of 18-27 °C [96]. Similarly, one of the systems proposed by Jung and Jazizadeh [102] defines the optimal point of thermal comfort in a way that it falls as close as possible to pre-established limit temperatures of 18°C and 28°C for winter and summer, respectively. Another solution presented by Li et al [88], rather than restricting the set point temperature, suggests that users open windows when the internal conditions are considered comfortable, increasing the use of natural ventilation and reducing the activation time of conditioning systems. The activation time of systems is also reduced by occupancy prediction models that indicate a great impact on energy consumption [84,92–94]. However, one of them [94] shows that the association between thermal comfort optimization and occupancy prediction generates greater savings as well as better adjustment than the occupancy prediction model alone, since the condition is defined based on personal models of present users. When compared to the consumption of the system with fixed set point, the control considering occupancy prediction reaches 29.5% of energy savings, while the personal comfort optimization associated to occupancy prediction reaches 41%, which means an increase of 11.5% of energy savings. It is necessary to emphasize that control by occupancy prediction produces good results only in spaces with regular occupation, otherwise it can generate unnecessary systems activation and energy waste [93,116].

As previously mentioned, only three proposals define a control system that aims at both goals simultaneously. Kalaimani et al [95] propose a system similar to [94] in which the optimization of thermal comfort conditions is calculated according to individual models of present users. However, when the user is present, his personal system (heater or fan) is automatically turned on and local conditions are considered when determining the environment temperature. In this way, the environment can be maintained at higher temperatures and there is no waste resulting from the conditioning of unoccupied spaces to more restricted conditions. The authors [95] indicate that, during summer, the use of fans allows energy saving up to 82% higher than that achieved by the optimization of temperature disregarding the local effect of fans. However, during winter, with total occupancy, the activation of local heaters can result in higher energy consumption when compared to the elevation of environment set point, because the power of individual heaters is 700 W, while the fan power is only 30 W. On the other hand, when there is partial occupancy, heaters activation is advantageous and can reach up to 32% of energy savings in relation to the adjustment of environment set point without heaters local effect.

The environment studied by Chaudhuri et al [100] does not have personal systems; however, an optimization algorithm that defines the set point temperature and HVAC operation settings is proposed in order to optimize the thermal comfort of users with the lowest possible energy consumption. To do so, the consumption of air conditioning system is predicted by a simplified computer simulation, based on measurement data from a real system. Personal prediction models based on different variables are tested to determine optimal thermal comfort conditions. Applying the optimization algorithm and thermal perception feedback from users, an energy saving of 36.5% is estimated in relation to a standard operation with fixed set point at 24 °C. On the other hand, among the tested personal models, the one that achieved the closest results to the users' feedback allowed 34% savings in relation to the standard operation. This means there was a difference of 2.5% between the performance of the system with feedback and with the prediction model, resulting in the reduction of energy savings with the prediction model. In any way, the reduction was small considering the benefit of the prediction model of not depending on continuous user feedback.

The system proposed by Xu et al [80] combines the solutions indicated in the above mentioned studies adding one step ahead. It presents a system that considers the local effect of individual fans (PCS) and an optimization algorithm that predicts the energy consumption of systems while also considering the energy cost to define the optimum set point. In this case, the activation of desk fans is automated and the reduction achieved by the system is presented in terms of energy cost, considering 3 price schemes. The optimization of thermal comfort is made by activating fans up to the maximum acceptable speeds, previously identified for each user, and adjustment of the environment temperature within the range of individual thermal comfort, also initially established, so that the temperature is comfortable for all. System tests indicate that it is possible to keep the maximum set point of 29°C with the fans, while without PCS the maximum comfort limit is 26°C. Thus, automation system with the fans reaches an energy cost 45% lower than the same system without the fans. As in the study by Kalaimani et al [95], this demonstrates the economic advantage of considering the presence and local effect of PCS for the definition of environmental conditions. If the system of Xu et al [80] included individual heaters, the problem indicated by Kalaimani et al [95] would probably be avoided, because the proposed algorithm would automatically select the most convenient modification: activation of local system or modification of the environment set point.

Although these proposals present very interesting results, only the system of [80] was validated with users. However, this was done in a climate chamber with few people and the estimates of energy savings presented in the studies were calculated by computer simulation. Field validation plays a very important role in identifying gaps and conflicts, as well as verifying users' acceptance of the proposed automation and adjusting environment conditions. Despite the limitations, the study of [80] indicates that the implementation of environment management system, despite being complex, is feasible and achieves excellent results.

4.2. Thermal comfort scales and index

As indicated by Kim et al [19], Table 1 shows that different scales and index to set thermal comfort are used among the proposed personal models. In some cases, the scales used for user input do not coincide with the models' predicted output scale. Reductions and changes in terms are also verified. However, all studies define a reference index used to define the ideal conditions to be sought. In most cases, this is done from the thermal perception votes of the users who, after processing, are associated to the thermal conditions to define the comfort indexes [84,100,103]. Other studies do not involve surveys with users and are based on theoretical or simulated situations. In these cases, the predicted mean vote (PMV) is used as an index to define the thermal comfort condition [101,109] or simplified versions of the PMV-SET calculation [86,95]. The use of the PMV and its variants as a reference index is suggested in [75] as a way to define comfortable conditions without users participation and tasks interference. Nevertheless, studies show that PMV is not an adequate index to predict individual comfort, and may present a difference of 17% up to 42% in relation to the actual thermal sensation indicated by users [98,100]. Guenther and Sawodny [97] show that, for individual comfort prediction, a simple linear model has 40% more prediction accuracy than the PMV calculated from the average variables of the environment. Moreover, even if the PMV is calculated considering the environmental conditions close to the user and individual adjusted factors (clothing and activity), the proposed linear model has 70% predictive capability, which is 10% greater than PMV [97]. Kim et al [81] also compares the prediction capacity of a model generated through machine-learning based on the use of personal systems with the prediction accuracy of the PMV, and verifies 40% higher performance of the proposed model. However, the linear model proposed by [97], as well as the one generated by machine learning [81] does not use the same feedback scale on which PMV model is based, comparing the mean thermal sensation predicted votes to the votes of thermal comfort [97] and thermal preference [81]. Using common scales, Chaudhuri et al [100] conclude that a machine-learning prediction model based on the thermal sensation of women in a multi-user environment would be at least 20% more accurate than the PMV model, even considering adjusted versions of the PMV including adaptation (aPMV) and expectation (ePMV) factors. Enescu [22] inquiries about the lack of an automation system using adaptive model as the thermal comfort index. However, the prediction accuracy of users' thermal preference using the adaptive model as reference index is shown to be only 50%, which is similar to random guessing [81]. A more appropriate way to use PMV and PMV-SET are seen in studies [80,108], which use it as an indicator to adjust the temperature and air velocity, but previously define the acceptability and comfort ranges, customizing the target interval for each user based on their thermal perceptions. In any case, it is interesting to note that the only two studies covering the goals of optimizing thermal comfort and energy efficiency (optimizing TC & EE), including personal systems [80,95], use PMV as reference index. This indicates that, despite the accuracy problems, the PMV should not be disregarded, as it can solve complex situations where the applicability of more simple indexes may be insufficient.

Most of the reviewed studies (see Table 1) employ the users' thermal sensation (TS) feedback to define thermal comfort but, to do so, different ranges of the scale are selected, as shown in green in Table 2. Most of them use the seven-point scale used by Fanger [117] to define the PMV, but only two studies [82,100] consider the thermal comfort range proposed by him [117] - between +1 and -1. Most of them [92,93,98] consider only thermal neutrality (central scale value) as thermally comfortable. The authors [87,104] also define the central point of the thermal sensation scale as the system's target, but using a scale of 5 values in which the centre corresponds to "OK". Jiang et al [96] propose a correction of the seventh scale based on users sensitivity, so that the scale is simplified to only two values for those with low sensitivity: 0 and 1; where 0 corresponds to thermal sensation of -1 and 0; and 1 corresponds to thermal sensation of +2 and +1. This way, the scale is personalized for these users, and can be added to others seeking to define the thermal condition between +0.5 and -0.5 for all. The interval between +/- 0.5 is also considered comfortable in the work of [83].

Table 2. COMPARISON BETWEEN THERMAL SENSATION SCALES - VALUES CONSIDERED COMFORTABLE IN GREEN

Num.	[87,88]	[92,93,98]	[83]	[96]		[82,100]	[84,94]
+3		Hot	Very hot	Hot		Hot	
+2	Hot	Warm	Hot	Warm		Warm	Very warm
+1	Warm	Slightly warm	Warm	Slightly warm	Warm / Slightly warm	Slightly warm	Warm
0	OK	Neutral	Comfortable	Neutral	Neutral / Slightly cool	Neutral	Neutral
-1	Cool	Slightly cool	Chilly	Slightly cool		Slightly cool	Cold
-2	Cold	Cool	Cold	Cool		Cool	Very cold
-3		Cold	Very cold	Cold		Cold	

Another commonly used scale is the Bedford scale [97], which defines the thermal comfort associated with thermal sensation. This scale has 7 values, but there are many variations and uses, such as the reduction to 5 values and the modification of the nomenclature of terms, as shown in Table 3. As commented by Kim et al [19], these scale simplifications can be questioned because they are based on the authors' interpretation and not on traditional thermal comfort research.

Table 3. COMPARISON BETWEEN THERMAL COMFORT SCALES - VALUES CONSIDERED COMFORTABLE IN GREEN

Num.	[24,106,107]	[89,97]	[90,91]	[102]
	TC local	TC	TC	TC
+3		Too much warm		
+2	Too warm uncomfortable	Too warm	Warm discomfort	
+1	Cold uncomfortable	Comfortably warm	High warm discomfort	Uncomfortably warm
0	Neutral comfortable	Comfortable	Comfortable	Comfortable
-1	Warm uncomfortable	Comfortably cool	Cold discomfort	Uncomfortably cool
-2	Too cold uncomfortable	Too cool	High cold discomfort	
-3		Too much cool		

For example, in [84,94,102], the same scale of thermal preference is used for data collection with 100 values between cooler and warmer and a central "no change" value. However, in two of them [84,94], the scale was reduced to 5 fuzzy sets of thermal sensation, as shown in Table 2; while it was reduced to a 3-value thermal comfort scale [102], as shown in Table 3. In another case [112], the authors apply a 9-value thermal sensation scale and a 9-value thermal comfort scale, associating them to produce a 3-value discomfort scale. In the case of Aguilera [99], a 18-values thermal preference scale was also simplified to a seven-value scale (shown in Table 4), but the input and output scales are thermal preference scales, which keep the coherence of votes. Kruusimägi et al [92,93] associated a 7-point preference scale to a 7-point thermal sensation scale using the same terms. To do that, the authors asked the occupants how they would “like to feel”; and set the preference target value to “slightly cool” since the ambient was warm. These examples show a lack of pattern for scale terms and reduction methods. To avoid these issues, it would be better to unify input and output scales.

Table 4. COMPARISON BETWEEN THERMAL PREFERENCES SCALES - VALUES CONSIDERED COMFORTABLE IN GREEN

Num.	[99]	[92,93]	[81,110]	[87,88,104,105]	[111]
+3	Much warmer	Hot			
+2	Warmer	Warm			
+1	Slightly warmer	Slightly warm	Warmer	Warmer	Uncomfortably warm
0	No change	Neutral	No change	Neutral	No change
-1	Slightly colder	Slightly cool	Cooler	Cooler	Uncomfortably cold
-2	Colder	Cool			
-3	Much colder	Cold			

The reduction of scales after data collection for model training is used in several studies [89–91,100,102,112] to simplify the models, since the goal is predicting only thermal comfort or discomfort [89,112]. The greatest possible simplification would be to reduce the scales into two values, which would simplify the decision making on whether or not to modify the ambient set point, for example. However, it would not allow to define an adjustment direction and intensity, e. g. if the set point should be lowered or increased. Therefore, the largest feasible reduction is to a 3-value scale to allow understanding the required adjustment. Kim et al [81] suggest of the 3-values thermal preference scale of ASHRAE 55 [70], which besides allowing the simplification of the model is a well-established scale among thermal comfort researches. Other authors found this scale could also help increasing the models accuracy [111].

The reduction of comfort conditions to a single central point, as verified in Table 2, also seems to aim at defining a thermal condition that is closer to the ideal. However, it is shown that this constrain of thermal sensation or thermal comfort reference interval do not lead to higher thermal satisfaction [118]. Even the temperature range that ensures good cognitive performance is wider than thermal neutrality range [60]. On the other hand, the analysis of field data indicates that the central point of the preference scale is associated by users to a more restricted condition than that considered acceptable, comfortable or neutral, which should indicate a condition closer to that considered ideal [118]. Thus, using the thermal preference scale, besides being more suitable for the development of personal comfort models, allows the environment control to set conditions closer to those considered ideal by the user. Therefore, it is more suitable than the other scales for PCS automation, as they allow generating a condition that goes beyond comfort, being able to provide thermal pleasure. However, as it indicates a more restricted thermal condition, the use of this scale in an environment without PCS can have a negative impact. Controlling the environment by adjusting the central system set point to meet individual thermal preference may be challenging as it will probably increase the differences between comfort ranges of each user, and will likely lead to an increase in energy consumption compared to using other index such as thermal acceptability. In order to achieve this more restricted condition, while preventing the mentioned disadvantages, it is necessary to consider the local effect of PCS, which allows individual adjustment, supplementing the environment set point. A drawback of scale-value reduction is the loss of nuances of tolerance, which are helpful to define the intensity of adjustment to each user. Therefore, a solution for the diversity of preferences should be designed considering the combined adjustment of local and general systems and the level of adjustment.

4.3. Models output diversity solution

Less than half of the studies listed in Table 1 approach the second step of Figure 6 on how to solve the differences in predicted thermal perception among users for the definition of the environmental conditions that would please the group. Some studies with personal systems do not define a solution, but it is understood that it consists of the definition of a fixed room temperature and the automated adjustment of individual local conditions [67,86,108]. However, as Shetty et al [67] indicate, users do not always accept the same ambient limit, so it would be necessary to identify this limit and its hour-seasonal variations for automation. The adjustment of the temperature from users' average votes is the strategy proposed by the PMV model [70] and by other revised studies, such as [101]. Jiang et al [96] propose the use of the average vote, but this average is calculated with scales adjusted to the different sensitivities of users, resulting in a weighted average. The definition of the set point temperature considering the users sensitivity is also shown by [102] as the solution with the highest probability of predicting comfortable conditions among those tested by the authors. This solution defines the broadest temperature from the average user preference and their sensitivity ranges. The analysis of [102] compares this strategy to two others: the selection of limit temperatures that meet the majority (similar to that proposed by [80,84,94,98]); and the minimum deviation of individual preference (also used by [75,92,93]), proving it to be the most accurate one. Nevertheless, the authors [102] argue that definition of thermal conditions based on mean or majority vote may not be fair, because it can keep a small portion of people under constant discomfort. On the other hand, they comment that the use of personal systems may solve this problem, providing additional possibility of local adjustment.

Kim et al [19] mention that the ideal solution would be by consensus, but the definition of a actual consensual condition, which depends on the acceptance of all users [119], can be difficult and stressful to achieve. The only proposal that comes close to a consensus solution is that of Li et al [87] in which, after identifying more than half of the users in thermal discomfort, a temperature change of 1 or 2 °C is proposed depending on the level of discomfort, and must be accepted by more than 2/3 of the users to be implemented. Thus, the final decision is taken by the majority, and may not coincide with the consensus, but it generates more opportunities to express disagreement. He et al [53] apply a non-automatic process of consensual decision of set point adjustment in an office with two people with desk fans and show some possible consequences. The proposed process informs users about the modification requested by one of them and only applies it when the two members are in full agreement. However, it can be seen that, due to the difference in sensitivity of users, one of them ends up being the only driver of choice, so that the final set point is only 25.7 °C while the predicted limit of acceptability for similar conditions is 30 °C [4,5,66]. In addition to the negative impact on energy consumption of this solution, another disadvantage was the increased demand for user participation and time to set the temperature, which in the study by He et al [53] took more than 5 minutes. In a space with more people, the solution may require much more time and may be more complex, to the point of failing to reach consensus, which would require a complementary strategy.

On the other hand, the importance of considering the sensitivity of users in the solution of diversity is noted among the articles, since those who feel more discomfort suffer greater impact of the adjustment of the environment than those who are constantly comfortable. Jung and Jazizadeh [102] are the only ones who compare solutions for divergence of preferences that cover most of the presented proposals, so that the best solution suggested by them can be used as a reference even though it requires validation with users and incorporation of PCS. This solution could be used to improve the model of Xu et al [80], for example, including the consideration of sensitivity in the definition of thermal comfort and energy cost optimized conditions. The complexity of systems versus their production and response times also needs to be assessed. Not all studies validated with users indicate the temperature adjustment interval of the set point or other PCS controlled variables, as shown in Table 1. Among those including this information, most of them indicate the adjustment level should be of 1 °C or the value defined as the necessary to reach the comfortable target. And the adjustment interval should be of 10 or 30 minutes. In [97] it was identified a greater precision in the adjustment with a shorter interval. Li et al [88] indicate that the choice of a longer interval relates to the acclimatization period, as a variation in an interval shorter than 30 minutes would not be perceived. This point needs to be further studied, preferably with field tests that apply different adjustment intervals with user feedback, in addition to the evaluation of the technical feasibility of applying the adjustment interval. Discussion of the best modelling methods is not the focus of this paper, but studies comparing some methods indicate that Random Forest (RF) is one of the most accurate methods for modelling [67,81,87,88,91,104,110,111]. In Table 1, only those selected as the best solution or the one used in the study are indicated. It can be noted that, in addition to RF, there is also a significant number of studies that use Support Vector Machine (SVM) or Support Vector Clustering (SVC). Cosma and Simha [90] verify very similar accuracy between the SMV model and the RF.

4.4. Real-time personal data acquisition technologies

It is notable among reviewed articles that the method of data acquisition during the operation of automation systems is an important point. There is a tendency to look for non-invasive alternatives for data collection so that the control of the systems is as independent as possible on the input of users, especially in offices. In general, in the model production process, user feedback is required, but only to train a model that can predict these responses from other automatically collected variables. Although air temperature and relative humidity are the most frequently used variables in monitoring during operation, as shown in Table 1, it is necessary to predict personal comfort personal variables, which are captured by sensors and new proposed technological systems.

In the case of the study by Liu et al [86], occupancy sensors used by [67,83,84] would be insufficient to detail the position of users for fans rotation automatic adjustment. Therefore, the authors propose a tracking system with video georeferencing. However, most of the studies aim to track the skin temperature in one or more points and, to do so, they also need to locate the user and those specific body points, for which they present other solutions. One of them would be to associate a 2D reading sensor with a depth sensor [90] but, in general, as indicated in Table 5, it is used image reading (2D) sensors associated with processing systems that track points of interest. This way, it is possible to monitor users at a greater distance (~1m), which is perceived as less invasive. On the other hand, direct contact sensors [82,111] and infrared sensors close to the skin [89] simplify the mapping of surface temperature, although they are impractical for daily use for being uncomfortable and invasive. Smartwatches [83,88,98] also allow direct surface temperature monitoring in a comfortable way, but only the wrist temperature is measured, which may not be the best indicator for predicting thermal comfort. The main point measured by remote systems is the face temperature, which has a high concentration of blood vessels and, therefore, is indicated as more sensitive to environment variations, besides generally not being covered with clothing [24,91,104,120]. It would be possible to reduce the measured surface to the nose area, because it is one of the points that indicate greater correlation between surface temperature variation and users thermal perception [104,106]; in addition to not being obstructed by glasses like other sensible points [104].

Table 5. COMPONENT CHARACTERISTICS OF REAL-TIME TRACKING POSITION AND SURFACE TEMPERATURE ACQUISITION SYSTEMS

Reference	Tracking position system	Tskin capture system	User-system distance
[86]	Georeference + camera	-	0.5 to 4.5m
[101]	Camera + OpenPose + ML	-	
[90]	RGB camera + depth sensor	Thermographic camera	-
[91]	RGB camera + ANN OpenPose	Thermographic camera	-
[89]	Glasses	Infrared thermography	Almost direct contact
[24,106]	Kinect	Thermograph camera	1.2m
[104]	Haar Cascade algorithm	Thermograph camera	1.0m
[82]	-	Thermocouples	Direct contact
[103,121]	camera + Deep learning	Image colour & saturation	-
[122]	On-board pyroelectric infrared sensors + algorithm	8 Infrared sensors and 1 ultrasonic sensor.	0.05 to 1m

ANN – artificial neural network
ML – machine learning

To reduce equipment costs, [104,105] show that a thermographic camera with lower resolution is precise enough to measure the surface temperatures of the face (and nose) and its oscillations. However, Cheng et al [103] advocate the use of an even simpler and more economic system, in which the surface temperature is measured from images colour saturation captured by common cameras, such as those of computer monitors during work [121]. In this study, instead of the face, the temperature of the hands is monitored [103]. The thermal sensitivity of the different points of the body is also a current discussion (discussed in the subsection 5.1), and could also be applied to the case of automation systems, so it would be interesting to compare the models generated from images of the hands and face (or nose) to identify the most relevant point. Also aiming to reduce costs and insuring users privacy, Shaabana et al [122] propose the monitoring of clothing through infrared sensors and an ultrasonic sensor. This system allows to differentiate the skin temperature from clothing temperature and, applying a mathematical model of heat exchange, estimate with an accuracy of 0.07 clo the insulation of a user's clothing. The system proposed by [101] has a similar purpose - the monitoring of the metabolic rate and clothing - for which they propose user position tracking and a neural network to identify clothing and activities by images. However, the outcomes are standard values of the two variables, which indicate small differences between users without covering the real variability involved. On the other hand, with the increasing use of smartwatches among people, the acquisition of other personal variables becomes easier, such as Heart rate variability, identified by [123] as a very accurate indicator (94%) to predict thermal discomfort. It is also possible to measure the metabolic rate that can be used to replace users' anthropometric characteristics, because the basal metabolic rate corresponds to 45% to 70% of body daily energy expenditure and varies according to age, gender, body dimensions and constitution [124]. Luo et al [124] indicate that smartwatches are low-precision monitoring equipment, and Kobiela et al [112] indicate that, by associating the superficial temperature of the skin with the reading of the heart rate, it is possible to increase this precision. In addition, smartwatches have important advantages over other metabolism [124] and heart rate [112] monitoring devices, which are portability and pleasant aesthetics, which make them more acceptable to users. It is foreseen that these technologies will be further developed and become more precise, as well as other wearable sensors, according to current market trends [20,125].

4.5. Alternatives to system automation and other spaces

Inappropriate operation of conditioning systems can lead to great energy waste and thermal discomfort in shared spaces [114,126]. Therefore, most of the reviewed articles propose solutions that involve automation, however, some authors believe that systems providing users with awareness and information about the environment could also be efficient [114,127–130]. In [114] the authors found that users with greater control opportunities had a negative impact on building energy consumption, and they pointed out that the problem could be solved by indicating the best strategies of conditioning to the users. The authors recommend a system with lights that indicate to the user the most appropriate time to open windows, taking advantage of natural ventilation depending on external thermal conditions. The system would also shut down automatically the central cooling when the user opens the windows. This idea is no further detailed, but the authors indicate a possibility explored in other articles that propose ways to help the user to control the environment more appropriately. Since these proposals rely on manual operation and direct human action, they can be understood as alternatives to full automation. Table 6 summarizes the information about the system proposed that will be discussed in this subsection.

Table 6. Summary data of studies on alternative environmental control systems

Reference			System components					Conditioning systems	Application				Validation with users?
Authors	**Year**	**Building type**	**Collected data**	**Target**	**model method / prediction**	**Goals**	**Interaction platform**		**Control type: variable**	**Operator**	**Diversity solution**	**Input frequency**	**Number of people/ method**
Karatzoglou et al [116]	2017	Office	TS (7)	TS (7) = 0	-	Optimize TC	Web application for thermostat control	AC	Indirect manual (web): set point direct: on/off	occupants	Mean vote	1h	9 / field survey
		Office	ta; rh; Text; occupancy; TS (7); EC	TS (7) = 0; EC = 450 W	Proposed algorithm with 4EC to 5TC weight	Optimize TC & EE			Automatic: set point direct: on/off	auto/ occupants		1h	
		Office	ta; rh; Text; occupancy; TS; EC	TS (7) = 0; EC = 450 W	SVR / next hour TS, EC, occupancy	Optimize TC & EE			Automatic: set point; on/off	auto		10 min	
Shahzad et al [131]	2019	Office	ta; rh; TS (7); TP (7); TC (7); Tsat (7)	TP=0; TS=0; TC > 0; Tsat>0; PMV=0	Real-time PMV calculation	Optimize TC	Visual panel	NV/AC	Manual (BMS): set point	manager	Manual decision based on data visualization	-	12 / field survey
Harfield and Rattanongphisat [129]	2017	Public: University lecture room	ta; rh; EC	Ta>20°C; AC on if occupancy on	-	Optimize TC & EE	Visual panel; smartphone app for notification	AC	Manual: set point	manager	Fixed target value (no user vote)	15 min	No user vote
Gaonkar et al [130]	2018	Public: Gym/ Shopping mall/ Movie hall	ta; clo; met; building characteristics; internal loads	PMV simplified closest as possible to zero	GA; multiple Pareto / Energy cost; Thermal discomfort	Optimize TC & EE	Direct data to BMS controller	AC	Aanual (BMS): set point	manager	Pre-established fixed range (no user vote)	30 min	no

Rajus and Woodbury [128]	2018	House	Tset point; clo; met; TS (7); building characteristics; weather file; windows/ blinds status	User define	Computer simulation / EC; ta	Optimize TC & EE	Interactive visual panel - input/output data or smartphone notification for automatic output	NV/ HVAC	manual: set point; windows and blinds operation; clothing or auto /	residents	-	When needed	6 apartments / field survey
Botticelli et al [127]	2018	House	ta; occupancy; light; EC; GC; appliance status	User define	-	Optimize TC & EE	Smartphone interaction platform - control and notifications	HVAC	indirect manual (smartphone app): set point; on/off	residents	-	-	no
Caldevilla et al [132]	2017	Car	occupancy; ta	Preconditioning	-	Optimize TC & EE	Smartphone interaction platform - control and proximity sensor	HVAC	indirect manual (smartphone app): on/off	occupant (unitary)	-	-	no
Stephen [133]	2019	Car	ta; clo, vel	Fixed Ta set by user or PMV simplified = 0	Fuzzy logic / Tset point target	Optimize TC & EE	Control panel - input/output	AC	indirect manual: (control panel) or auto: set point	occupant (unitary)	- (single user)	-	no

ta – air temperature
rh – relative humidity
vel – air velocity
trm – mean radiant temperature
clo – clothing insulation rate
met – metabolic rate
Tset point – Set point temperature
Text – External air temperature
RHext – External relative humidity
EC – Energy Consumption
GC – Gas consumption
SVR – Support Vector Regression
GA - Genetic Algorithm
TC (n) – Thermal Comfort vote with “n” values scale
TS (n) – Thermal Sensation vote with “n” values scale
TP (n) – Thermal Preference vote with “n” values scale
Tsat (n) – Thermal satisfaction vote with “n” values scale
TC – Thermal Comfort
PMV – Predicted Mean Vote
EE – energy efficiency
HVAC – heating, ventilation, air conditioning system
AC - Air conditioning system
NV – Natural ventilation

Shahzad et al [131] propose a system for visualizing users’ thermal perception votes, so that adjustments can be made considering personal variations. The proposed system presents a visual diagnostic of occupants’ thermal perception based on their real-time feedback and also the calculated PMV based on local environmental variables. The goal is to help the controller to visually identify the position of uncomfortable users in the open office layout for adjusting the correct equipment. The manager or controller would receive this information on a tablet or panel, but it does not indicate how to proceed, such as how to solve the preference diversity or the level of needed adjustment. As a result, changes would be based on manager's judgment and ability to deal with possible conflicts. It does not include energy consumption either, which would be an important decision-making parameter. The systems proposed by [129,130] have the advantage of including real-time measurement of energy consumption associated to thermal comfort target. In study [129] the goal is to avoid energy waste caused by overcooling and cooling activation during unoccupied hours. Therefore, a panel and smartphone notifications are used to indicate when a room is unoccupied or its indoor temperature approaches 20 °C, as in both cases the cooling system must be turned off. The study [130] goes a little further using thermal comfort limits based on PMV to suit different types of space and including an algorithm to associate the tendency of discomfort to system energy consumption and set point temperature. The resulting model allows the manager to choose the ideal set point, understanding which of the two goals (thermal comfort or energy savings) is being prioritized, and at which ratio. However, unlike [131], propositions of [129,130] do not include users’ feedback.

In public spaces, like shopping malls, movie halls and gyms, studied by [130], the occupancy is not constant and the occupants vary a lot, so the use of a general thermal comfort index is understandable, as interactive options may lead to frustrating results [134]. Considering non-automated control, directing information to a central person who is not an occupant, and is responsible for the building’s energy consumption is assertive, as it removes this burden from users and allows impartial and reliable decision making. However, the system proposed by Gaonkar et al [130] could be fully automated, excluding the need for a manager, if the priority ratio between goals was pre-defined, like done by [116]. In lecture rooms (studied by [129]) the occupants stay in the same place for a longer time, which would allow them to interact more actively with the systems, like proposed by [75]. The proposition of manual control associated to informative panels and smartphone notification is argued by [129] to allow the optimization of old systems control that would be unfeasible to automate. However, [135] presents some ideas of how new technology could help solving this issue allowing automation by infrared signal codification.

Systems with interactive panels and smartphone notifications are also proposed for residential environments, but directed to the occupants and not a central manager, since unlike public spaces, they have direct economic motivation to take actions to reduce energy consumption and usually pursuing further thermal comfort adjustment [88,92,93,127,128]. Botticelli et al [127] propose a mobile interactive platform that allows residents to activate the heating system previous to arrival, increasing thermal comfort, but also indicating real-time energy and gas consumption to grow their energy awareness. In the study carried out by Rajus and Woodbury [128], the occupants of 5 residences were interviewed about what type of systems they would like to have at home: 1) a feedback system, in which they indicated their thermal sensation and received suggestions for action; 2) a fully automated system, which would anticipate better solutions and send notifications via smartphone; or 3) a system with a panel where it was possible to compare action by simulating building temperature and consumption. Although unexpected, users preferred the first option, because they considered it important to give their input, but preferred to receive suggestions only when requested. In contrast, the full automated alternative for housing proposed by Kruusimägi et al [92,93], which predicted occupancy and occupants thermal comfort, had a bad performance because the diversity of preferences was not properly considered and. By maintaining indoor temperature at the lower acceptable limit to save energy, the users felt disregarded and without any control. The authors concluded that in houses there is low number of occupants; thus, adjusting personal factors such as clothing or an individual conditioning system is more effective than changing the environment set point temperature [87]. Behaviour, tolerance and adaptation opportunities in residential buildings are very different from work spaces [136–140]. Even the types of PCS used in residential sector can be different from office spaces [50,51,54]. Therefore, it is necessary to better understand these circumstances in order to propose more appropriate prediction models. In this case, systems that allow users' input and interaction to assist in decision-making will be more suitable and should include adaptation strategies and their energy impact.

In cars, the situation is different from other spaces, the area is limited and most of the reviewed studies do not address the personalization of occupants' conditions like proposed by [24,47], but rather the control of the environment as a whole, focusing on a single user. In this case, the occupancy zone and environment are practically the same, and the proximity between the user and the air outlets turns the HVAC of cars into personal systems when only the driver is present. Therefore, studies indicate that the improvement of thermal comfort and system response can be achieved by better capturing environment conditions [133,141]. Stephen [133] shows that an automated system with fuzzy logic can maintain a target temperature more accurately than a fixed set point because it considers ambient temperature fluctuations; while [141] shows the capturing of variables could be improved, including the solar radiation effect, which is highly influential in this context. The automation system proposed by [132] aims to improve an electric car efficiency, besides generating thermal comfort, since the heating generates depreciation of performance and batteries. As a solution, the authors propose automatic preheating before the car is started, by identifying the proximity of the user, and using a small heat pump system [132]. Despite these proposed improvements, the system in vehicles could be more efficient if direct body contact systems such as seat and backrest heating systems were used [47]. This allowed the maintenance of a slightly warm to warm thermal sensation in an environment at 16 °C [47]. And it could also allow greater personalization of conditions to individual demands when there is more than one person in the vehicle, similar to personal ventilation (PV) systems in aircraft cabins [34–37,142]. However, the reviewed articles do not include ways to control these PCS automatically, they only include manual control.

Regarding shared offices, manual control for central system adjustment is not the best option. Even when users have access to the thermostat they could not feel comfortable using it, as it may have a negative effect on their colleagues [87]. In these cases, users can likely prefer to directly control a personal system rather than a central system thermostat, and to accept broader conditions when informed about the ecological benefit of ambient set point [143]. Thus, using automation may help defining an optimal point for all users, solving the diversity of preferences, besides allowing the consideration of energy consumption in the definition of environmental conditions. These optimization solutions can be included in partially or fully automated systems. The partial automation of central systems includes an indirect control of thermostat as proposed by [59,116], where users access a web platform to indicate their preferences; this feedback is automatically processed to determine a common set point for a shared space. However, for this system to work, constant users' feedback is necessary, which demands time and effort. Full automation aims to solve this disadvantage using a network that predicts users' thermal preference based on data collected for a short period of time [24,107,116]. However, predictive models always include a percentage of error, which must be compared to its benefits to determine whether or not it is advantageous.

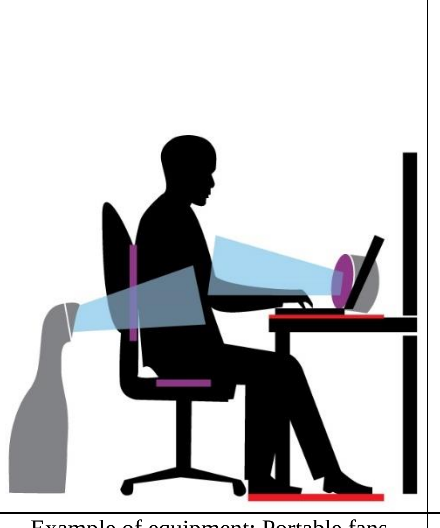
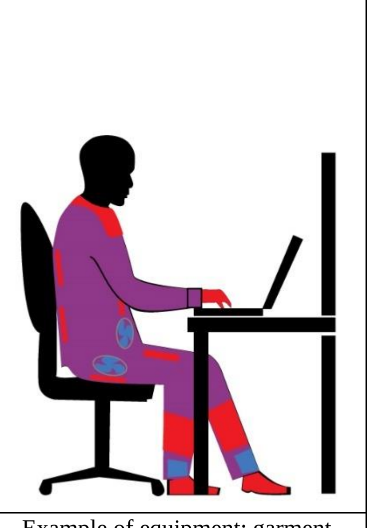
The conclusion about the best automation option for the central system and PCS is not that simple, since there are few studies that compare partial to full automation. One of them is the study of Karatzoglou et al [116] in which partial automation of central set point showed better performance than full automation because the occupancy prediction was disadvantageous. When the occupancy pattern is not constant, including its prediction in automation systems can lead to the activation of conditioning systems in unoccupied rooms or delay of activation, which generates energy waste or thermal discomfort [92,116,135]. On the other hand, partial automation depends on user feedback, which can cause the set point temperature to be fixed or adjusted according to a small number of more participative or uncomfortable occupants [109,134]. That is the reason why most of the reviewed studies (shown in Table 1) stand for full automation of central system set point in shared spaces. In addition, the automation of central systems and PCS could lead to greater energy savings, as it allows environmental conditions to be set at a further comfort range forcing PCS activation [67,80,86,108]. However, users usually prefer to have control over personal conditioning systems [55,108,144,145], and manual control may allow a fine-tune of local conditions that compensate prediction models inaccuracies [86,115]. While more studies are needed to compare the options, the solution might lie in automation of the central system and manual control of PCS. This configuration would enable the main advantages of both systems and higher performance. The manual control of PCS keeps the user's perception of control and makes local adjustment more accurate, while central system automation brings a broader set point, yet adjusted to daily and annual climate variations. Regardless of the selected automation level, consideration of local PCS settings for definition of ambient set point temperature is very important for increasing energy performance (see subsection 4.1). This can be achieved in two ways, with direct control and sensors that record and transmit local conditions, or by indirect control, through a digital platform that applies and transmits settings directly to central control. None of the reviewed publication have combined and tested this option with users. In addition, for ensuring the effectiveness of local control, personal systems need to meet users demand [146], so the correct selection of equipment is required, which will be addressed in the next section.

5. Selection of personal conditioning system

In the previous section, the steps and questions regarding the configuration of environmental system controls considering personal comfort models and personal conditioning systems were discussed. Few studies [67,75,80,86,95,97,108] included personal conditioning systems (PCS), although they have confirmed the great advantages to increase thermal comfort and energy efficiency. Some of them [67,75,80,86,97,108] included different types of fans and personal heaters [95], but there is a wide variety of equipment that could be used instead. Therefore, it is important to discuss how to select the PCS to be implemented in an environment in order to achieve the best performance.

In order to make comparison possible, studies usually separate equipment by two main classification criteria: equipment type and generated effect [4,23,24,42,49,50]. The effect relates to the local conditions and climate in which the building is located, since in a cold location there will be greater demand for heating, while a predominantly hot climate will have greater demand for cooling. However, it is also possible to provide both types of equipment forecasting seasonal variations throughout the year or select an equipment that has both functions [23]. Warthmann et al [24] propose this classification to be more specific based on the associated physical phenomenon, since they will be felt differently, which may be: radiant, convective, evaporative or conductive. On the other hand, system classification by type is generally based on the associated support, such as furniture (chair, table, task, panel) or a room surface (partitions, ceiling, floor) [4,23,24]. There are few systems associated with accessories and almost no clothing or textile system - i.e., wearable systems - identified as current research focus, thus not being included in these reviews and comparisons. In general, garment and textile systems are assessed against each other and reviewed separately, as in the case of [21,125,147]. Studies such as [42,44,61,144,148] compare wearables and garments with other types of PCS. Among PCS studies, an effort is observed to produce more portable, low cost and efficient equipment, which reduce the implantation cost and allow the maintenance of thermal comfort when the users are away from their workstations. In this way, mobility becomes a key point for current system characterization. So, three system conditions can be defined, as shown in Table 7. The first (Table 7a) corresponds to fixed systems in the workplace, i.e. stationary. Although they allow some position adjustment, many of them depend on a duct connection to auxiliary systems to work. The portable ones (Table 7b) do not have such restrictions, work independently of the ambient systems and can be positioned as the user prefers, as well as easily removed or included in the environment. The effect of the portables depends on the proximity to the user, which does not occur when he is absent from the workstation and moves around the environment. The revolving comforter (RoCo) is a portable system that tries to keep the cooling effect constantly following the user through the environment. To enable a mobile conditioner, an integrated condenser with the phase change material (PCM) is used to store the heat that the system would need to dissipate [39–41]. However, this system will still be part of the workplace and will depend on user proximity being maintained to take effect. The wearable systems, as shown in the Table 7c images, do not face this barrier because, instead of being part of the building as fixed or portables systems, they are in direct and constant contact with the users, which allows total mobility.

Table 7. Personal conditioning Systems classified according to mobility – colours represent: cooling (blue), heating (red), both cooling and heating (purple)

a) Fixed PCS	b) Portable PCS	c) Wearable PCS
		
Example of equipment: Personal ventilation systems (PV) [38,82,142,149]; radiant cooling and heating table [49,55,150]; heating and cooling panel [49,150]; fixed fans [14,97,108]; underfloor controllable systems [151]	Example of equipment: Portable fans [42,49,53,61,144]; portable evaporative cooler [56]; portable heaters [50,51,144]; chair systems (heated/cooled) [23,42–48,148]; feet mattress [148]; table pad [148]; movable systems (RoCo) [39–41]	Example of equipment: garment with attachments [31–33,152,153]; cooling/heating textiles [21,62,154–156]; thermal accessory like: pads to neck, belly, ankle, wrist, legs, and heated gloves, shoe insoles and socks [42,44,144]; wrist bands [157,158]

PCS selection can first be based on the classification criteria presented above: what kind of physical effect is produced, what is the type of equipment support, and what degree of mobility does it allow. A tendency for searching greater mobility was identified in the reviewed studies. The use of wearable systems highlights the importance of discussing which body part the stimulus should target in order to obtain the best thermal effect, since there is a great diversity of spots that can be affected, as illustrated in Table 7 (further discussed in subsection 5.1). Besides the thermal effect generated by the systems, it is also important to consider the energy consumption or power; thus currently proposed performance indexes are another selection criteria that will be discussed in subsection 5.2 [42,49,50]. Finally, subsection 5.3 will present more details about the revised wearable systems and other factors that should be considered in order to select the most appropriate system, as well as possible ways of integrating these systems into environmental control.

5.1. Targeting the stimulus to a body part

The first point to be considered for the definition of the stimulus to be used is related to the environment. It is verified that the local stimuli opposite to the ambient temperature has a greater effect on the overall body sensation. In other words, in warm environments a cold stimulus will has a greater global impact than a hot stimulus. However, because of the non-homogeneous distribution of thermoreceptors in the body, it is also important to evaluate on which point or points this stimulus should be applied. The cold thermoreceptors are located closer to the skin surfaces, while the hot thermoreceptors are deeper and concentrate mainly on the core of the body: the torso and the head [66,159]. Zhang et al [15] indicate that in uniform environments, global comfort is proportional to the body point under greater discomfort, but in non-uniform environments, such as those defined by the use of personal systems, the level of global comfort is defined by the average between the body point under greater comfort and the two with greater discomfort. This indicates that, if the right point is stimulated, it can modify the overall thermal comfort, because the points in discomfort will have less influence on the overall comfort [13,15,66]. This finding makes it possible to propose punctual systems, with low energy power, to maintain users' overall thermal comfort [5]. As shown in Table 8, the findings from the studies of [15,160] indicate the points of greatest influence on global sensation, which are distinct in the uniform and non-uniform environment. Thus, in environments where personal systems exist, the conditions will be non-uniform, and the overall thermal sensation will be closer to the local thermal sensation of the extremities of the body (hands and feet) in the cold environment and closer to core thermal sensation on warm environment defined by: chest, back and pelvis. In relation to thermal comfort, the points with the greatest local correlation to overall thermal comfort are the head and the face in warm environment, while in cold environments the foot is the main body part to target. Other studies also identify the head as a relevant spot in warm environments, especially because it concentrates the highest density of cold thermoreceptors in the body [161].

TABLE 8. MOST INFLUENTIAL BODY PARTS TO OVERALL THERMAL SENSATION/ COMFORT INDICATED BY ZHANG ET AL [15] AND ARENS AT AL [160]

Ref.	Zhang et al [15] and Arens et al [160]		Zhang et al [15,18]		Zhang et al [18,79]	
Condition/index	Uniform – Thermal Sensation		Non uniform – Thermal Sensation		Non uniform – Thermal Comfort	
Analysed body parts	Head/ face/ neck/ chest/arm/leg/ /back/pelvis/hand/foot		Head/ face/ neck/ chest/arm/leg/ /back/pelvis/hand/foot		Head/ face/ neck/ chest/arm/leg/ /back/pelvis/hand/foot	
Environment condition	Cold	Warm	Cold	Warm	Cold	Warm
Temperature	16-32°C				16-32°C	
Main effect/ correlate	Foot	Face/ Head	Foot / hand	Back /chest /pelvis	Foot	Face/ Head
Low effect	Neck/chest/ pelvis	Foot/pelvis	-	Hand	Head/face	Foot

The studies by Zhang et al [15] are an important reference on the subject, but the current reviewed studies indicate other results, as shown in Table 9. Despite the thermoreceptor density, Fang et al [161] found that thermal sensation in the head is less influential than that of the upper body part (chest, back, arm and hands) in a warm environment. This result is similar to what Zhang et al [15] found in a non-uniform environment. Upper body parts prevail among indications of influential parts in studies because they are highly correlated or vary according to the overall thermal sensation in non-uniform environments (Table 9). On the other hand, the results of Wang et al [150] are opposed to the others by pointing out the legs and thighs as more influential body parts, while the other studies indicate these lower body parts as the least influential ones. This difference may be due to the fact that the study by Wang et al [150] considers mainly the heat flow and skin temperature for defining the points, while other studies are based mainly on users' thermal perception. In [150], researchers indicate upper back as an important body part and, according to Yang et al [162], among the four main parts of the torso this is the most important one for receiving local stimuli, achieving greater effect. In order to identify more precisely the sensitive body spots for the application of punctual stimuli, Filingeri et al [163] performed a sensitivity mapping of the hand and foot thermal sensation that more recently (retrieved after the research date) was extended to other body parts [164]. Results indicated the most sensitive body parts for both hot and cold would be: the cheeks, back of the neck and buttock. This result can be regarded similarly to those identified for warm environment by Zhang et al [15] and other studies, if the back of the neck is considered as an extension of upper back, since this part is not addressed in those studies. The same occurs with the pelvis, which is rarely included, but is part of the torso and upper body parts. The cheeks might be a more sensitive spot on the face and the whole head might actually have less effect than the torso, although it is an important body part. In contrast, hands and feet are not identified as relevant in any of the studies in Table 9, while they appear as important in Table 8, especially the feet. The sensitivity mapping [163,164] also identifies greater sensitivity of hands than feet, which coincides with the higher concentration of thermoreceptors in hands [161], going against the findings of Zhang et al [15]. However, this may result from the study conditions, because body sensitivity mapping was done in a neutral environment (at 25°C) applying hot and cold stimuli. In turn, Zhang et al [15] focus on opposing situations between environment and local stimulus, because they identified that, in the condition studied by [163,164], these stimuli have less correlation with the global condition, indicating less impact.

TABLE 9. MOST INFLUENTIAL BODY PARTS TO GLOBAL THERMAL SENSATION (TS) – OTHER STUDIES RESULTS

Reference	Wang et al [150]		Fang et al [161]	Yang et al [162]	Fang et al [34]	Luo et al [164]
Condition	Uniform – TS		Uniform - TS	Non uniform - TS	Non uniform - TS	Non uniform - TS
Analysed Body parts	Chest/upper arm/thigh/lower leg/ belly/upper back/ lower back		Head; Upper Body Parts (BP): chest/ back/arm/hand; Lower BP: thigh/ lower leg/foot	Local stimuli: Chest/ belly/ upper back/ lower back No cooled: head/hand/forearm/ lower leg/ thigh/foot	Local stimuli: upper head aircraft PV Head / Upper BP/ Lower BP	Local conduction: hot/ cold stimuli Whole body: 318 local skin spots
Environment condition	Cold	Warm	Warm	Warm	Warm	Neutral
Temperature RH	21-15°C 50%	25-31°C 50%	26/28°C 40%/60%/80%	28/30/32°C 50%	25-28°C 25-30%	25°C 40%
Most influential	Lower Legs/ thighs/ upper back	Lower Leg/ thighs/ upper back/ Upper arm	UpperBP: mainly chest and back/ Head	Upper back	Upper BP	Check / buttock /neck back
Least influential	Chest/ belly/ lower back	Chest/ belly	LowerBP	Chest / no cooled Body parts had no significant change	Lower BP	Foot/ lower leg/ chest

In view of the foregoing, there is no consensus among studies concerning the definition of the most influential body part to overall thermal sensation, possibly because of the varying conditions of the studies. This suggests this topic still needs to be further studied, perhaps by conducting studies such as [163,164] in non-neutral environments, with application of other thermal perception scales such as thermal comfort or preference. Another way would be conducting more studies like the one of Fang et al [34], where a PCS is tested and the overall and local effect on the different body parts are evaluated. Hence, better solutions can be devised, as occurs in the study by Fang et al [34], where it is proposed to re-position the air nozzles of aircrafts closer to the users' torso, which avoids directing cold air jets to facial mucous membranes. It is also interesting to note that each study is done applying a different effect on the body, such as convective [15,34] or conductive [162,164], which can be related to the study target system. This topic requires further discussion and studies using similar methods so the results can be properly compared.

5.2. System performance index

Despite the search to identify the most influential body part on the overall sensation of comfort, it is observed among studies that the best thermal effects are achieved by the association of different devices, increasing the affected body surface area [24,42], which is also preferred by users [49]. In the study by Luo et al [42], for example, in an environment at 18°C, a heated insole or wrist pad was not enough to modify the body's thermal sensation. Therefore, these systems that affect the wrist or feet needed to be associated with a chair that affects the pelvis and the back in order to achieve comfort; and their resulting effect and energy consumption should be considered when choosing the best option. The chair of this study in heating mode has a maximum power of 14 W, while the wrist pad 7 W and the insole 2.4 W [42], so the association between the chair and the insole results in lower electrical power, which may result in lower energy consumption. However, [44] indicates otherwise, since the association of a leg warmer to the heating chair made users reduce the chair heating power, which results in lower energy consumption than using only the chair. In warm environments, it is noted that desk fans are the most efficient equipment [24,42,49], but users may prefer the effect of a radiant cooling desk to a high speed air flow [38]. Hence, the ideal way to assess equipment performance is to use indexes that associate the thermal effect to energy consumption and user perception. One of the first proposed indexes assesses thermal effect by calculating the temperature shift perceived by occupants with the use of the personal system, which is called Corrective Power (CP) [4]. To do this, the user's neutral temperature with (Tn_{with}) and without the personal system ($Tn_{without}$) is compared using the equation indicated in Table 10. Cooling-Fan Efficiency Index (CFE) is proposed by Schiavon and Melikov [165] as an index to compare the effect of multiple types of fans based on the concept of efficiency: power out/power in. In this case, power in is the electrical input power of the equipment (W), while power out is the difference between the equivalent body temperatures measured on a thermal manikin, with and without the system effect (Δteq), as shown in Table 10. Thus, the CFE is determined based only on physical phenomena, while the CP considers the users' perception through thermal sensation votes (CPs) or thermal comfort votes (CPc).

TABLE 10. SYSTEM PERFORMANCE INDEXES PROPOSED BY [4] AND [165], RESPECTIVELY, FOR PCS.

Corrective power (CP)	Cooling-Fan Efficiency Index (CFE)
$CP = Tn_{with} - Tn_{without}$	$CFE = (-1)\ \Delta teq / W$

More recently, Luo et al [42] proposed three indices that connect CP to CFE, including a weighting factor by the surface area of the affected body part, as indicated in Table 11. The first

(CP_{EHT}) is similar to Δteq, indicating the modification of skin temperature (T_{sk}) due to surface heat loss (Q) by its area (A), also considering the clothing insulation (I_{clo}). The second is the heat loss rate with (Q_{with}) and without ($Q_{without}$) the personal system multiplied by the surface area (A), indicating the total energy variation generated by the equipment (CP_Q). And the third is the performance coefficient (COP_Q) calculated by the ratio between CP_Q and the equipment electrical input power (W).

TABLE 11. SYSTEM PERFORMANCE INDEXES PROPOSED BY [42] FOR PCS.

Equivalent temperature CP (CP_{EHT})	Heat loss CP (CP_Q)	Coefficient of performance (COP_Q)
$EHT = T_{sk} - Q/A \times I_{clo} \times 0.155$ $CP_{EHT} = EHT_{with} - EHT_{without}$	$CP_Q = A (Q_{with} - Q_{without})$	$COP_Q = CP_Q / W$

As indicated by the authors [42], the disadvantage of proposed indexes lies in the fact that they are based only on thermal manikin measurements, which disregards the effect of body sweating and the variation of the local effect. As noted earlier, the point of effect of the stimulus will modify its impact on the overall thermal comfort and sensation, so equitable consideration of surface areas disregards this factor. The study by Fang et al [161] proposes different coefficients for each body part in the calculation of global mean thermal sensation. However, it shows that many other equations were previously proposed, each of them with different coefficients, indicating a lack of consensus on the matter [66]. As an alternative, the effect is considered to be better evaluated by users, so a similar index to the one presented by He et al [49] can be proposed, maintaining a similar ratio to that of COP_Q or CFE, as shown in Table 12.

TABLE 12. PERSONAL CONDITIONING SYSTEM PERFORMANCE INDEX PROPOSED BY THE AUTHORS.

Preference Corrective power (CP_p)	Preference Coefficient of performance (COP_P)
$CP_p = \|Tpn_{with} - Tpn_{without}\|$	$COP_P = CP_p / (\sum W)$ W = electric power or W = capacity/SCOP

As commented in subsection 4.2, instead of using the sensation or thermal comfort votes (as used in CP), it is recommended to calculate the thermal effect of the equipment by comparing the temperatures that generate the majority of preference votes for "no change" (neutral preference). Thus, the preference correction power (CP_p) would be calculated by comparing the preferably neutral temperatures with (Tpn_{with}) and without ($Tpn_{without}$) the personal systems. Then, the equipment performance index (COP_P) would be calculated dividing the CP_p by the sum of the electric power (W) of all personal systems activated at the voting moment (∑W). In the case of indirect personal systems (water or air conditioning systems), the power would be calculated by the equipment capacity (in W) divided by the seasonal coefficient of performance (SCOP). This proposal aims to align the reference scales used in the production of personal models with those used to assess the personal systems performance. The application of this proposed index, as well as other indexes, should be done in the field and not only in climatic chambers to evaluate the performance of the equipment during daily use by users with different characteristics. In this case, to enable the comparison between votes with and without PCS, the equipment can be introduced in an environment that does not have PCS, or be temporarily removed from an environment with PCS. In addition, it is important that more studies include wearable and garment system so they can all be compared under similar conditions.

5.3. Other selection factors and new technologies

In addition to the above-mentioned criteria, other factors should be considered for PCS selection, such as facility of use, versatility of use, adjustability [144], adjustment response time, cost and user willingness to use or purchase the system [49]. In an office space, it can be considered that the fixed PCS and part of the portable PCS will be part of the environment equipment, and the person responsible for its acquisition will be the same responsible for the payment of the energy bill, so that the financial return is directly perceived. However, the user of the equipment will not have the perception of economic or energetic benefit and, as shown by [49,53,145], occupants may prefer the use of air conditioning to the use of a desk or ceiling fan [49,53,145], for example. In this context, ease of control, adjustability and other settings will be important to determine the willingness to use the equipment [49,144]. Many portables can also be purchased by users, in which case cost becomes a determining factor of choice [49]. In addition, wearables are usually personal items purchased by users unless their use is mandatory in the workplace, such as uniform. Considering this, clothing and accessories enter the world of fashion, so that aesthetics and ergonomic and tactile comfort becomes crucial for these systems to be accepted [144]. This has a great effect on proposed garment systems with attached boxes. These solutions come from the adaptation of clothing used in extreme - generally fixed - thermal conditions, such as in aircrafts, hospitals, military use [147] and protective clothing [166,167] for everyday use in offices. For this purpose, garments with air or water circulation were adapted with attached boxes that produce the necessary cooling and/or heating of the circulated fluid [152,153]. Garments with attached phase change material (PCM), pockets and fans that cool the body directly, are also used for a similar purpose [31–33,61]. Despite presenting significant thermal effects and being even more efficient than other PCS [61,148], the ergonomic discomfort generated by the direct contact of fluids and PCM with the body and the unpleasant appearance and bulkiness [21] may make them less accepted by users. The pads are an alternative that allows greater flexibility of use, as they can be overlaid on clothing and be used only when necessary [44,144,162]. The tests performed by Knecht et al [144] indicated that, among several types of cooling pads and a desk fan, the last one is indicated by users as the most convenient for work space use, allowing greater adjustability of position and cooling affect. In addition, this study showed that users prefer solutions that require less interaction to run, so that solutions with PCM, which need to be loaded and unloaded for use, have been considered impractical [144]. As an alternative, cooled and heated pads are proposed with Peltier plates that are small in size and produce an instantaneous effect with low electrical power, close to 1W [157,158]. These boards were also adapted to accessories similar to watches, improving the aesthetics and user acceptability [157,158]. Flexible versions of Peltier plates are also being developed to facilitate their integration into wearable devices and garments [168].

The textile development presents alternatives that can be incorporated into regular clothes, without a considerable aesthetic impact and, in many cases, providing thermal adjustment with zero energy consumption. The evolution of these systems has occurred due to the development of nano technology, 3D printing and studies with new materials (such as graphene). Pakdel et al [21] presents a review on some textile systems, mainly for cooling, while Hughes-Riley et al [125] presents a review on electrical-textile, used for heating. Using the classifications presented by them, some examples of innovative textiles and clothing are shown in Table 13. In most cases, the performance of fabrics is assessed in comparison to cotton, which is considered a regular or traditional clothing textile.

TABLE 13. INNOVATIVE TEXTILE SYSTEMS CATEGORIES AND EXAMPLES

Type	Strategy	Example
Near- infrared (NIR)	reduce absorption of solar radiation, with a wavelength between 800-1100 nm	• Regular textile: cotton 63% reflectance (ρ) to NIR • Janus-cotton (TiO_2–SiO_2): 79% reflectance (ρ) to NIR [169]
Conductive	acceleration of body heat conduction to the environment	• Regular textile have low conductibility: cotton, wool, nylon, and polyester fibers are 0.07, 0.05, 0.25, and 0.14 W/m.K, • 3D printed a-BN/PVA: 0.078 W/m·K; achieved 1°C above cotton and 5W/m² more heat loss [170]
Photonic structure	Transparent to the wavelengths emitted by the body: between 7-14μm, increasing the loss of radiant heat.	• Regular textiles have low transmittance (τ) and reflectance (ρ) to IR: cotton and polyester 0.4-0.5 (ρ), 0.3-0.4 (τ) • ITVOF: 0.021 (ρ); 0.972(τ) would allow more than 23W cooling power [171]
Passive cooling/ heat	increasing/decreasing the surface emissivity of coatings	• Regular textiles: cotton 0.8 emissivity (ε) • Skin emissivity: 0.894 (ε) at 33°C • NanoPE reversible: carbon side 0.8-1 (ε); cooper side 0.303 (ε). Can increase or decrease skin temperature in 3°C [172]
Phase change materials	Provides thermal barrier effect against the environmental temperature fluctuations	• Aerogel-eicosane microparticles: latent heat enthalpy of 198.38 J/g – 37.2°C melting temperature [173]
Innovative Design	Changes in clothes design to increase heat loss or insulation	• Two Reversible Humidity Sensitive with nafion: smart sweating pore mimetic opening at 87% relative humidity increasing evaporative cooling (decrease 1.1°C in Tskin depending on Ta); Smart interlayer for adaptive insulation thickness-adjustable from 1mm to 15mm to reduce heat loss [154]
E-textile	Electronic Textiles for heating	• Polyester/Ag Nanowires/Graphene: motion generated energy 7nW/cm² [174] • 3 layers Janus reversible: Cu nanowires layer 0.3-0.5 emissivity (ε) to 2–18 μm wave length and 1.8-2.5°C decrease in surface temperature compared to cotton over a hand; including 8.4 V supply power in 15 s this layer goes from 18°C to 36°C; cellulose layer 0.973 (ε) and 1.4°C decrease in skin temperature compared to cotton over a hand [175]

As can be noted, there are a lot of diferent proposals for smartclothing and all cooling options do not depend on input power; they only enhance natural body heat loss or reduce sun heat absortion. There are passive and active heating solutions, and Hughes-Riley et al [125] also indicate the association between wearable computing and clothing to be a late trend. Most of these solutions are evaluated by laboratory or simulation experiment, and their effect over human body has not yet being tested considering skin and ambient temperature fluctuations. Issues related to transparency, sweat porosity, mechanical resistance and foldability are also mentioned as important for textile systems assessment, in addition to the safety linked to the use of nanotechnology and electric current close to the body [21,125]. One of the only studies found involving tests with people is that of Ke et al [62], who evaluate a shirt made of nanoporous polyethylene (nanoPe) fabric in a climate chamber set up as an office. The long sleeve shirt had 0.15 W/m.K conductivity and 0.879 transmittance, which allows increased body heat loss in comparison to a similar cotton shirt. The results showed that nanoPe allowed greater thermal comfort in an environment at 27 °C, where most users (94.4 %) indicated a preference for "no change", while with the cotton shirt, the maximum percentage of preference (83.3 %) for "no change" occurred at 25 °C, which would indicate a corrective power of thermal preference (CPp) of 2K. However, at the other temperatures tested, the nanoPe shirt caused the "no change" votes to be lower than those of users with cotton by: 20 %, 40 % and 33 % in environments at 23 °C, 25 °C and 29 °C, respectively [62]. This suggests that the use of nanoPe shirt would require low fluctuation of the ambient temperature around 27 °C for maintaining its positive performance, which may make its use in everyday situations unfeasible. That demonstrates the demand for further studies on this and other textile solutions.

It is a challenge to take into account the effect of these solutions on environmental management. Fixed PCS are more easily considerable because they are part of the environmental equipment and, in many cases, connected to auxiliary conditioning systems that work together with central controls. For fixed systems and some portable ones, some solutions are presented among the studies that involve personal models, such as automatic activation, and remote control [73,75,80,86] sensors for data acquisition to allow control by predictive models [81,95,97]. In the case of clothing and wearables, it is necessary to detect the presence of equipment that does not necessarily have energy power. Moreover, more than one type of PCS can be used simultaneously, and this would also need to be detected. An option would be remote detection of clothing characteristics by sensors communicating with the environment management system, such as using thermography [90] or infrared sensors [122]. However, these systems still need to be developed since, for example, the network developed by Shaabana et al [122] did not present good results for the identification of garments with low IR absorptance. Another option would be the use of a mobile phone as control interface, allowing both the indication of the presence and the adjustment of different active PCS [25,75,81,125], organizing and transmitting data.

6. Conclusion

This review addressed the implementation of personal conditioning systems (PCS) by discussing the latest articles on the subject, from 2017 to 2019 (available on Scopus platform), and focusing on multi-occupant office environments. Among publications, two main themes were identified: proposition and evaluation of different types of PCS, and development and application of personal comfort models for system automation and control. It was inferred that personal comfort models are a key tool for the implementation of PCS, allowing them to achieve the highest performance. Such models are suitable for the evaluation of non-uniform environments, considering inter-personal and intra-personal variations; therefore, they are the most appropriate models for predicting thermal comfort of users with PCS. Hence, they can be used as a reference for control and automation of ambient conditions. Automated control of environments with PCS was identified as necessary to achieve both systems goals simultaneously: generate maximum thermal comfort and maximum energy savings. Considering PCS local effect, automation allows the establishment of a broader ambient set point than would probably be set by users' manual control. Automation can include algorithms that calculate the optimal point between thermal comfort and energy consumption to adjust environmental settings considering the energy impact. It also enables to include mechanisms for solving preference differences and make these settings more appropriate for a diverse group of people. Several comfort indexes are used to establish the thermal comfortable conditions, based on the association and modification of different thermal perception scales. This diversity arises from trying to find an index that indicates a condition closer the ideal from the user point of view, reducing the number of scale values, facilitating and increasing the accuracy of prediction models. Based on the reviewed articles, it was found that the use of the 3-value thermal preference scale could meet all these demands and also unify the input and output scales, thus being recommended for model production. The solution of preference diversity should consider this index associated to a user sensitivity factor, and not just the average of votes. In this sense, the best solution identified is based on the probability of discomfort (or preference for colder/warmer) of each user in relation to a thermal condition to define the level of environment set point adjustment.

To operate controls based on personal comfort models it is necessary to measure environmental variables and consider personal variables. The studies tend to look for ways to reduce the need of users' feedback by monitoring the variation of personal factors through automatic collection, which is primarily based on skin and clothing surface temperature. These technologies aim to allow the most accurate monitoring of demand variations without requiring user interaction.

The dissemination and development of these technologies, as well as wearable sensors to increase their accuracy, is imminent. Contrary to this proposal, options with manual control and partial automation for offices, public spaces, residences and vehicles have been discussed. These options have the main advantage of being suitable for environments with variable occupancy rates, and events that may not be predicted by automated systems based on predictive models. It was concluded that the appropriate level of automation varies according to space usage. Although the revised studies are not conclusive, it seems that automation of central systems considering the manual adjustment of PCS is more appropriate for shared offices. To do so, the local conditions or PCS settings would need to be recorded and transmitted in real time to central control. This method would require several local sensors adapted to different types of PCS, which may become challenging when wearable systems are considered. Another option is the indirect control of PCS from a digital platform to adjust settings and transmit them automatically to the central control system. This last option could also include a feature for the user to indicate when they are wearing clothes made of special fabrics.

There are many reviews that address the comparison between different PCS. So, instead of comparing results from PCS evaluation studies, this review addressed the criteria used for comparisons and classifications that could be applied to select the most appropriate equipment for implementation in a shared office. A main criterion used is the effect produced, which can be heating or cooling, and the associated physical phenomenon: convective, conductive, evaporative or radiant. In addition, associated supports such as floors, ceilings, or parts of furniture are also used as a classification criterion. However, among the studies, there is a tendency to propose equipment that are not fixed to any ambient surface or furniture in order to maintain the effect on users even when they move around the environment. Therefore, mobility is a proposed criterion for PCS classification and selection. This proposal follows the growing trend of research on wearable equipment and textile development. For this system type, it is important to choose the best application spot for reaching the highest performance, as the stimulus of certain spots can generate overall body thermal pleasure. So a selection criterion could be choosing a system capable of targeting these specific spots. However, the results of the studies concerning this subject are conflicting, and hinder a conclusion on the most effective body spots to be targeted, as well as the use of the related criterion for selection. For performance evaluation indexes that relate thermal effect to energy consumption should be used. To evaluate PCS performance, it is suggested the use of indexes that relate thermal effect to energy consumption. In this article, a performance index based on the same thermal scale indicated for generating personal comfort models is proposed. In this way, the equipment assessment and application are aligned with field data gathered from users' thermal preference feedback. Other factors such as acquisition cost, bulkiness, aesthetics and versatility of use are also important, especially for wearables.

Regarding gaps and future work, the following topics have been identified:

- There is a general demand for more field studies, testing the acceptability of users to the proposed automation systems, especially in the case of PCS automation, so their feasibility can be proven. It would be important to compare the acceptance of different levels of automation, automation systems based on different thermal perception scales, adjustment periods and ranges (of temperature, air speed, humidity, etc.).
- There is also a need for studies that seek to identify the most sensitive or effective body spots for targeting stimuli. In this sense, it would be important to include a varied sample of people, with different physical characteristics such as age, gender and body constitution. In addition, it would be important to conduct studies using the same conditions to compare the effects of radiant, convective and conductive stimuli.
- It is important that PCS performance indexes be based on user feedback from the field, so that the thermal effects considered would be closer to the actual levels. To enable

this, the number of field studies with the use of various types of PCS, including wearable and garments under development should increase.

- Studies that include different types of PCS in environment control and automation systems should be performed to test other ways of integration to find which is better.

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APPENDIX B – PAPER 2

TITLE

Users' Assessment of Personal Fans in a Warm Office Space in Brazil

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ABSTRACT

The use of personal fans allows improving thermal comfort and energy savings in warm office spaces. This is due to individual adjustment and extended indoor temperature acceptability. However, to achieve that, the usability of fans must be assured. Therefore, an experiment with 40 people of various age groups was carried out to assess four types of fans, one of which is an evaporative cooling device. The goal was to find out which criteria should be used for selecting a fan to implement in an office space. Results show that air flow sensation and speed adjustment are considered the most important, although, noise is also very important, and cost can be an eliminatory criterion. The evaporative device was the best rated even in a space with 70 to 80% relative humidity, as users considered it to have a smooth controllable air flow. The results highlight these aspects should be considered in the selection of a personal fan and could also drive the industry to improve fans design for increasing usability and expanding the use of these systems.

Keywords: Desk Fan; Thermal Comfort; Office; Warm Environment; Personal Conditioning System

1. INTRODUCTION

In the face of the prospect of global warming, it is important to rethink the way we condition buildings, so lower energy-consuming strategies are expanded. To do that, conditioning design could change the focus from room to microclimate conditioning by applying stimuli close to the body. Personal conditioning systems (PCS) allow local adjustment of thermal conditions, enabling a group of people in the same space to control their microclimate according to personal demands (Brager, Zhang and Arens, 2015). In addition, local stimuli can generate alliesthesia, which produces overall thermal comfort (De Dear, 2011) with much lower energy consumption than needed from conditioning the total air volume of a room (Xu *et al.*, 2017). This approach allows the extension of cooling set point temperature, which could produce up to 70% energy savings (Hoyt, Arens and Zhang, 2015).

Many types of personal devices have been proposed and studied in the last decade (André, De Vecchi and Lamberts, 2020b). However, desk fans are considered one of the most efficient devices for warm conditions (M. He *et al.*, 2017; Luo *et al.*, 2018; Warthmann *et al.*, 2018). They are also easy to implement for being independent of the cooling system infrastructure (Boerstra, 2010). Previous studies indicate occupants find 30 °C acceptable when they have desk fans (Mishra, Loomans and Hensen, 2016; Warthmann *et al.*, 2018), since the increment of air movement reduces the warm sensation up to 3 °C (Zhang, Arens and Zhai, 2015). In shared office spaces it is common for the occupant to buy the fan when he/she is uncomfortable (Boerstra, 2010), but the energy savings are not perceived by him/her, because the building's consumption is paid by his/her employer (Y. He *et al.*, 2017). Therefore, to achieve the energy savings potential allowed by the extension of setpoint temperature, fans usability and attractiveness are very important to increase occupants' willingness to use them and meet users' needs. Knecht at al. (2016) indicate usability can be influenced by aesthetics, ease of use of controls and the level of adjustability provided by the device. So, design issues can decrease the device usability, hindering its potential to improve users' thermal comfort and energy savings. Some design issues have already been identified in previous studies.

André et al. (2020a) identified users avoided increasing the fan speed because it also increased the noise level, causing acoustic nuisance. Schiavon et al. (2017) indicate that, in shared office spaces, fan noise might be more annoying to the person who is not using it, as no positive effect is perceived by he/she. Therefore, the multiple domains of comfort must be considered as thermal, visual, acoustic and air quality may influence each other (Schweiker *et al.*, 2020). Another important aspect is fan air speed adjustment limitation, which may constrain the maximum air speed and the fine tuning, as usually fans have fixed speed levels. In some studies, it was identified that users wanted higher air speed, but did not increase it to the maximum possible level (Zhai *et al.*, 2013), probably because they preferred an intermediate speed level which could not be set by the device. In warmer environments users indicated the preference for more air speed even though the maximum speed level was selected (M. He *et al.*, 2017; Zhai *et al.*, 2017). This indicates that the maximum speed achieved by the fan was not enough, which may have limited the temperature acceptability. To achieve a higher body cooling effect, the stimuli of the device should target the torso and face (Zhang *et al.*, 2010). These are usually affected by desk fans (Schiavon and Melikov, 2009; Simone *et al.*, 2014). However, depending on the fan size and vertical rotation adjustment capability the air jet might hit only the belly and arms (André, De Vecchi and Lamberts, 2020a). Thus, rotation adjustment in the vertical axis is also important to boost the fan effect. On the other hand, fan size has two implications – restriction of the affected surface area and adaptation to a workstation, where the space available is usually limited for each person. Schiavon and Melikov (2009) found that increasing the affected body surface area increases heat loss and fan cooling effect. However, in a shared workspace, an individual table area is limited and occupied by paperwork, computer and other supplies that constrain available space, so smaller devices are usually easier to implement.

As identified in the literature, design aspects can influence desk fans usability. However, few studies were found comparing devices to address these issues. Therefore, the aim of this study is to identify the criteria users find most important when choosing and using a personal ventilative device. These criteria could be used for proposing guidelines for the industry and designers to improve this type of devices. It could also help researchers and users to select devices with better usability.

2. METHOD

To assess users' acceptability and willingness to use personal fans in shared office spaces, an experiment was set in the Laboratory for Energy Efficiency in Buildings (LabEEE) of the Federal University of Santa Catarina. The building is in Florianopolis, a city in the southeast of Brazil with a climate classified as subtropical by Köppen-Geiger (Peel, Finlayson and McMahon, 2007) and as 2A by ASHRAE 169 (2020). Ten 2-hour sections were carried out in February and March 2020, as they are summer months. Four people – working in laptops – were included in each section. The experiment room has 17 m² with two external masonry walls and lightweight internal partitions (drywall and plywood with acoustic insulation). Windows were shaded externally by fixed shading and internally by blinds, which were controlled by the researchers during the experiment to allow diffused daylight and prevent direct solar radiation. Throughout each experiment section, environmental thermal conditions were measured with data loggers (HOBO UX-100) at three different points, one inside the room, one in the hallway and another in the building corridor. This way, the different thermal conditions participants would be exposed to during the experiment could be registered. Sensors were turned on 30 minutes before the beginning of each section, and they recorded air temperature (from 20 °C to 70 °C ± 0.21 °C) and relative humidity (from 15% to 95% ± 3.5%) every minute.

Experiment procedure

Each section followed the procedures summarised in Figure 1**Figure** . The sections started when participants entered the room, opened the laptops, and filled a Personal Information Questionnaire (InfoQ). Then, participants received instructions about procedures. The experiment was developed so that each occupant could use four personal ventilation devices and could evaluate them comparatively at the end of the experiment. The assessment was done by completing the Fan Assessment Questionnaire (FanQ). Each device had the same period of usage (15 minutes) and their order was drawn randomly before each section.

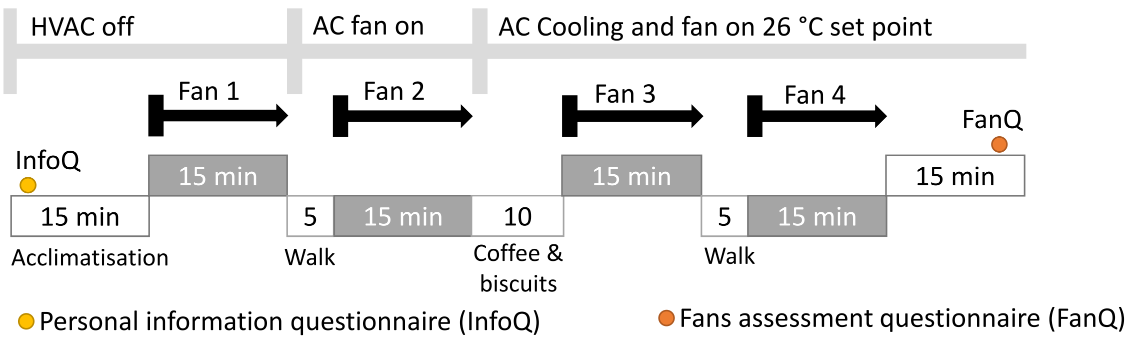

Figure 1. Experiment procedure

Participants were allowed to freely activate the device, adjust air speed and position the fan as they please during each usage period (indicated in grey in Figure 1). An interval was established to create a gap between the use of each device, lowering the influence of one equipment over the next. Continuous use was also avoided as it could reduce the fan cooling effect (Parkinson and De Dear, 2016). To maintain the use demand, the experiment included variations on personal and environmental conditions during these intervals. The personal variation was based on increasing participants' metabolic rate. This was achieved with walks through the building and a food break. The walk break consisted in participants walking a 5-minute path outside the experiment room, passing through the laboratory hallway, crossing the building corridor, going down two flights of stairs down to the lower floor, crossing the corridor again, going up two flights of stairs, passing the lab hallway and returning to the experiment room. Building corridors were always naturally ventilated, while the lab hallway was not controlled by the researchers during the experiment; therefore, it could be either naturally ventilated or air conditioned, depending on the day. Food break lasted 10 minutes, and participants were led to a naturally ventilated kitchen in front of the experiment room, where sweet foods, coffee and water were offered.

Environmental conditions variation was based on changing the conditioning mode. The air conditioning (AC) started completely off, simulating a dead band condition. After the use of the first selected fan – Fan 1 in Figure 1 – during the first break, the AC fan was turned on at air speed level 2. And during the second break (after Fan 2 usage), the cooling was turned on at the 26 °C set point temperature and the AC fan air speed was reduced to level 1. These variations were not communicated to participants so their decisions on whether to turn on the devices were not influenced by their knowledge of system operation, but mainly by their thermal perception and demand. This strategy was intended to mimic an automatic operation where occupants are not aware of the system status. However, HVAC status was informed when requested. It is noteworthy that the room was kept with all windows closed and open blinds before the beginning of the experiment to increase indoor temperature. Therefore, in the first 15 minutes of the experiment participants would have to acclimate to a warm condition. This first phase also aimed to level participants' initial metabolic rate, so that any activity performed before the beginning of the experiment would be stabilised and would not influence either their thermal perception or demand.

Selected Devices

During the experiment sections, each participant received one the same group of devices at a time. Therefore, each participant evaluated all four devices shown in Table 1. The devices were selected based on availability in the local market and their characteristics, to bring more variety to the experiment. Their main differences are different levels of air speed adjustment; vertical rotation adjustment in just two of them; slightly different sizes; and very different aesthetics. In addition, option d is an evaporative cooling fan, which recirculates air through an internal filter soaked in water. This option has also a much higher purchase cost than the other ones.

Participant Selection

To reduce bias of age and gender, a heterogeneous group of participants was selected. Forty people participated in the experiment and each section included two women and two men, from three age groups: 20-30, 31-50 and more than 50 years old. The ethical code in Brazil requires that the participation on research experiments to be voluntary, so the sections were arranged based on participants' availability.

Table 1. Tested devices specification

Fan label and main characteristic	a) 3-speed ventilative			b) 1-speed ventilative	c) 2-speed ventilative		d) 23-speed evaporative		
Sales image									
Number of Speed levels	1	2	3	1	1	2	1 5 tracks	2 12 tracks	3 23 tracks
Air speed (m/s)*	1.25	2.40	2.98	1.17	1.88	2.33	0.81	1.30	1.78
Sound power level (dBA)[a]	43.50	48.50	51.90	42.30	43.20	44.40	39.90	48.60	53.90
Power (W)[b]	4.50			3.00	10.00		10.00		
Cost (USD)[c]	$ 6.12			$ 8.45	$ 11.02		$ 367.33		
Dimension h x w x d (cm)	10 x 15 x 5			15 x 15 x 12	21 x 20 x 15		17 x 17 x 17		
Colour	Orange /green /black			Black	Blue & white		White or black + 7 light colours		
Rotation adjustment	none			horizontal	vertical and horizontal		none		
Other	works unplugged w/ rechargeable battery			-	clamp-fixing option		water tank for evaporative cooling		

[a] Measured at 50 cm distance from the centre of the fan
[b] Indicated by supplier
[c] Currency of 4.0835 BRL to USD on 01/07/2020. Reference: http://www.ipeadata.gov.br/

Data analysis

The collected personal information (InfoQ) and assessment questionnaires (FanQ) were processed in tables and matrices to analyze the results. Also, statistical analysis was performed to verify whether final preferences were dependent on fan assessment selection order or the experiment room operation mode variation. The same analysis was applied to verify if a significant relation could be established when comparing device selection with participants' anthropometric characteristics (weight, height, and gender). To do so, Fisher's Exact Test was conducted considering a confidence level of 95% ($p<0.05$). This statistical test is the most appropriate for small sample sizes ($n=40$) and categorical data analysis. The participants' weight and height collected in InfoQ were used to calculate body mass index (BMI) according the nutrition ranges of World Health Organization (WHO, no date). The measured environmental variables were also tabulated to analyze air temperature and relative humidity variation in each section.

3. RESULTS

Participants' anthropometrics

The participant selection was successful in building a heterogeneous group. As shown in Figure 2, 19 out of 40 participants were women (W) and 21 were men (M). The number of younger people (20 to 30 years old) was a little higher (42%) than other age groups – 30% were 31-50 and 28% were more than 50 years old. Regarding body mass index (BMI), most of participants (62%) are considered to have a normal nutrition rate (WHO, no date). However, 28% fit into the pre-obesity category and the other 10% into obesity. Thus, the sample does not include underweight people and BMI groups are not similar in the set.

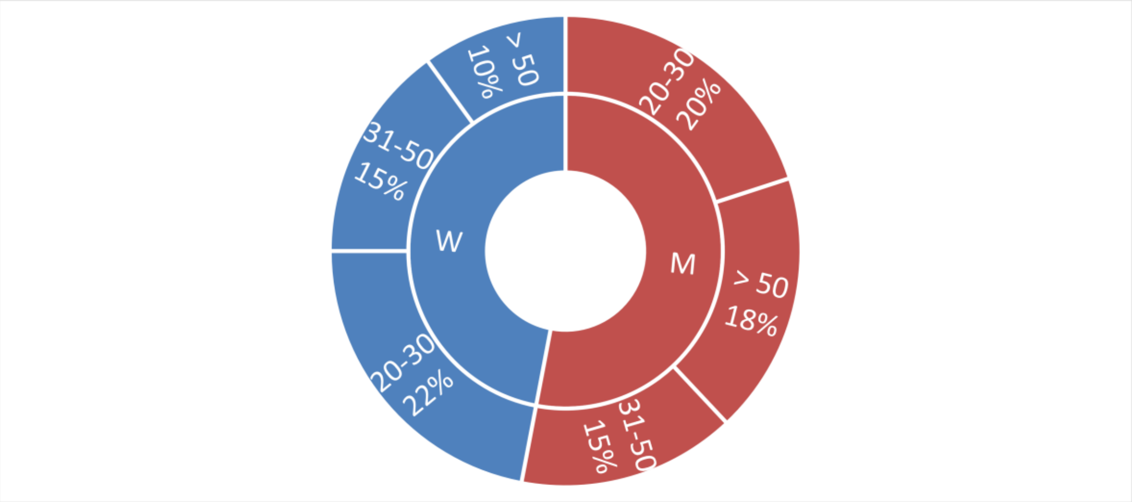

Figure 2. Proportion of participants per gender (Women in blue and Men in red) and age groups in years

Environmental variables

The average indoor air temperature (T_{air}) among all experiment sections was 28 °C, reaching a maximum of 29.3 °C in one section and a minimum of 26.9 °C in another, while average relative humidity (RH) was 70% ranging from 57% to 82%. Room thermal conditions varied throughout the experiment in a similar way in all sections. Figure 3 illustrates this variation in the second section of the experiment, showing the gradual drop in air temperature (T_{air}) after cooling activation and variation according to occupancy. When occupants left the room, air temperature and relative humidity tended to drop due the decrease of humidity produced by breathing and transpiration and the reduction of heat exchange between participants and room air. While the air temperature kept decreasing, the relative humidity (RH) increased again quickly when occupants returned to the room. Average variation of T_{air} was 1.5 °C and RH was 15%. Highest air temperature variation verified during the same section was of 2.1 °C while RH reached 19% variation.

Air temperature and relative humidity registered in the lab hallway and the building corridor, to which participants were exposed during breaks, were always lower than in experiment room. On average, the hall was 1.5 °C and 5% below the experiment room; and the corridor, 4.7 °C and 9% below the experiment room. Thus, when people left the experiment room during breaks (walks and coffee breaks) they likely felt this difference and a cooling sensation that may have affected their perception of experiment conditions. It has been observed in studies on transient spaces that this change between spaces with different temperatures can generate a sense of relief (Yu *et al.*, 2016). And in this case, returning to the experiment room would generate the opposite effect, intensifying thermal discomfort by heat.

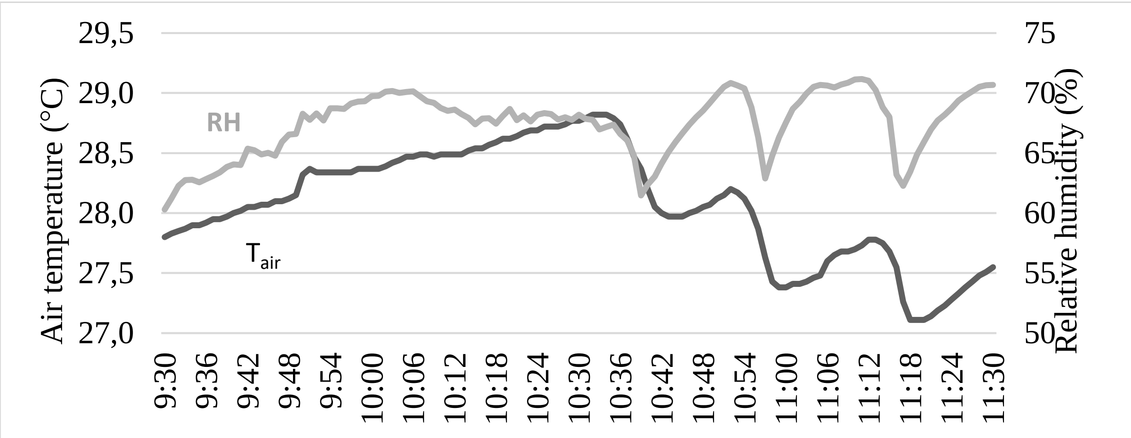

Figure 3. Air temperature (T_{air}) and relative humidity (RH) registered during the second experiment section

Willingness to use a personal fan

In the first questionnaire applied (InfoQ), participants were asked if they have a fan, and most of them (78%) indicated they have it mainly at home; and 55% have a fan in their workspace. This could indicate that most would have a pre-disposition to use and may already like to use fans. However, the type of fan was not specified, so they could be used to either ceiling or standalone fans instead of small personal devices. As shown in Figure 4A, when initially asked (InfoQ) which operation mode they would usually use in a day with similar conditions to the experiment day, half of the participants indicated natural ventilation (NV) and the other half indicated air conditioning (AC). But fans would only be used with NV (NV+fan). However, Figure 4B, shows that 2 of those participants who use AC (5% of total) and 1 of those who use NV+fan (2% of total) preferred to use NV alone. By the end of the experiment, as shown in Figure 4C, some participants changed their opinion and most of them (62%) indicated they would prefer either to use a fan associated to natural ventilation (NV+fan) or air conditioning (AC+fan) in a day like the experiment day. Preference ratio between overall AC and NV did not change significantly from 4B to 4C. However, almost half of those who prefer AC seemed to like the idea of using it with a personal fan and most of those who prefer NV thought it would be better to associate it to a personal fan. In the last questionnaire (FanQ), 72% of participants indicated they would like to have a personal fan in their workplace.

This result indicates that participants probably had no experience using a personal fan in a conditioned room before the experiment and being exposed to the test settings made them consider this possibility. Perhaps, turning on the fan while the air conditioning is on is counterintuitive. However, fans were accepted by part of participants as thermal offset in simulated situation, so the set point could be automatically extended to save energy. The impact on those who prefer natural ventilation was also noticeable. This result might indicate that a possible barrier to spread personal fans is the lack of experiences and opportunities to use them, as they are not usual in office buildings (Liu *et al.*, 2018).

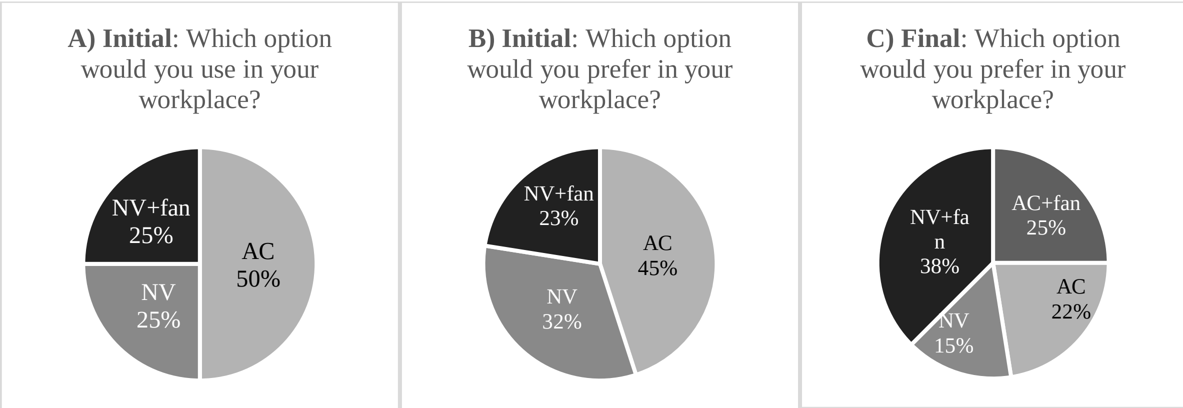

Figure 4. Preferred operation mode: natural ventilation (NV), natural ventilation with fan (NV+fan), air conditioning (AC), air conditioning with fan (AC+fan)

Assessment of fans aspects

Participants were asked to indicate how important they would consider each of a set of criteria when buying a personal fan. Results are shown in Figure 5, in which the assessed criteria were grouped based on related aspects. Participants rated as the most important the criteria related to thermal and acoustic aspects. The most important criterion for most participants (73%) was air flow sensation, followed by speed adjustment capability, considered the main aspect by 68%. The only acoustic criterion in this rank – noise produced by the fan – was considered the most important by 63% of people. While the third thermal criteria – vertical rotation adjustment capability – was rated as the most important by only 48% of participants. And the last thermal criterion, the possibility of reaching higher air speeds (higher maximum speed) was evaluated as the most important by a small number of people (18%), and it seems to be either second or fourth most important criterion for many participants. This means, adjusting and controlling air speed is important, but not necessarily by increasing it. Financial aspects such as fan energy consumption and cost were also rated as the most important criteria for 40% of people each, and the second most important by most of them, especially the cost issue. The next most important criteria were the functional and practical ones, such as size and USB charge connection availability. By last, aesthetic aspects were rated as the least important, and the possibility to choose the device colour (18%) seemed more important than general aesthetical issues (8%).

It was expected that criteria related to controllability, like rotation and speed adjustment, would be highly rated by participants as control is one of the main functions of a personal conditioning device. However, results show people want to be able to control air speed and direction, but the device must produce a pleasant sensation without noise and must be affordable as well. Achieving a higher air speed seems, on the other hand, to be secondary to the participants.

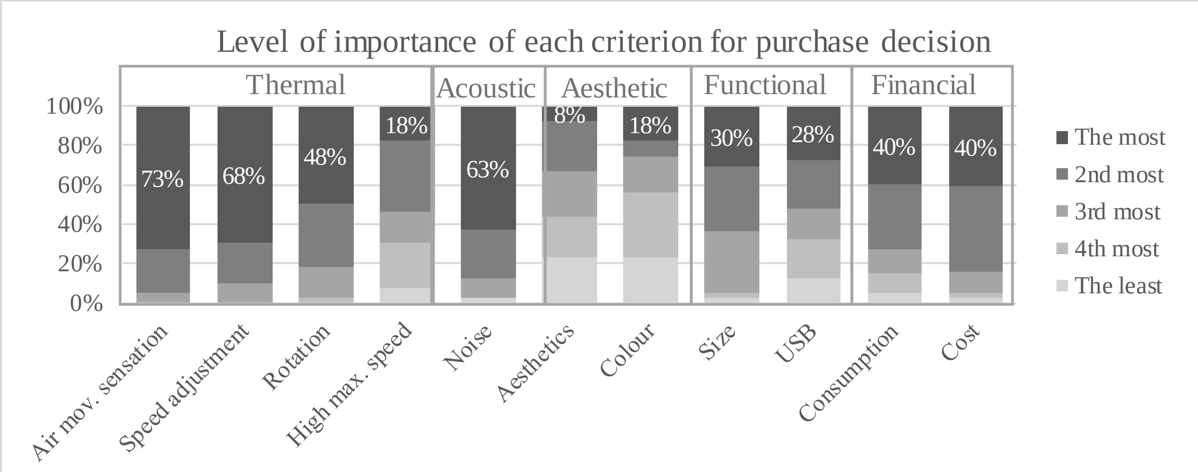

Figure 5. Importance of each criterion for purchase decision - FanQ

Device selection

The last outcome of this experiment was to know which device participants would prefer, but before doing that the results were statistically analysed.

Fisher's statistical analysis indicated that the selection of devices was not significantly influenced by the order in which they were evaluated. The same occurred with the operation mode of the air conditioner, the variation of operation mode did not significantly influence the selection of the fans by participants. Thus, it can be concluded that setting a random order of fan evaluation helped reduce the interference of other variables and the bias of device selection. This prevents, for example, that everyone preferred the first fan evaluated or the one that was in operation when the air conditioner was turned off. The FanQ questionnaire asked for an initial overall preference, and after asking which device they would consider the best regarding some specific aspect, the overall preference was asked again, but at this time considering a purchase situation, first disregarding the cost, and then considering the cost information presented. As can be noted by the results shown in Figure6A, the evaporative device – d – was evaluated as the best in most aspects by most participants. Only in the criterion related to the produced noise, device b was considered the best for most of the participants (48%). Option c was pointed out as the quietest for only two people (5%) even though options b and c show similar sound power measured level (42 and 44 dBA), as indicated in Table 1. Option d stands out mainly on the aesthetic criterion, in which 68% of people found it the best option, while only one person pointed out option c as the best in this matter. Option c was chosen by more people than b mainly regarding the evaluation of which device provides the better thermal adjustment. The difference between b and c in this matter (8%) was expected to be even greater, considering option b has only one air speed level while option c has two, and both allow vertical rotation. Option d also stands out in this aspect, by having 23 air speed levels (dial-like button), but no vertical adjustment capability.

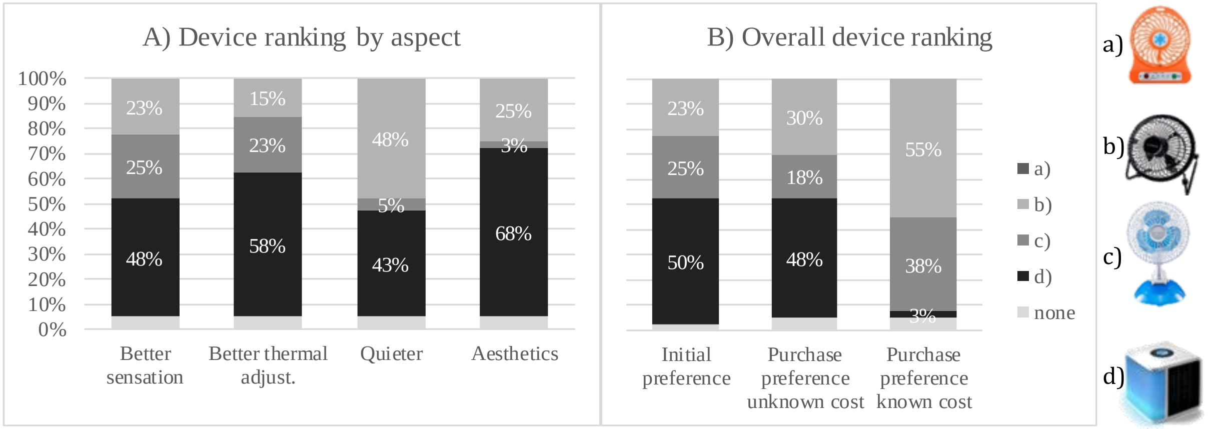

Figure 6. Device ranking by aspect and overall preference – FanQ

Figure 6A shows the aspects ranking considering the importance of criteria analysed in section 3.4, where the most important is to provide a better sensation and the least important is aesthetics. Hence, the results of purchase preference disregarding the cost shown in Figure 6B is very consistent with the device ranking by aspect and the weight of aspects. By comparing initial and final preferences in Figure 6B disregarding cost, slight changes are observed. The evaluation per aspect seems to have influenced participants' perception and the main impact is the increase in votes to option b and the decrease in votes to option c. Option d prevails as the preferred option in both initial and final questions disregarding the cost. However, when the cost was revealed – which is 40 times greater than the cost of option b, the cheapest device –, only one person indicated to be willing to purchase the evaporative device. As option b is cheaper than option c, the difference between them, which was 12% in the no-cost question, rises to 18%, and option b is positioned as the preferred option by most participants. This result show that as the difference in costs becomes greater, this aspect becomes an eliminatory criterion. It is noteworthy that option a was not indicated as the best or preferred option in any question by any participant. On the other hand, the initial preference indicated that one person did not prefer any option and, after the evaluation by aspect, this number grew to two people. In other words, two people would not buy any of these fans, considering the options unsatisfactory.

By analysing the final choice of participants disregarding cost in face of their anthropometric characteristics, there was not enough evidence of statistically significant association between purchase preference and categories of age, gender and BMI. Despite that, the evaporative device – d – was preferred mainly by people with normal BMI, women and people aged 31 to 40 years or over 50 years old in this experiment (see Figure 7). Regarding options b and c, it is noted in Figure 7 that men were equally divided in preference while women showed a higher preference for option b. Regarding BMI, option b stands out for people of nutritional level considered normal (WHO, no date). And more people over 50 years preferred option c while the youngest – between 20 and 30 years – indicated a preference for option b. In a way, as the distribution of age groups and BMI among participants is not equitable, it could be considered that the sample generated a trend that favours option b over option c. In this way, both options could be considered satisfactory and with good cost-benefit by participants. On the other hand, if option d had a more affordable price, it would probably be the preferred option for most people and could achieve a better overall evaluation if it produced less noise.

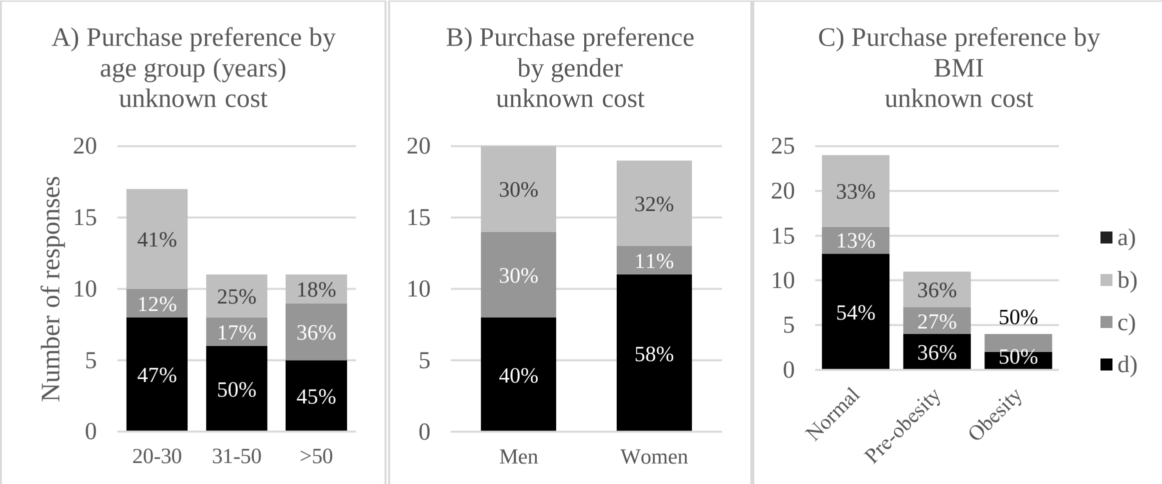

Figure 7. Device purchase preference disregarding cost by participants' anthropometric characteristic

4. CONCLUSION

The results presented in this paper allowed to assess users' preferences regarding personal ventilative devices in a warm controlled working condition. The study highlights which aspects are considered most important for usability and device selection. As expected for a personal conditioning device, criteria related to controllability, like rotation and speed adjustment, were highly rated in importance by participants (the most important by 48% and 68% of participants, respectively). However, noise produced by the fan was indicated as the third most important aspect (the most important by 63%). However, two devices with similar measured sound power level – b with 42 dBA and c with 44 dBA – may be perceived differently, affecting their assessment regarding noise performance. Option b was considered the quieter by 48% of people while option c was rated as the quieter by 5%. As human sensory system receives information regarding multiple indoor environmental exposures simultaneously, sound effects should not be neglected when designing a personal device. Contextual factors such as affordability were also pointed out as an important criterion (the most important by 40% of participants), which was confirmed by the change in trend of selected devices when purchase cost was revealed. Most participants preferred option d (48%) but only one (3%) was willing to pay for it. Interestingly, the possibility of increasing air speed was not deemed as one of the most important like other thermal related criteria. It was considered the most important criterion by only 18% and the second most important by 33% of the subjects. The most important criterion for most people (73%) is the air movement sensation. Therefore, a smooth air flow with good controllability – such as the air flow produced by the evaporative device labelled as d – would be an optimal choice for office occupants in Brazilian offices in case this device becomes more affordable and quieter. Option d was considered by 48% to produce the better sensation and by 58% to allow better adjustment, which are the most important criteria for most participants. Moreover, the conducted experiment may have enlightened participants with the possibility of using both air conditioning and portable fans to achieve thermal comfort in their workspace during warm weather conditions. The cost was considered the second most important criteria for most participants (45%) and had great impact on final choice. So, apart from improving design aspects, innovative solutions should be affordable in order to become popular. Also, if office occupants are stimulated to experience the use of desk fans and evaporative cooling devices with air conditioning, this operation mode might become usual.

The results discussed in this paper can help researchers to choose better equipment for their studies and help designers and companies to identify ways to improve the characteristics of desk fans. From the perspective of implementation, the use of desk fans in shared office spaces usually occurs in two ways, one in which the occupants purchase their own equipment and another in which they receive the fan from someone like their employer. The initial omission of cost in the FanQ questionnaire intended to identify which aspects caught the participants' attention more regarding usability. Therefore, the results could guide both employers and employees to select a better device by knowing which aspects would be compared to achieve a good usability performance. Cost is a high impact factor, but cost-benefit will be different for an employer and an employee considering that employees do not have to deal with office space's energy cost. From the users’ standpoint the most expensive device (d) was the best for most people, but it was not cost-beneficial. They would rather buy a cheaper fan, so the difference among fans regarding usability was evaluated as lower than cost differences. However, the cost-benefit calculation for the employer is more complex as it should consider employee satisfaction, productivity, the purchase cost of multiple devices and the possible energy savings achieved by the extension of set point temperature. From this standpoint, if the most expensive device would significantly increase users’ satisfaction and their willingness to accept higher set point temperatures, it could be a cost-effective option. However, further analyses would be needed to evaluate this long-term thermal comfort and energy saving potential.

Participants’ thermal perception responses during the experiment were collected, so a future publication will present the results regarding whether the thermal acceptability was the same using each fan. The impact of environmental conditions on device activation, air speed and position adjustment will also be addressed. Another important issue that should be further investigated is the energy savings potential of using desk fans and extending setpoint temperature in the Brazilian context. This analysis will be carried out by computer simulation considering different setpoint temperatures and locations.

CONFLICT OF INTEREST

The Authors declare there are no conflicts of interest regarding this publication.

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APPENDIX C – PAPER 2 QUESTIONNAIRES

Table C. 1 - Personal information (InfoQ)

N°	Question	Answering options
1	What is your name?	Open-ended
2	How do you identify?	female/male/other
3	What is your age?	Open-ended
4	What is your weight?	Open-ended
5	What is your height?	Open-ended
6	Select all the clothes you are wearing now:	list of clothes from ASHRAE 55-2020, and "other"
7	Do you exercise regularly?	"No", "Yes, once a week", "Yes, two or more days a week", "other"
8	How did you get to this building today?	"on foot", "by car", "by bus (got off in front of the building), "by bus (further away)", "by bike"
9	How did you get to this room?	"elevator", "stairs"
10	Do you have air conditioning? If yes, indicate in which places:	"Yes, at home", "Yes, in the car", "Yes, at my workplace", "no", "other"
11	Do you have a fan at home or workplace? If yes, indicate in which places:	"Yes, at home", "Yes, at my workplace", "no", "other"
12	Which systems are available at your workplace?	"air-conditioning", "operable windows", "ceiling fan", "floor fan", "standing fan", "mini desk fan", “other”
13	At your workplace which of these options would you USE on a day like today and which option you would PREFER to use (2d question):	"air-conditioning", "natural ventilation", "natural ventilation with fan", "air conditioning with fan"
14	What reasons lead you to PREFER the system indicated in the previous item:	"The other options make me feel very hot", "the other options cool the environment in excess", "I like the thermal sensation it produces", "It allows me to feel comfortable with less external noise", "it improves my control over the environment", "the other options are too noisy", "other"

Table C. 2 - Fans’ assessment questionnaire (FanQ)

N°	Question	Answering options
1	Name	Open answer
2	Which of the devices have you preferred?	photo of the tested devices
3	Which device has the best aesthetics?	photo of the tested devices
4	Which device allowed you to adjust better the thermal conditions?	photo of the tested devices
5	Which device generates the best thermal sensation?	photo of the tested devices
6	Which device did you find most silent?	photo of the tested devices

7	During the experiment have you turned off the fan? If yes, please inform your motivation:	"because of the noise", "I don't like the feeling of wind", "Even the lower air speed was too high and made me uncomfortable", "I did not need it, I was feeling comfortable", "No, I have used it all the time", "other"
8	If you would purchase one of these devices, how would you rate the importance of each of these criteria:	On a liker 5-level scale from more important to less important, list of criteria: aesthetic, noise, air movement sensation, possibility to adjust air speed, possibility to rotate vertically, size, energy consumption, USB connection, different options of color, cost, able to provide higher air velocity
9	After this experiment, do you feel like having a fan at your workplace?	"yes", "no", "indifferent"
10	After this experiment, which one of these options would you PREFER to have at your workplace on a summer day:	"air-conditioning", "natural ventilation", "natural ventilation with fan", "air conditioning with fan"
11	If you would purchase one of these devices, which one it would be? (Disregarding the cost)	photo of the tested devices
12	If you would purchase one of these devices, which one it would be, considering the cost?	photo of the tested devices with their prices

APPENDIX D – PAPER 3

TITLE

Achieving mid-rise NZEB offices in Brazilian urban centres: A control strategy with desk fans and extension of set point temperature

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ABSTRACT

Positive energy buildings (PEB) are foreseen to help achieving global emissions reduction targets and decarbonisation. However, for vertical office spaces in urban centres the photovoltaic (PV) production area is restricted, so innovative strategies are needed. For cooling-dominated climates the extension of set point temperature associated to local control of air movement has the potential to increase the use of natural ventilation and generate a great amount energy savings. . Therefore, this study aims to identify to what extent adopting a mixed-mode operation with desk fans could help mid-rise office buildings to become NZEBs in warm climates. To verify the impact of this strategy, computer simulations were carried out with three building heights in four Brazilian cities. Results show this strategy can generate 20-40% energy savings and the set point could be extended up to 28 °C or 30 °C depending on the climate, without jeopardizing occupants' thermal comfort. Thus, in warm climate cities, the strategy allows lower buildings to become PEBs and mid-rise buildings to become NZEBs. In addition, the demand for extra PV area is expressively reduced, increasing the viability of mid-rise PEBs. This study adds innovative knowledge for achieving PEB targets under suboptimal conditions and highlights multiple aspects that should be considered for applying this strategy.

Keywords: Personal Conditioning Systems, Nearly Zero Energy Buildings, Set Point, Building Performance Simulation, Thermal Comfort, Positive Energy Building, Desk fan.

1. Introduction

The concentration of people in urban centres and population growth generates the continuous expansion of building stock, energy demand and consequently environmental impact. Indeed, a rising tendency in energy use has been reported worldwide: recent values in the global electricity demand are 57% bigger than those observed in 2000 [1]. Additionally, buildings are responsible for 30% of world energy consumption, 55% of demand, and produce around 40% of global carbon dioxide emissions [2]. Brazilian reality is similar to the global trend, and buildings are responsible for more than 40% of the national electricity demand [3]. Such high values – combined with the increasing tendency on energy use – put efforts to reach energy-efficient strategies for the building stock in a prominent position.

Achieving so-called Zero Energy Buildings (ZEB) is among the solutions to minimise the environmental impacts of building stock. The term Zero Energy Buildings has been used for more than 40 years; initially to designate self-sufficient houses [4,5], and currently adapted to address grid-connected buildings able to zero their annual energy consumption [6]. Nowadays, other terms are used, and the definition of ZEB may vary. For instance, a Brazilian regulation also includes the concept of nearly zero energy building (NZEB) and positive energy buildings (PEB). NZEB are defined as those that supply at least 50% of the total annual primary energy demand (thermal and electrical) with on-site renewable energy production. Whereas PEB are those which achieve annual renewable energy production equal to or above the total annual primary energy consumption [7]. Williams et al [6] indicated a need for an international standard after reviewing 38 different local propositions and definitions of ZEB. In order to make this possible, the authors indicate that buildings consumption should be standardised in primary energy per square meter (kWh/m²) [6]. There is also a consensus that the starting point of a ZEB should be an energy-efficient building, reducing the amount of renewable energy required to meet the total demand [8,9]. Therefore, energy efficiency standards play an important role on defining metrics and strategies to achieve ZEB.

Although the clear feasibility and recent advances regarding ZEB, most guidelines and information available came from heating-dominated climates – as little attention has been given to achieve ZEB in warm climates [10]. Therefore, it is important to assess different strategies in cooling-dominated locations. Natural ventilation potentials and the possibility for renewable energy production are expected to play important roles in such places. Brazil location, climatic and geographical conditions represent great potentials for renewable energy production [11,12] and the use of passive cooling strategies [13]. Compared to European countries with consolidated photovoltaic production, Brazil has a higher irradiation rate with smaller annual fluctuations, which indicates a great potential for photovoltaic (PV) production [11,14]. A good correlation between different highly-dense urban centres and the availability of solar irradiation is observed throughout the country [14]. However, there are only 52 ZEB-certified buildings by the Green Building Council [15] in the country, and most of them are one-storey buildings with large roof areas, such as school facilities. Buildings with 3 to 12 floors, such as medium-sized office buildings [16] are not included. This could be because the higher the building the less favourable is the relation between the roof area available for PV installation and the energy demand. Therefore, for medium-sized office buildings the reduction of energy demand plays a key role for achieving NZEB.

According to the Brazilian Association of Refrigeration, Air Conditioning, Ventilation and Heating, cooling is one of the main end uses in commercial buildings corresponding to 30-40% of their total energy consumption [17]. Since the country climatic conditions are predominantly warm, heating systems are not common in offices even at lower latitude locations [18]. In addition, the demand for air conditioning is expected to increase in the coming years, driven by the country development and global warming [19,20]. The expansion of national labelling application helps this reduction as it encourages increasing building thermal performance and the efficiency of lighting and air conditioning equipment. However, other conditioning strategies could be more extensively applied to take advantage of the favourable climatic conditions. Natural ventilation and intensified air movement have a great potential for decreasing cooling energy consumption and low implementation cost [13]. Indeed, natural ventilation is presented as a passive-cooling strategy able to improve buildings' thermal and air quality conditions in warm locations [21].

To extend the use of natural ventilation while guaranteeing occupants' comfort, mixed-mode operation (MM) could be applied associated with the extension of cooling set point temperatures. This would allow the cooling system to be activated only when unfavourable indoor thermal conditions are reached. The proposition of MM to achieve energy consumption reduction is not new, but it has become more pronounced given the growth in air conditioning use over the years and the current climate emergency [22]. A recent review on MM carried out by Kim and De Dear [23] shows study results indicating that this operation strategy can provide significant energy savings and occupants' thermal comfort. However, in most of the articles reviewed by the authors, the energy savings compared to fully conditioned buildings are lower in hot climates [23] such as those prevailing in Brazil – classified as 0 to 2 by ASHARE 169 [24]. Cooling energy savings are indicated to be between 10-50% in these studies, while in studies at climate zones from 3 to 8 – in which there is also heating demand – up to 94% of conditioning energy savings are achieved. These results indicate energy savings provided by MM strongly depend on climate conditions and, hence, on selected set point temperatures [25]. Usually, in MM office spaces the control of air conditioning and windows relies on occupants' behaviour [26]. As a consequence, inadequate system control could lead to energy waste in individual offices [27]. In shared spaces, it could also trigger tension among occupants as individual choices affect the group thermal comfort [28]. Automation is a way to prevent those issues, but the downside is that occupants lose the perception of control, which has a negative effect on thermal variation tolerance [29]. For this reason, further studies on the balance between manual control and automation in MM buildings are indicated [23,30].

Chen et al. [31] show that controlling mixed-mode operation based on adaptive thermal comfort model extends the potential use of natural ventilation as it considers the occupants ability to adapt and acclimatise to thermal conditions. In addition, low potential for application of natural ventilation and controllability issues could be solved by desk fans. The air movement produced by them increases the convection around the human body which becomes a good strategy for warm climates [32]. Studies show desk fans can produce up to 3K of corrective power, i.e., the elevation of the temperature at which users feel neutral thermal sensation [33]. The offset of thermal neutrality allows the extension of acceptable set point temperature and broader usage of natural ventilation, reducing cooling energy demand. In the study of Hoyt et al. [34], expanding cooling set point temperature in US climates from 22.2 °C to 30 °C enabled savings from 30% up to 70% of the estimated energy consumption. A previous study indicated ceiling fans could increase energy savings in mixed-mode operation buildings up to 23% [35]. And the association of ceiling fans to the extension of set point temperature was able to generate 30% cooling savings in Singapore [36]. Omrani et al. [37] highlight the need for more studies on the energy savings produced by the association between MM and intensified air movement. Regarding this gap, desk fans seem to be less studied in office spaces compared to ceiling fans [38]. However, as a personal device, closer to the user, it allow local adjustment of thermal conditions [39] and can be more efficient, producing great cooling effect with low energy consumption [40,41]. Schiavon and Melikov [42] estimated that fans should have a maximum power of 30W for being more efficient than keeping the air conditioner at a lower temperature. Currently, 2-3 W desk fans are available in markets worldwide, capable of producing air speed greater than 1.5 m/s [43].

Higher set points could produce a great amount of energy savings; but the temperature extension limit should be carefully analysed to avoid occupants' thermal discomfort. Many studies carried out in climate chambers indicate most occupants (80%) accept indoor temperatures up to 30 °C when desk fans are available [33,40,43–46]. This could indicate that office set points could be extended to 30 °C when occupants have desk fans, and their thermal sensation would be similar to an environment at 27 °C without fans due to the 3 K corrective power. Moreover, considering this local control as an adaptation opportunity [47], the set point limit could be defined based on the adaptive thermal comfort method, which is based on field data and considers the local climate influence [48,49]. Occupants' acceptability in mixed-mode buildings is much closer to what is observed in naturally ventilated buildings than fully conditioned ones [50,51]. Therefore, many studies show the adaptive model is more appropriate to predict occupants' thermal comfort in mixed-mode operation buildings than Fanger's PMV-PPD model [18,50–53]. In this context, the effect of desk fans in mixed-mode operation buildings could be evaluated by the extension of the upper limit of thermal acceptability of the adaptive thermal comfort model, as predicted in ASHRAE 55 [54]

Thus, this study aims to evaluate the impact of the change of conditioning control strategy for achieving ZEB in verticalised urban centres in hot climate locations. The proposed conditioning strategy associates two solutions with high energy efficiency potential – mixed-mode operation and desk fans. The low consumption of desk fans associated with set point extension allow to increase natural ventilation and reduce cooling consumption. So, the association of these strategies could boost the building energy efficiency while thermal comfort is also guaranteed. For doing so, the study relies on building performance simulation analysis based on annual consumption and thermal comfort prediction for office buildings with variable number of floors and roof-mounted photovoltaic system. The mixed-mode operation is considered to be automated (to change over windows opening and split activation) associated with the extension of set point temperature, which is compensated by local air speed control – provided by desk fans. The purpose is to verify to what extent adopting this strategy could help to achieve NZEBs in different Brazilian climates. This low-cost strategy depends mainly on a change in user behaviour and a simplified automation system, which could be applied in developing countries even under suboptimal technical conditions (e.g., vertical buildings with small roof area available for PV generation). To the best of the authors' knowledge, this study provides innovative information on: (1) the energy savings potential of associating mixed-mode to desk fans, and (2) the performance of NZEBs in warm climates once most of previous research focus on heating-dominant locations. Finally, the study highlights the importance of putting occupants' comfort in a paramount position for decision-making to improve building energy efficiency by applying multiple criteria analysis to define suitable set point temperature extension limits.

2. Method

The method implemented in this article is synthesised in Fig. 1. It comprises the analyses of the potential to achieve NZEB or PEB vertical office buildings in different cities of Brazil with mixed-mode operation and extension of set point temperature associated to the use of personal fans. To evaluate that, as illustrated in Fig. 1, a common office floor plan in 3, 6 and 12-floor buildings was simulated in 4 different cities. The buildings were evaluated by the national labelling systems considering the reference set point temperature of 24 °C to assure compliance to high efficiency level (A). After that, they were simulated in mixed-mode operation with 26 °C, 28 °C and 30 °C set point temperatures. These set point temperatures were based on an initial analysis of the city's climate and suitable temperature limits. Later on, thermal comfort and energy performance were evaluated to verify the maximum applicable set point temperature and its impact on energy consumption and met demand. The method is further presented in the following sections: 2.1 Climate characteristics of evaluated cities; 2.2 Building energy performance simulation; and 2.3 Analysis of simulation results. The first presents the cities and their climatic characteristics; and a subsection justify the choice of set point temperatures applied in the simulation. The second presents the software used for photovoltaic production calculation and for building energy performance simulation. Its subsections present the buildings characteristics, building simulation details and settings. Section 2.3 presents the parameters used for evaluation of buildings performance and analysis performed to define the feasibility of the proposed strategy. This evaluation considers thermal comfort indicators, photovoltaic production, and annual energy consumption.

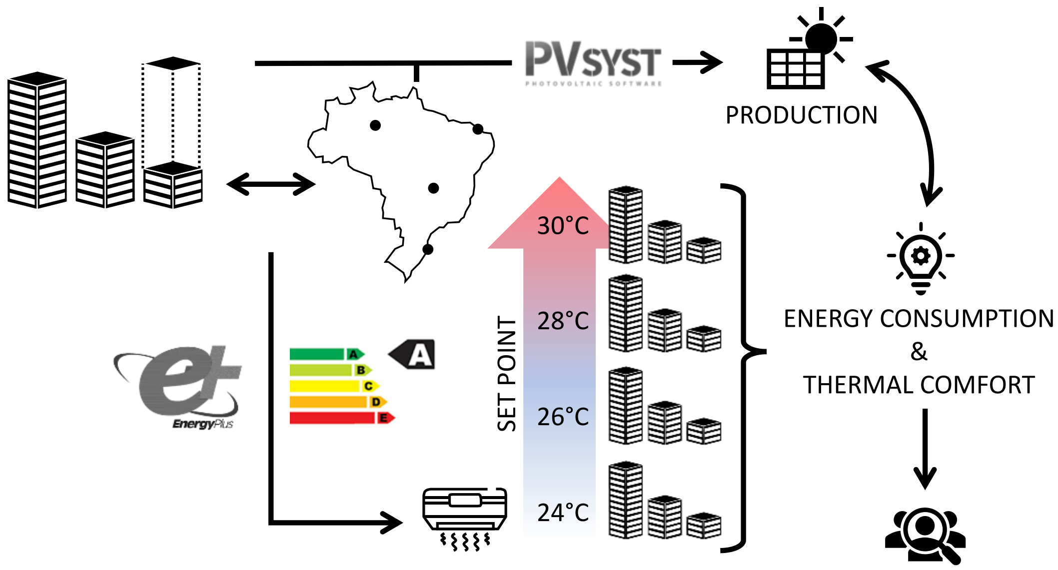

Fig. 1. Method Overview

2.1. Climate characteristics of evaluated cities

Four cities located in different regions of Brazil (see Fig. 2) were selected for the analyses: Florianopolis, in the south; Brasilia, in the mid-west; Fortaleza, in the northeast; and Manaus, in the north. It is important to highlight the variability of climates among those cities; therefore, Fig. 3 shows the maximum, minimum and mean temperatures, as well as relative humidity variation, for each city. These data are from typical meteorological data (TMYx) derived from hourly weather data from 2004 to 2018 years [55]. Florianopolis and Brasilia present milder climates, classified as 2A by ASHRAE 169 [24], both have maximum and minimum annual temperature ranging approximately from 30 °C to 15 °C. However, in Brasilia there is a greater daily amplitude ranging from 7 °C to 13 °C, while in Florianopolis the seasonal variation is more pronounced, reaching a difference of 7 °C between summer and winter. Fortaleza and Manaus are hotter cities, classified as 0A by ASHRAE 169 [24], the maximum averages are always above 30 °C, reaching up to 33 °C in Manaus, while the minimum temperatures are 23-24 °C.

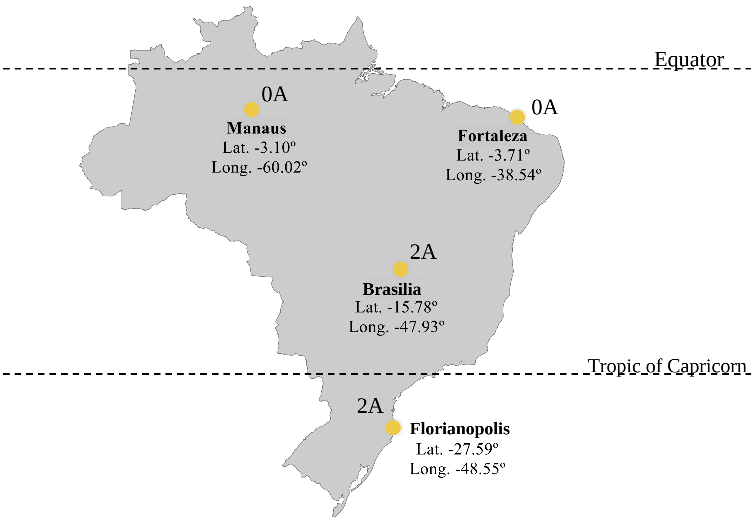

Fig. 2. Illustration of the Brazilian cities' location by latitudes and longitudes, and climate classification

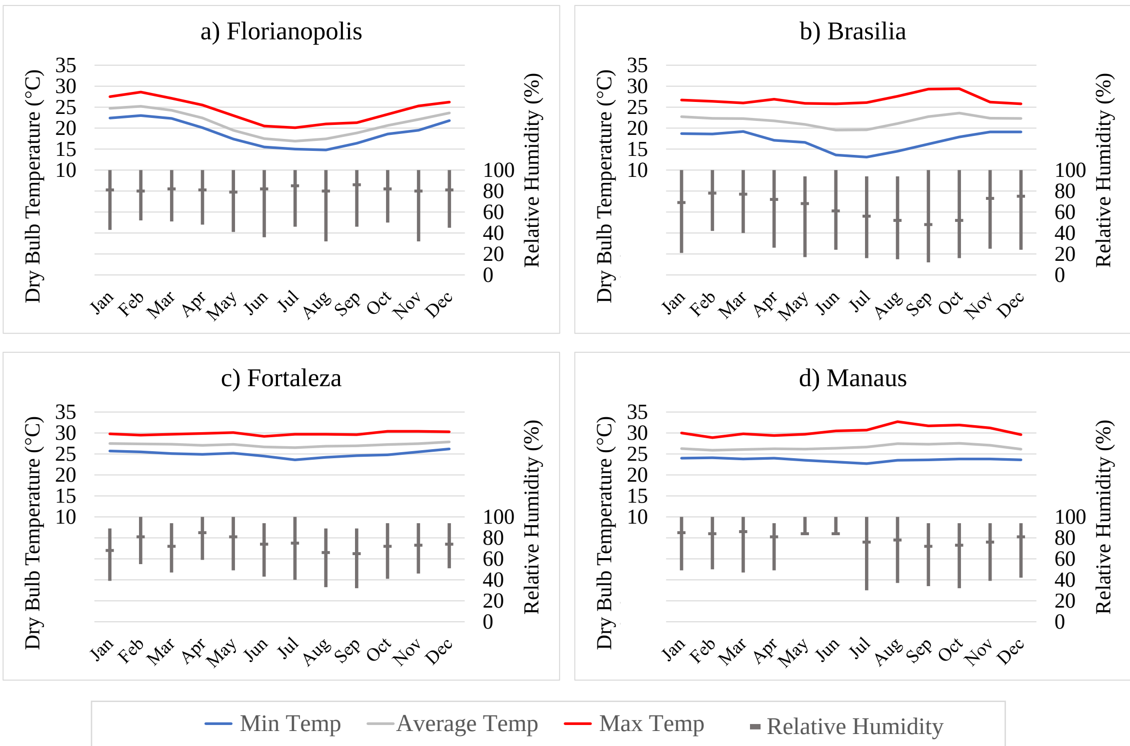

Fig. 3. Monthly average maximum, minimum and mean outdoor dry bulb temperature, and same variations are indicated for relative humidity in each evaluated cities considering TMYx weather data from 2004-2018 [55]

Regarding relative humidity, mean monthly values are high in most of the cities throughout the year, ranging from 65% to 85%. Brasilia has the greatest monthly variation of humidity, reaching the maximum of 100% and the minimum of 12% in the same month. Its mean values are also the lowest among all cities – 48%. Besides dissimilarities in temperature and air humidity, there are also variations considering the availability of solar radiation among the cities. As shown in Fig. 4, Florianopolis reaches the highest solar radiation, but predominantly maintains the lowest horizontal global radiation rates along the year. Brasilia, even though having lower geographical latitude than Fortaleza and Manaus, maintains a level of radiation similar to those cities throughout the year. Fortaleza and Manaus are both very close to the Equator, but show different levels of horizontal radiation, which is higher in Fortaleza. The radiation profile of Florianopolis is different from the other cities, as it reaches the highest levels at the beginning and end of the year, while the others show a drop.

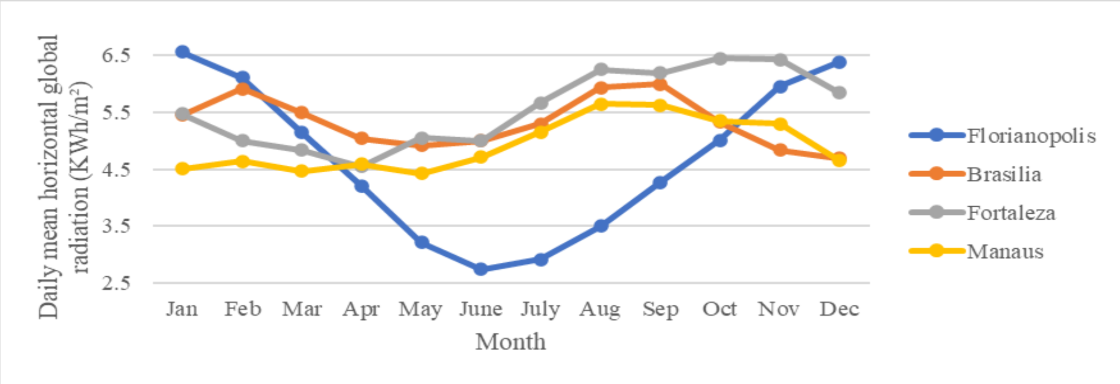

Fig. 4. Daily mean horizontal global radiation per month (from 2004-2018 TMYx [55])

2.1.1. Selection of simulation set point temperature based on climatic characteristics

As mentioned in the introduction, several studies indicate that the adaptive model is more suitable for evaluating environments with mixed-mode operation [50,53,56,57]. Therefore, the temperature limit up to which it would be possible to run natural ventilation with desk fans without activating the air conditioning was defined based on the adaptive model [58]. Thus, the thermal comfort zone (CZ) of each city was calculated based on the monthly average outside temperature by applying equations 1, 2 and 3. Equation 1 defines the minimum limits, 2 the maximum limits at low speed (< 0.3 m/s) and 3, the maximum limits at high speed (between 0.9 and 1.2 m/s). T_{op} corresponds to indoor operative temperature and T_{ext} is the monthly mean outdoor air temperature.

T_{op} upper limit (°C) = 0.31 T_{ext} + 21.3 (1)
T_{op} lower limit (°C) = 0.31 T_{ext} + 14.3 (2)
T_{op} extended upper limit (°C) = 0.31 T_{ext} + 23.5 (3)

The comfort zone (CZ) limits per each city are presented in Table 1 and the monthly mean outdoor temperature were extracted from simulation weather data [55].

Table 1. Thermal comfort zone (CZ) with natural ventilation per city.

City	Month / T_{ext} and T_{op} CZ Limits	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
a) Florianopolis	T_{ext} average	25	25	24	22	19	17	17	17	19	21	22	24	
	T_{op} extended upper	31	31	31	30	30	29	29	29	29	30	30	31	30
	T_{op} upper	29	29	29	28	27	27	27	27	27	28	28	29	28
	T_{op} lower	22	22	22	21	20	20	20	20	20	21	21	22	21
b) Brasilia	T_{ext} average	23	22	22	22	21	20	20	21	23	24	22	22	
	T_{op} extended upper	31	30	30	30	30	30	30	30	31	31	30	30	30
	T_{op} upper	28	28	28	28	28	27	27	28	28	29	28	28	28
	T_{op} lower	21	21	21	21	21	20	20	21	21	22	21	21	21

c) Fortaleza	T_{ext} average	27	27	27	27	27	27	27	27	27	27	27	28	
	T_{op} extended upper	32	32	32	32	32	32	32	32	32	32	32	32	32
	T_{op} upper	30	30	30	30	30	30	30	30	30	30	30	30	30
	T_{op} lower	23	23	23	23	23	23	23	23	23	23	23	23	23
d) Manaus	T_{ext} average	27	26	26	27	27	27	28	28	28	29	28	27	
	T_{op} extended upper	32	32	32	32	32	32	32	32	32	32	32	32	32
	T_{op} upper	30	29	29	30	30	30	30	30	30	30	30	30	30
	T_{op} lower	23	22	22	23	23	23	23	23	23	23	23	23	23

It can be observed in Table 1 that the average extended upper limit of Brasilia and Florianopolis is 30 °C and in Manaus and Fortaleza is 32 °C. As considering a higher temperature than the extended upper limit would result in thermal discomfort, 30 °C was selected as the maximum set point temperature applicable to all cities. This means that it would be the temperature above which it is necessary to start the air conditioning and close the windows. However, the cooling system is usually controlled by air temperature, not operative temperature. Therefore, the occurrence of operative temperature higher than the set point temperature is expected because of the solar radiation effect. To address this issue, two other set point temperatures between the baseline (24 ºC) and the maximum limit (30 ºC). Thus, the fully conditioned situation at 24 °C is compared to a mixed-mode operation including increased air speed produced by personal fans with three set points of 26 °C, 28 °C, and 30 °C. Each simulation was carried out considering a single set point throughout the year. As can be seen in Fig. 5, an annual set point temperature may be more appropriate for warm climate cities, with more constant outdoor temperatures, than for mild climate cities, where seasonal and daily thermal conditions are more variable. Fig. 5 also shows that outdoor temperatures in Fortaleza and Manaus fit better the comfort zone (CZ) than in Florianopolis and Brasilia. However, all set point temperatures are included within the CZ in all four cities and the goal is to compare the application of the same strategy to different contexts and its impact. Therefore, the most restrictive maximum limit (30 °C) was chosen. Also because it matches the maximum acceptable limit identified in studies with people when individual fans were available [40,45,59,60]. Thus, the choice considers cities climatic characteristics and the state of the art of thermal comfort studies. To increase the air speed, it is considered that each person would have a desk fan with 3W power able to produce air speed of 1.17 m/s near a person seated 50 cm from the fan.

Regarding the window opening temperature to allow natural ventilation, a minimum value of 21°C was adopted in all cities, considering the lower limits of mild climates. In mild climates, opening the windows under low outdoor temperature could generate cold discomfort. However, as shown in Fig. 5, in warmer climates the occurrence of outside temperatures lower than 23 °C, which is the lower limit CZ is unlikely. Thus, even if the window opening is possible from 21 °C onwards, cold discomfort is unlikely.

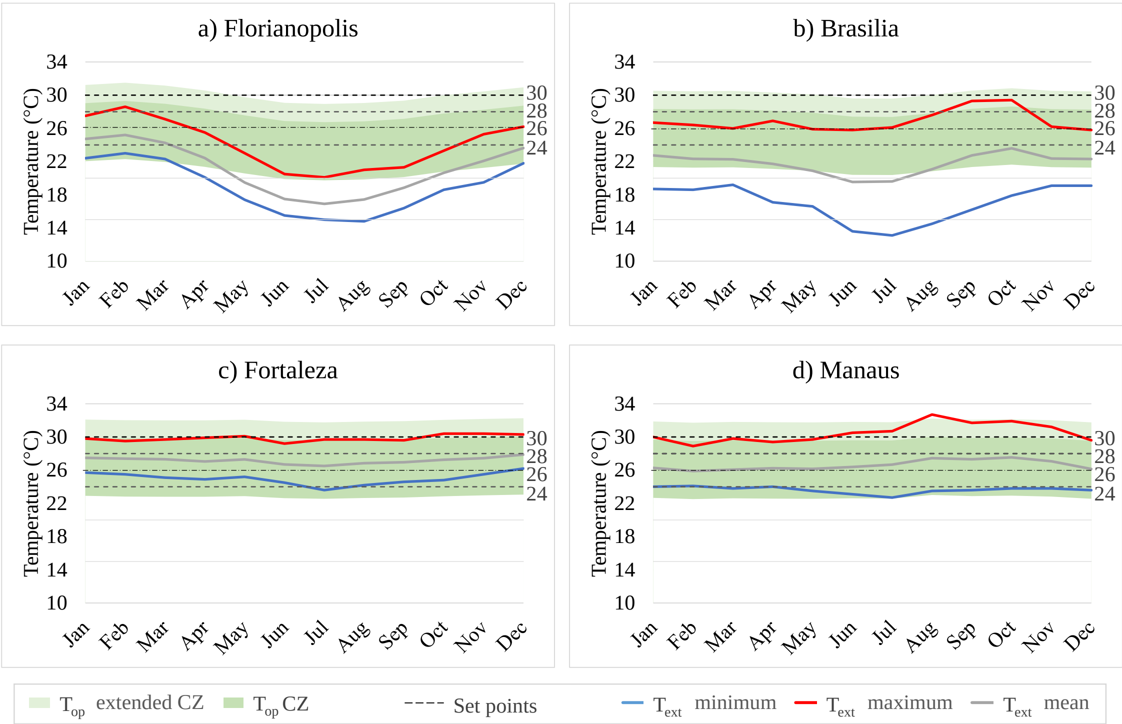

Fig. 5. Monthly external temperature variation (T_{ext}) – minimum, maximum, and mean –, thermal comfort zone operative temperatures limits (T_{op} CZ) per city and upper comfort zone extension limit due to increased air speed (T_{op} extended CZ).

The proposed set points were also verified against PMV-PPD thermal comfort limits of ASHRAE 55 [58]. As shown in Fig. 6, under common office conditions and with air speed adjustment, the proposed set points could be within thermal comfort limits, +/- 0.5 PMV. In this analysis, indoor air temperature is considered equal to mean radiant temperature, relative humidity (RH) to be 55%, occupants' metabolic rate (M) 1.1 met and with 0.57 clothing insulation (Icl). Fig. 6 and PMV calculation was performed on CBE comfort tool which considers the correction of PMV based on SET for better consideration of convective effect on PMV [61]. However, this method will not be applied in this study because the adaptive method is considered more suitable for the evaluated conditions.

Based on the adaptive model, the extension of upper acceptable limits by increment of air speed occurs when indoor operative temperature is higher than 25 ºC. Nicol et al. [47] indicate 60% of people would be expected to turn fans on when outdoor temperature reaches 25 ºC. A review of field studies, however, show in office buildings this percentage of activation on average is reached around 28 ºC of indoor temperature and in mixed-mode operation it could even be higher [38]. Nevertheless, fan activation vary a lot among users and can be driven by other factors like time of the day [62]. Therefore, to consider a more conservative condition, where the fans would be activated for a longer time, the fans were considered to be activated whenever the indoor operative temperature (T_{op}) exceeded 26 ºC. In addition, the fan energy consumption was calculated by multiplying each occupancy hour in which T_{op} > 26°C in a thermal zone by the number of occupants and the fans power (3W). This was calculated based on the simulation output for each building zone, summed up and included in the building annual energy consumption post-simulation.

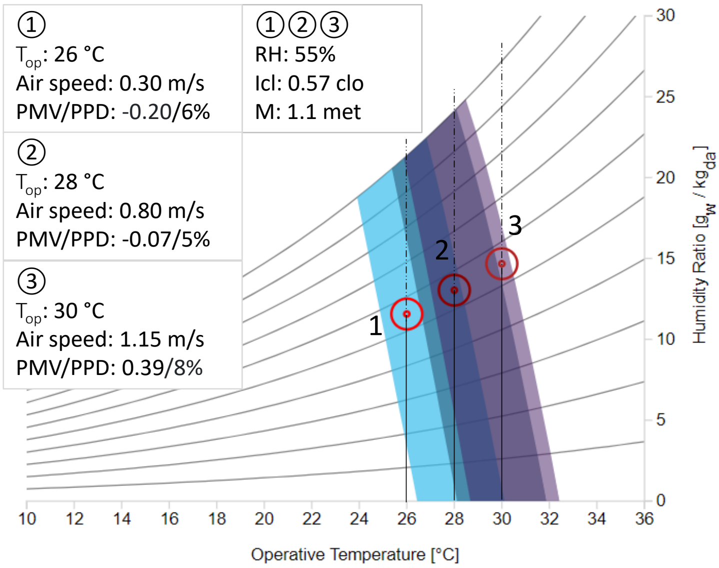

Fig. 6. PMV analysis of the proposed set point temperatures, carried out on [61]. Operative temperature (T_{op}), Predicted Mean Vote (PMV), relative humidity (RH), clothing insulation (Icl) and Metabolic rate (M).

2.2. Building Energy Performance Simulation

Building performance simulations were conducted using the EnergyPlus software [63]. The cities weather data used were typical meteorological year data (2004-2018 TMYx) available at the international building climate database (http://climate.onebuilding.org/). The energy simulation was carried out to calculate the energy consumption of buildings and the baseline was based on the national labelling system. The annual and end use energy consumption were analysed. In addition, the simulation was used for providing annual indoor operative temperatures for thermal comfort prediction assessment. Annual energy demand was then compared to on-site production to assess whether the proposed strategy contributes to achieving a NZEB for each studied case.

The photovoltaic energy production was calculated with PVsyst Photovoltaic Software [64]. The pre-sizing module was used, so the annual production calculation was based on the building roof area, modules technology type, orientation, and tilt angle. Monocrystalline technology was selected for having the highest efficiency (around 18%) compared to other technologies [65]. The tilt angle depends on the city as it was based on geographical latitude angle to reduce losses. The modules were positioned facing North to achieve maximum production [66]. The module area is the same for all buildings as total cover of roof area is considered. And the simulation does not include shading from other buildings as the models are simulated considering the worst thermal conditions of exposure, which is without surrounding buildings.

2.2.1. Reference building

The simulated building has a common open office floor plan. The rectangular area illustrated in Fig. 7 includes perimetral occupied zones and a vertical circulation core space. The low depth of the plan and the perimetral occupancy optimizes the availability of natural ventilation but can also have a negative effect of exposing the occupancy areas to external conditions and solar radiation. A review of typical construction patterns in a city of Brazil carried out by Neves et al. (2019), indicates mid-size office buildings are usually rectangular, have 30% window-to-wall ratio and no external shadings. The floor plan was divided in four zone areas, so the effect of solar radiation was properly considered in the air conditioning sizing calculation. The building was modelled with split systems in "auto size" and has 3 m ceiling height. The partitions between the occupied zones have large openings to allow cross ventilation between facades. Thus, the building considers 18 m² of unconditioned core area and 153 m² of conditioned open offices – without enclosed partitions.

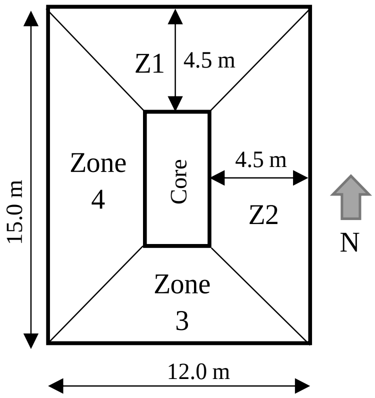

Fig. 7. Model floor plan

The three simulated buildings have the same floor plan with different number of floors – three, six and twelve floors – so the impact of verticalisation on NZEB target could be assessed. Conditioning, lighting and envelope systems were defined to achieve maximum energy efficiency according to the Brazilian energy efficiency labelling standard for commercial buildings [7]. To achieve a high energy efficiency level (A) based on this standard, buildings need to be compared to a Baseline with low performance (level D); and achieve a minimum percentage of energy savings stablished according to its typology, climatic group, shape factor and characteristics. The Baseline D level is considered to have standard envelope characteristics – 14 cm ceramic block walls and a concrete slab with cement tiles roof. The standard includes recommendations for lighting and cooling systems high efficiency benchmarks, which involve low lighting power density (LPD) and high cooling coefficient of performance (COP) – in full load. The labelling method proposes the cooling system type to be the same in both models and lighting power density is defined by zone activity. Outdoor lighting is not included in the analysis nor in this study. To achieve level A, the best lighting power density was selected for the proposed buildings. Also, an inverter split system with a high COP was selected. Regarding the envelope, wall materials were kept similar to baseline and the roof was improved and better adjusted to the office typology, by using a concrete ribbed slab with EPS filling and gypsum lining. Another important point is that the baseline building has clear glass windows, so a high-thermal-performance glass was selected for the proposed buildings. The baseline set point temperature is 24 °C as required by the local standard [7]. Table 2 indicates the simulation input data for the standard baseline and proposed buildings.

Table 2. Baseline labelling standard and proposed improved building characteristics

Parameter	**Unit**	**Baseline building**	**Proposed building**
Window to wall ratio (WWR)	%	50.00	40.00
Wall thermal transmittance	W/m².K	2.39	2.61
Wall solar absortance	-	0.50	0.30
Wall thermal capacity	kJ/m².K	150.00	98.00
Roof thermal transmittance	W/m².K	2.06	1.43

Roof solar absortance	-	0.80	0.40
Roof thermal capacity	kJ/m².K	233.00	145.00
Glazing thermal transmittance	W/m².K	5.67	5.67
Glazing solar heat gain coefficient (SHGC)	-	0.82	0.29
Lightning power density (LPD)	W/m²	14.10	8.10
Cooling system type	-	Split system	Split system with inverter
Full load Coefficient of Performance (COP)	W/W	2.60	4.79
Total Cooling Capacity	kW		
Cooling set point temperature	°C	24.00	
Outdoor air flow rate	l/s	2.50*area + 0.30*person	
Cooling fans delta pressure	Pa	250.00	
Cooling fans efficiency	%	65.00	
Occupancy density	People/m²	0.10	
Equipment power density	W/m²	9.70	
Windows discharge coefficient	-	0.65	
Air Mass Flow Exponent (closed apertures)	-	0.063	
Air Mass Flow Coefficient (closed apertures)	kg/s.m	0.00028	

Natural ventilation was modelled in EnergyPlus with the air flow network, which considers the effect of wind over time according to speed and direction indicated in weather data. The discharge coefficient, aperture exponent and coefficient are indicated in Table 3. Wind pressure coefficient was calculated based on average surface area and opening height.

The standard requires that baseline and proposed buildings be simulated with the same geometry, orientation, cooling system type, occupancy, equipment density and schedules, as shown in Table 3.

Table 3. Baseline standard and the proposed building simulation schedules

Schedules	Baseline / Proposed
Occupancy/ Equipment	30% from 6 to 8 am, 100% from 8 am to noon, 30% from noon to 2 pm, 100% from 2 to 6 pm, and 20% from 6 to 8 pm weekdays
Lighting	8 am-8 pm on weekdays

The energy consumption of the lift was calculated according to CIBSE Guide D [67] applying equation 4. Data and results are shown in Table 4. These equipment consumptions were added to both the baseline and proposed buildings.

$$\text{Lift annual consumption (kWh/year)} = \frac{S \times Motor\ Power \times Travel\ Time}{4} \quad (4)$$

Table 4. Lift energy consumption calculation

Parameter	**3-floor**	**6-floor**	**12-floor**
Starts per year (S)	750 s/day* x 261** days/year = 195750.000		
Motor power (kW)	8.000	8.000	8.000
Travel time (h)***	0.002	0.004	0.009

Annual energy consumption (kWh/year)	**650.000**	**1625.000**	**3575.000**

* Starts per day suggested in CIBSE Guide D for office buildings
** Number of occupancy days per year
*** Calculated by $\frac{ceiling\ height\ (3\ m) \times numbers\ of\ floor - 1}{3600}$

The building characteristics were set to achieve level A of energy efficiency based on the national labelling system. Thus, the starting point of the study is an efficient building, and the proposed strategy aims taking a step forward in achieving a ZEB. So, the performance of a fully conditioned office space with 24 °C set point temperature is compared to mixed-mode buildings with higher set point temperature arrangements considering the inclusion of desk fans. The mixed-mode operation considers natural ventilation through open windows and cross ventilation between adjacent zones in the same floor. When the operative temperature reaches the set point temperature, the windows are automatically closed, and cooling is switched on. The extension considers three set point temperatures: 26 °C, 28 °C, 30 °C. Next section details how this was done in the simulation.

2.2.2. Details of the simulations

To enable the simulation of the mixed mode operation the energy management system (EMS) of EnergyPlus was used to create a runtime to alternate the activation of the air conditioning (AC) and natural ventilation (NV) based on:

(i) Space occupancy
(ii) Indoor operative temperature
(iii) Set point temperature
(iv) Outdoor air temperature

The sequence of association rules for these variables is described in Fig. 8. The operation of the windows or air conditioning only occurs during occupancy hours (6 am-8 pm on weekdays); in the other periods the windows are closed, and the cooling system is off. To define if the cooling system should be turned on, the indoor operative temperature is compared to the set point temperature; if it is lower, and the outdoor temperature is lower than the indoor, the windows are opened, and the AC turned off. Once the indoor operative temperature gets higher than the set point, the AC is turned on and windows are closed. When outdoor air temperature is higher than indoor operative temperature, natural ventilation may increase the heat gain and generate discomfort. In addition, when outdoor temperature is lower than 21 °C, natural ventilation can result in cold discomfort. Therefore, in both cases, natural ventilation is not allowed, and air conditioning is also off. The EMS script presented in Fig. 9 is an example of how these rules were combined to control room operation. This scheme could mimic occupants' behaviour in a streamlined manner. However, the coordination of air conditioning activation and window closing would be better achieved by automation, based on indoor thermostat, occupancy sensor and an outdoor air temperature sensor.

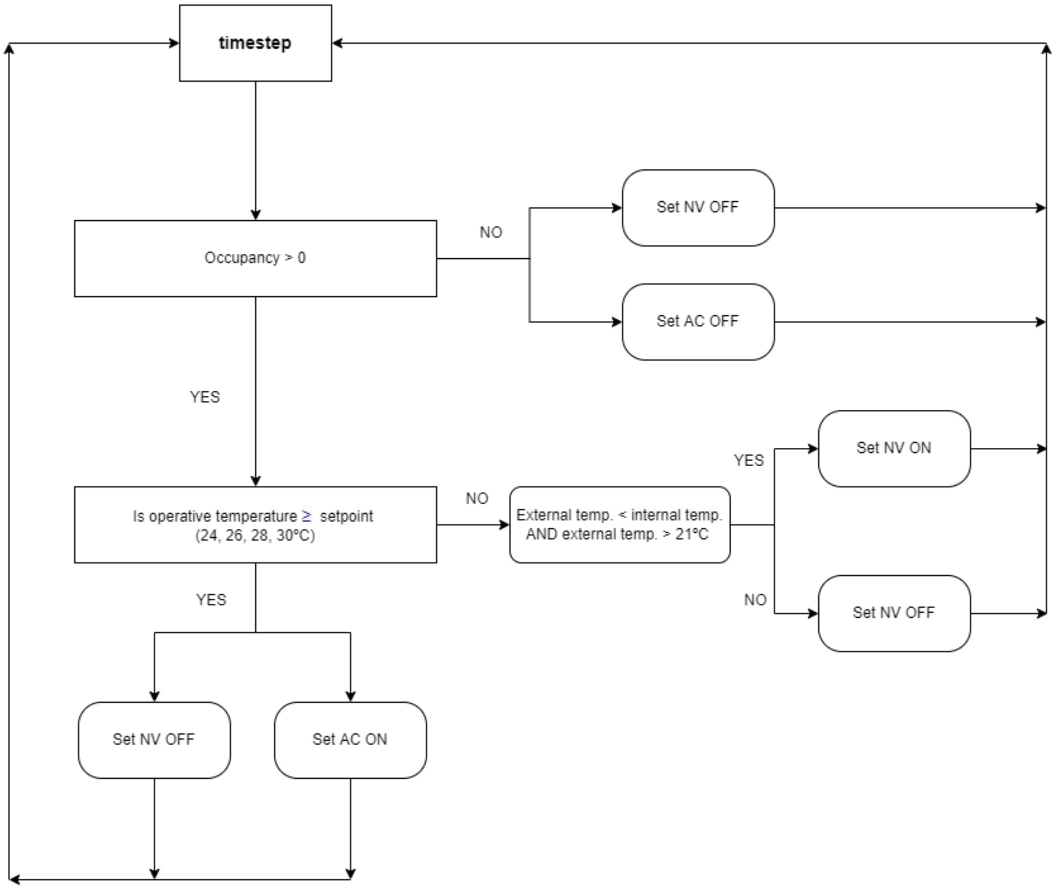

Fig. 8. EMS – Operation scheme

```
EnergyManagementSystem:Program,
    ProgramZ1COB,              !- Name
    SET Temp_Conf = ((Temp_Z1COB >= 26) || (Temp_Z1COB <= 16)),  !- Program Line 1
    IF ((Ocup_Z1COB > 0) && (Temp_Conf == 1)),  !- Program Line 2
    Set Controle_HVAC_Z1COB = 1,  !- A4
    Set Controle_Controle_VN_Z1COB = 0,  !- A5
    ELSEIF ((Ocup_Z1COB > 0) && (Sensor_HVACZ1COB > 0)),  !- A6
    Set Controle_HVAC_Z1COB = 1,  !- A7
    Set Controle_VN_Z1COB = 0,  !- A8
    ELSEIF (Ocup_Z1COB > 0), !- A9
    IF ((Temp_Ext<Tar_Z1COB) && (Temp_Ext>21)),  !- A10
    Set Controle_HVAC_Z1COB = 0,  !- A11
    Set Controle_VN_Z1COB = 1,  !- A12
    ELSEIF ((Temp_Ext>Tar_Z1COB) && (Temp_Ext>21)),  !- A13
    Set Controle_HVAC_Z1COB = 0,  !- A14
    Set Controle_VN_Z1COB = 0,  !- A15
    ELSEIF (Temp_Ext<21),      !- A16
    Set Controle_HVAC_Z1COB = 0,  !- A17
    Set Controle_VN_Z1COB = 0,  !- A18
    ENDIF,                     !- A19
    ELSEIF (Ocup_Z1COB == 0),!- A20
    Set Controle_HVAC_Z1COB = 0,  !- A21
    Set Controle_VN_Z1COB = 0,  !- A22
    ENDIF;                     !- A23
```

Fig. 9. EMS script – example for 26 ° C set point temperature

2.3. Analyses of simulation results

To evaluate the performance and viability of the proposed operation strategy for achieving NZEB and PEB, four main indicators are used. Two of them relate to energy aspects: annual photovoltaic production, annual energy consumption and savings. The first two are simulation outputs and the third is calculated mainly by comparing the energy consumption of the fully conditioned building (24 °C set point) with the buildings with mixed-mode operation, desk fans and extended set point temperature. The other two key performance indicators relate to thermal comfort: percentage of occupancy hours in thermal comfort and percentage of occupancy hours under high temperature, which increase overheating probability.

The percentage of occupancy hours in thermal comfort were calculated based on the adaptive thermal comfort model from ASHRAE 55 [58] as used before to define the set point temperatures. To do that, hourly indoor operative temperatures of each zone were compared to the thermal comfort zone limits for calculated per month for each city (by applying equation 1, 2, 3 from section 2.1.1). The sum of occupancy hours (from 6 am to 8 pm) within the comfort zone divided by annual occupancy hour (3654h/year) is the percentage of comfort per zone. A percentage close to 80% is considered a good threshold as it indicates the occupants would be comfortable during most of occupancy hours. Although, to assess the severity of exceedance hours regarding the upper comfort limit, the risk of overheating was also evaluated applying the most rigorous method described in CIBSE's Technical Memorandum number 52 – TM52 [68]. This method indicates that indoor operative temperatures 1 °C above the adaptive thermal comfort zone upper limit (T_{op} extended CZ+1 °C) should not occur in more than 3% of annual occupancy hours. To evaluate that, equation 5 was applied to each thermal zone.

$$\frac{\sum (Occupancy\ hours\ under\ Top > Top\ extended\ CZ + 1\,°C)}{3654} < 3\% \quad (5)$$

Both thermal comfort analyses were applied to define the maximum set point limit applicable in each city, i.e., the maximum temperature that will not jeopardize occupants' thermal comfort. To do that, the most critical thermal zones per city are used as reference and compared to the calculated limits illustrated in Fig. 10, and correlated to monthly outdoor temperature. Therefore, the effect of desk fans on occupants is considered in the analysis by extending the thermal comfort upper limit as proposed in the adaptive model method.

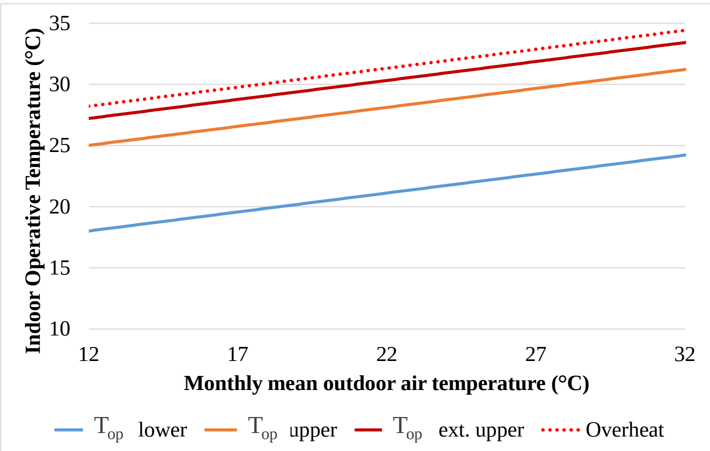

Fig. 10 Adaptive and overheating thermal comfort limits

The energy consumption and thermal comfort indicators were also cross analysed for defining suitable set point temperatures for the analysed cities. After that, the energy consumption and photovoltaic production were compared so the potential for achieving NZEB and PEB could be analysed. To this end, the definitions of NZEB and PEB were considered according to the Brazilian building labelling regulation. The regulation is based on primary energy consumption to allow the consideration of electrical and gas consumption under an equivalent base. However, the studied buildings do not include gas consumption, so electrical production and consumption were directly compared. Therefore, equation 6 is considered for defining a NZEB and equation 7 is considered for defining a PEB:

NZEB: annual PV production (kWh) ≥ 50% of annual building consumption (6)

PEB: annual PV production (kWh) ≥ 100% of annual building consumption (7)

3. Results

In this section, the results obtained in the simulations are presented in four sections: 1) photovoltaic potential; 2) annual energy consumption impact; 3) occupants predicted thermal comfort impact and set point temperature selection; and 4) NZEB and PEB potential evaluation. The first one evaluates the annual photovoltaic energy production achieved in each analysed city. The second compares the impact of the proposed operation strategy on the annual energy consumption among all studied conditions. To do that the consumption of the fully conditioned building with 24 °C set point temperature was compared to the ones with mixed-mode operation, desk fans and higher set point temperatures. Also, the influence of number of floors and climatic characteristics was analysed by comparing all tested scenarios. The third analysis is based on indoor operative temperatures primarily to identify the highest set point temperature of the proposed strategy that could be used in each studied case to achieve greater energy savings without jeopardizing occupants' thermal comfort. The last analysis compares energy demand and PV production to assess whether the proposed strategy contributes to achieve a nearly zero energy building (NZEB) or positive energy building (PEB).

3.1. Photovoltaic potential

Reaching NZEB and PEB depends on the photovoltaic power generation potential in each evaluated city. Table 5 shows the results of annual energy production in each city, and the relation to their geographical location is better visualised in Fig. 11. As shown in Fig. 11, although Fortaleza and Manaus have similar latitudes, close to the Equator line, their estimated photovoltaic production is quite different. This probably stems from the difference in daily available irradiation rate between the two cities, causing Fortaleza to achieve higher estimated production. The irradiation availability does not increase based on the latitude as it would be expected, and the highest photovoltaic energy production is found farther from the equator, in a city positioned on the central plateau of the country, which ends up having great exposure to radiation. On the other hand, the city with the lowest irradiation levels also achieves the lowest energy production. Manaus produces 245.3 kWh/m² while Brasilia produces 280.7 kWh/m².

Table 5. Photovoltaic estimation results

City	Latitude	Azimuth	Tilt	Modules Area (m²)	Annual Energy production (MWh)	Annual Energy production (kWh/m²)
Florianopolis	27.58° S	0.00° (facing North)	27.00º	162.00	40.73	251.41
Brasilia	15.55° S		15.00º		45.47	280.66
Fortaleza	3.72° S		4.00º		44.94	277.41
Manaus	3.11° S		3.00º		39.73	245.25

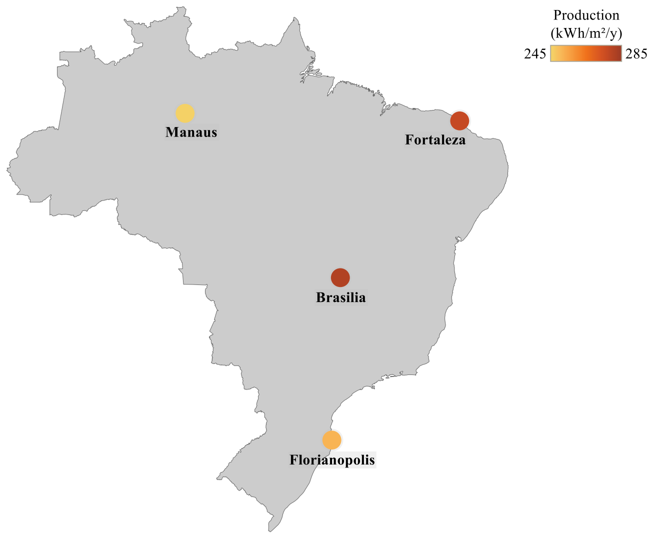

Fig. 11. Photovoltaic energy production per evaluated city

3.2. Annual energy consumption impact

After simulating the 3 buildings in each of the chosen cities, the energy consumption results were compared to the low-performance model (D) defined by the national labelling method [7]. The minimum savings compared to the baseline (level D) to achieve level A vary from 32% to 37% for the studied buildings and locations. As indicated in Table 6, the proposed buildings achieved the level A as sought, consuming from 23% to 30% less than the minimum necessary to achieve level A. It is noteworthy that buildings achieve greater energy savings when located in Brasilia and less when located in Manaus.

Table 6. Energy performance according to national labelling method

City	Climate group/ ASHRAE 169	N. of floors	Condit. area (m^2)	Annual electrical energy consumption (kWh)		Energy Savings %	Efficiency level
				Baseline	Proposed		
Florianopolis	1B / 2A	3	486	68,722.3	33,061.3	51.9	A
		6	972	140,506.5	66,609.0	53.2	A
		12	1944	282,391.5	133,413.2	53.4	A
Brasilia	10/ 2A	3	486	77,011.5	34,217.8	56.0	A
		6	972	155,668.5	69,245.9	56.1	A
		12	1944	311,932.1	138,580.3	56.2	A
Fortaleza	17/ 0A	3	486	101,924.3	48,381.0	52.9	A
		6	972	204,083.3	96,967.2	52.9	A
		12	1944	408,370.7	194,025.7	52.9	A
Manaus	18/ 0A	3	486	109,416.6	51,740.9	53.0	A
		6	972	215,980.2	102,826.3	52.8	A
		12	1944	429,047.6	204,884.8	52.7	A

To analyse the impact of increasing the number of floors on energy performance, energy consumption is standardised per square meter in Fig. 12. This figure shows that differences in consumption between 3- and 12-floor buildings are very small if the same set point temperature is considered. The biggest difference found is of 1.2% between 3- and 12-floor buildings in Brasilia at 24 °C set point. Although the gross conditioned area will be larger in buildings with greater number of floors, its proportion in relation to the total building area does not change much, since the unconditioned area (the core) is small. Therefore, it can be concluded by the results shown in Fig. 12 that the variation in energy consumption per area as a function of the number of floors is very small. Hence, this variation can be disregarded – and the average value can be used as a reliable reference.

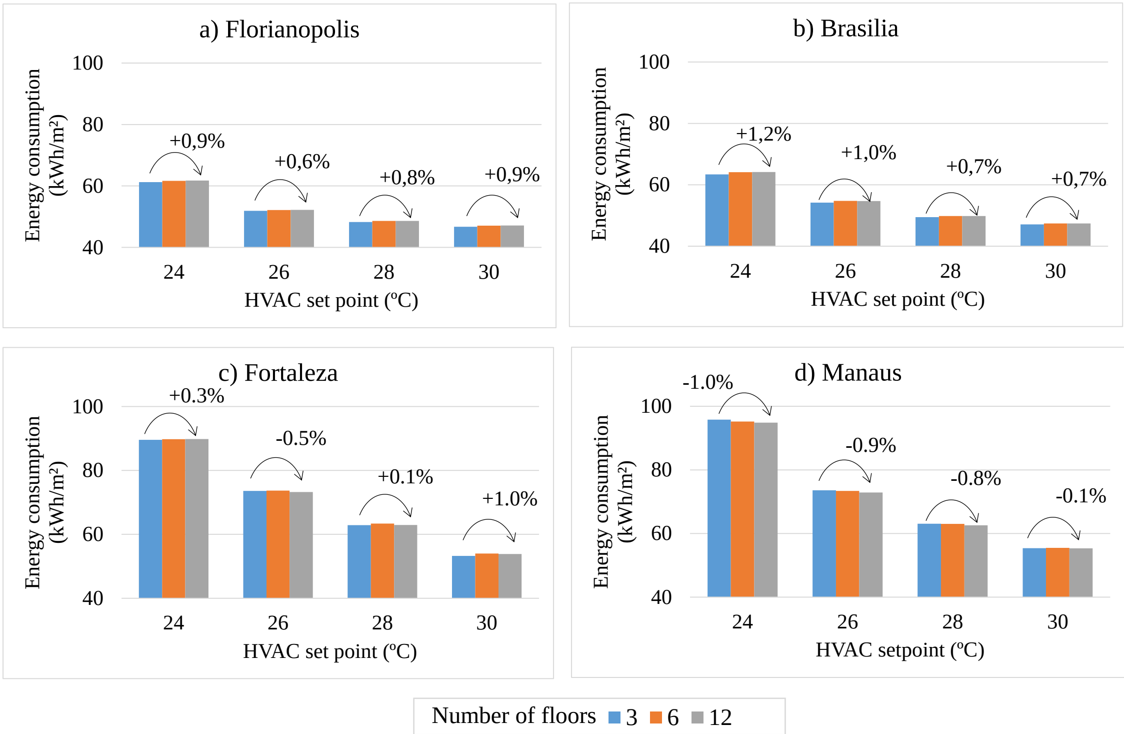

Fig. 12. Buildings annual consumption per area by city and set point temperature

Fig. 12 shows the great impact of set point temperature variation on energy consumption; as the set point temperature increases, the energy consumption decreases. By comparing the average values per set point temperature, shown in Fig. 13, it becomes clear that the local climate has a great influence on consumption. The average consumption per square meter in Fortaleza is very similar to Manaus, while Brasilia shows similar values to Florianopolis. The greatest difference between these two climatic groups occurs at 24 °C set point temperature where full air-conditioned buildings are compared. The greatest difference is observed between Florianopolis and Manaus – 33.4 kWh/m². Also, at that same set point, the difference between the cities with the same climate is also the greatest – 2.4 kWh/m² between Florianopolis and Brasilia and 5.3 kWh/m² between Fortaleza and Manaus. Energy consumption in Fortaleza and Manaus is higher than in the other two cities at any established set point temperature. The difference is lower when the set point is higher, but the curves do not converge, they go from 54% to 14% difference. This indicates that the difference in cooling demand remains significant, even with a high set point, since the other load densities – lighting and equipment – are the same in all cases. The small difference of consumption between the cities with mild climate – Florianopolis and Brasilia – converges when 30 °C set point temperature is applied.

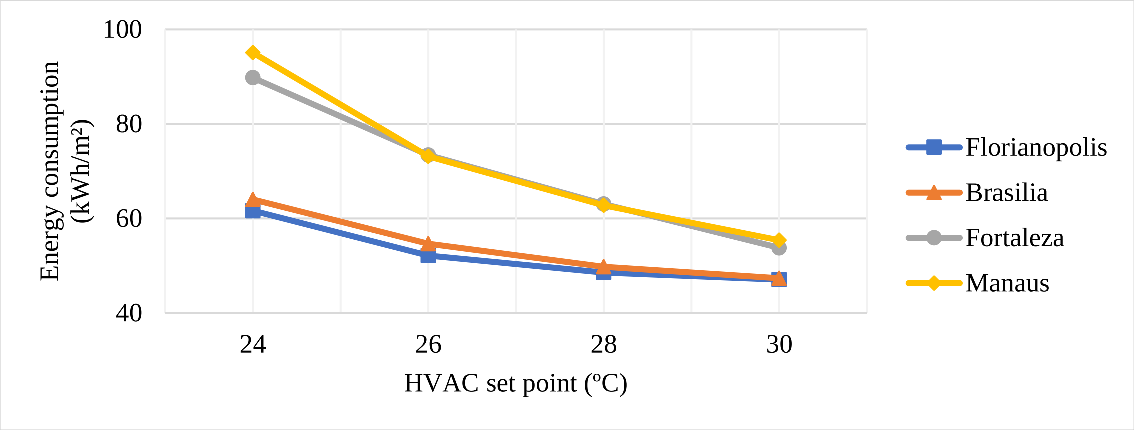

Fig. 13. Average annual energy consumption per area in each city and set point temperature

The benefit of extending the set point temperature is understood comparing the average energy consumption to the baseline condition, which is 24 °C, as shown in Fig. 14. This figure shows the extension of the set point temperature in Manaus and Fortaleza generates 18% to 40% energy savings and the increase is more linear in Fortaleza. On the other hand, the curves of Florianopolis and Brasilia deflects at 26 °C set point temperature showing that changing the set point from 28 °C to 30 °C has lower impact in those cities, increasing the energy savings by 2 percent points. This indicates that the higher limit tested does not bring as much advantage from an energy standpoint and applying 28 °C is similarly effective in these cities. On the other hand, in warmer cities energy savings tend to be greater with higher set point temperatures. As the frequency of temperatures above 30 °C is lower in Florianopolis and Brasilia, the set point of 28 °C or 30 °C generates similar results, i.e., the activation period of air conditioning and its consumption are very similar. However, in warmer climate cities, temperatures above 30 °C are recurrent, so the higher the set point the shorter the activation period of air conditioning and, consequently the lower its energy consumption.

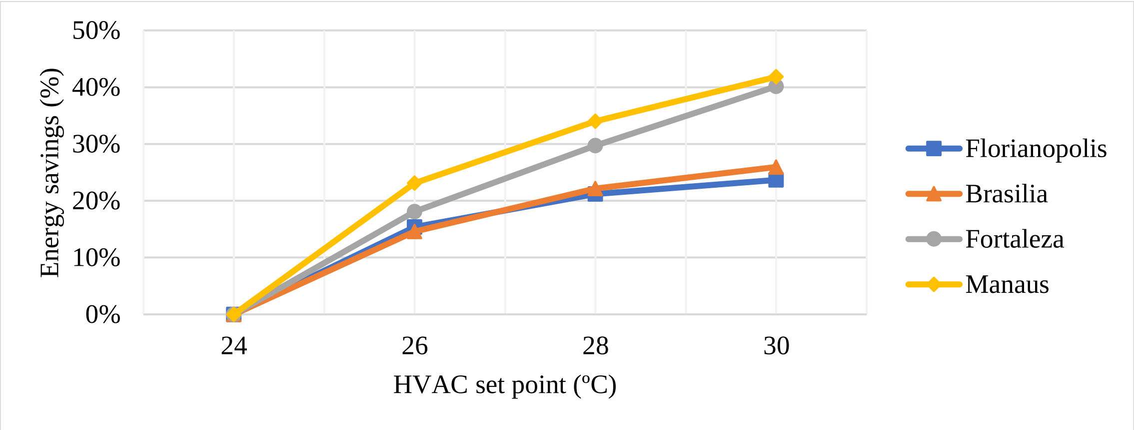

Fig. 14. Average annual energy savings by set point temperature extension per city

Thus, the proposed strategy has a greater potential for generating energy savings on warmer climates, achieving around 40% savings, while in mild-climate cities the maximum savings are around 26%. In addition, Fig. 15 shows that desk fans consumption represents a small percentage of total building energy consumption – from 0.4% to 1.4% in the 6-floor building – even at the highest set point temperature where they would be activated more constantly. In addition, Fig. 15 shows that set point extension from 24 °C to 30 °C has a great impact on cooling energy consumption, indicating this strategy can be very cost-effective.

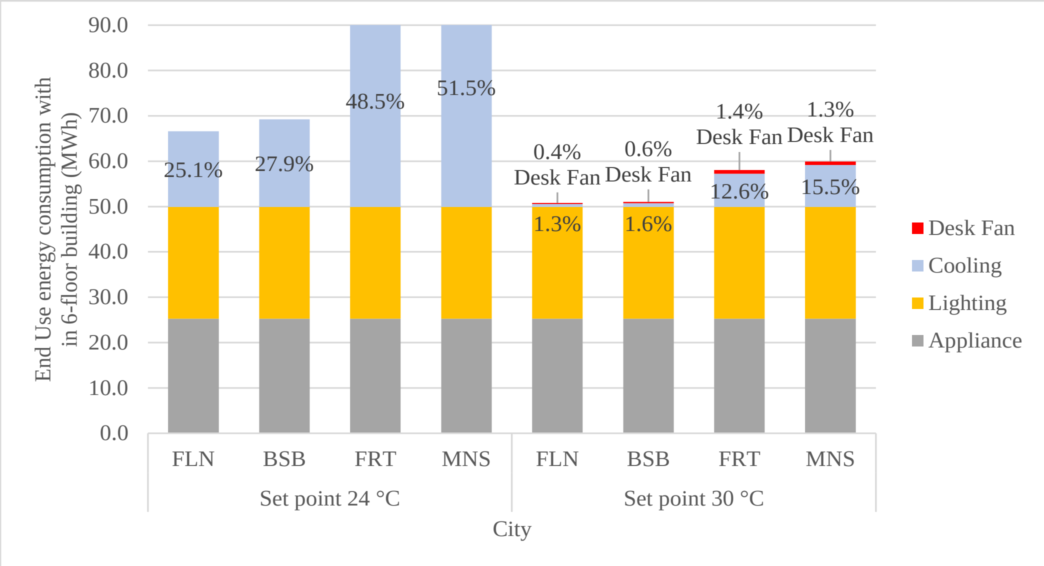

Fig. 15. End use energy consumption of 6-floor buildings with 24 °C and 30 °C set point temperature per city – Florianopolis (FLN), Brasilia (BSB), Fortaleza (FRT) and Manaus (MNS)

Taking the scenario indicated in Fig. 15 as an example, changing the set point from 24 °C to 30 °C in the 6-floor building in Fortaleza results in a total savings of 38.9 MWh/year, while desk fans consumption represents an increment of 0.83 MWh/year. Considering the energy tariff to be around 107.82 USD/MWh[1] in the northeast of Brazil [69], the energy cost savings are calculated to be 4.20 thousand USD per year and 349.64 USD per month. Considering the data indicated in Table 7, the investment for purchasing one fan per person for the building would be of 644 USD. Considering a simple calculation of the energy cost savings per month, the initial investment in desk fans would be paid back in less than two months – 0.15 year.

Table 7. Example of payback calculation for a 6-floor building in Fortaleza with desk fans and set point temperature extended to 30 °C

Energy savings (MWh/year)	Tariff (USD/MWh)	**Energy cost savings (USD/year)**	Condition. area (m²)	Occupancy density (people/m²)	Fan unitary cost (USD/fan)	**Invest. in fans (USD)**
38.92	149.56	**4,195.73**	972.00	0.10	6.57	**644.00**
Payback in years						**0.15**

In addition, the set point temperature change impacts on system sizing. As the set point increases, lower capacities are calculated by EnergyPlus, as shown in Table 8. The table shows the overall cooling capacity of the 6-floor buildings in each city per set point temperature. This result indicates extending the set point temperature would demand lower capacity splits, which could lead to financial savings. For example, in Manaus, changing the set point to 28 ºC allows a 24 MBtu/h split to be installed instead of a 30 MBtu/h split in the zone with maximum cooling demand. The proposed strategy allows the reduction of cooling capacity from 7% to 80% depending on the thermal zone, city and the selected set point temperature.

[1] Currency of 5.25 BRL to 1 USD in August of 2021. Reference: http://www.ipeadata.gov.br/

Table 8. Split system capacity calculated by EnergyPlus for 6-floor buildings in each city per set point temperature

City	Cooling Capacity [W]				
	Description	Set point: 24 °C	Set point: 26 °C	Set point: 28 °C	Set point: 30 °C
Florianopolis	Maximum	6,716.6	6,073.6	5,374.5	4,637.0
	Minimum	2,061.0	1,645.3	1,238.9	598.6
	Average	3,936.1	3,481.7	3,270.4	2,422.0
	St. Dev.	1,182.0	1,091.8	1,167.0	1,061.2
Brasilia	Maximum	8,857.1	8,134.6	7,370.5	6,567.7
	Minimum	2,187.7	1,700.0	1,178.0	430.2
	Average	4,473.1	3,863.7	3,145.4	2,388.1
	St. Dev.	1,599.1	1,535.8	1,508.3	1,489.2
Fortaleza	Maximum	7,178.3	6,586.1	5,952.6	7,873.5
	Minimum	2,526.2	2,054.2	1,699.3	935.9
	Average	4,165.5	3,713.5	3,419.3	3,048.9
	St. Dev.	1,121.3	1,061.9	1,113.4	1,455.5
Manaus	Maximum	8,311.8	7,706.6	7,061.1	6,379.6
	Minimum	2,911.0	2,374.6	1,994.7	1,456.1
	Average	4,713.3	4,263.4	3,827.9	3,413.1
	St. Dev.	1,213.8	1,158.4	1,117.3	1,056.7

3.3. Occupant predicted thermal comfort impact and set point temperature selection

As previously mentioned, the extension of set point temperatures is acceptable as long as occupants' thermal comfort is not compromised. Therefore, indoor operative temperature is compared to the comfort zone limits for the three simulated temperatures in the most critical thermal zones. The critical thermal zones indicated the lowest percentage of acceptable occupancy hour. In every simulated scenario the most critical thermal zone is the west-facing roof office. Fig. 16 presents the annual percentage of thermal acceptable hours of these zones in each simulated building and city. The darker colours represent the results achieved without fans, i.e., without the extension of upper comfort limit. The number of floors has greater impact on thermal comfort than on energy consumption. Most cities had warmer temperatures in the 12-floor building, except in Fortaleza where the most critical condition is observed in the 6-floor building. Fig. 16 shows that the increment of set point temperature reduces the percentage of thermal comfort, as expected. Fortaleza and Manaus have higher percentage of comfort hours with 26 ºC set point than the other cities. In general, all simulated conditions show more than 50% of acceptable occupancy hours in mixed-mode operation, without fans. Brasilia has the lowest percentages with 26 °C and 28 ºC set point. Fortaleza shows a good condition with 26 ºC (more than 90%), but percent comfortable hours drop drastically by the increase of set point temperature (around 73% with 28 ºC and 51% with 30 ºC). On the other hand, Florianopolis shows a more constant result; with the lower set point it achieves a little less than 80% of comfort hours; and by increasing the set point, this percentage drop to 75-73%. The use of fans in this city increases comfort in 5-9%, but greater impact is observed on the other cities. In

Brasilia, it increases in 11 to 17 percent points. However, the greatest impact is observed in Manaus and Fortaleza with 28 ºC and 30 ºC, where fans increase the percent comfort in 20-32%. Therefore, the positive impact of desk fans is confirmed and would allow the acceptance of higher set point temperatures in all cities. The 80% threshold is met in Fortaleza, Manaus and Florianopolis with fans and set point up to 30 ºC.

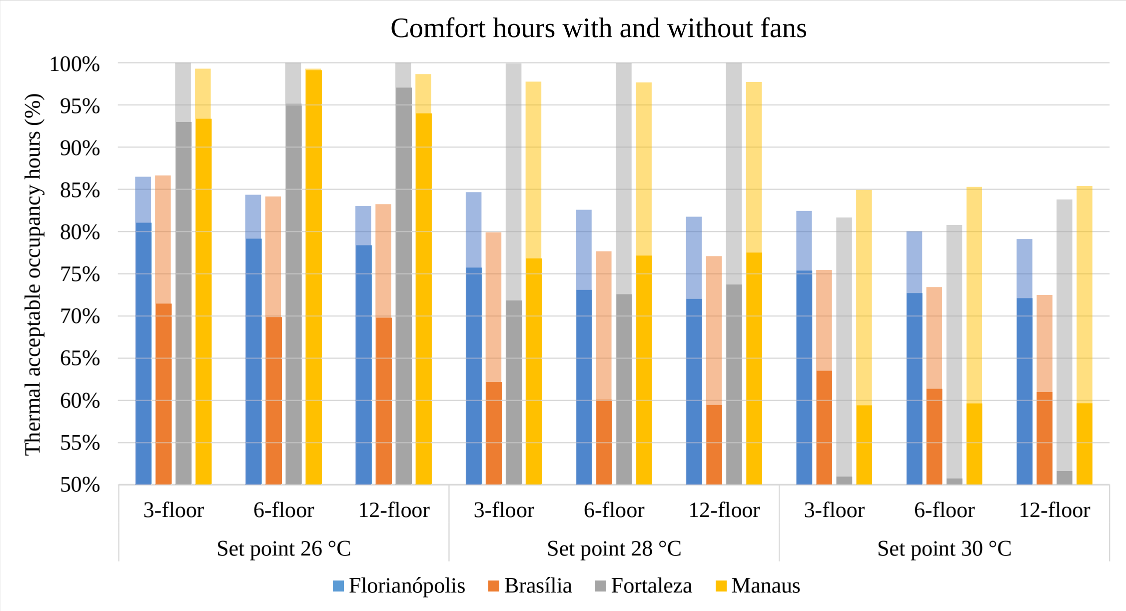

Fig. 16. Thermal acceptable occupancy hours per building height, city and set point temperature. Lighter colours correspond to the increment produced by desk fans

It can also be observed in Fig. 17 that some of the uncomfortable hours, mostly in Florianopolis and Brasilia, is caused by cold discomfort, even though windows only open at 21 ºC. In addition, temperatures 1 ºC higher than the acceptable limits, which could lead to overheating (shown by the red dotted line), mainly occurs under 30 ºC set point temperature (in yellow). The increase of set point temperature causes operative temperatures to also increase, however the lower temperatures do not change much. Finally, Fig. 17 shows the difference between air temperature – which is constant once the set point is reached – and operative temperature – which keeps rising.

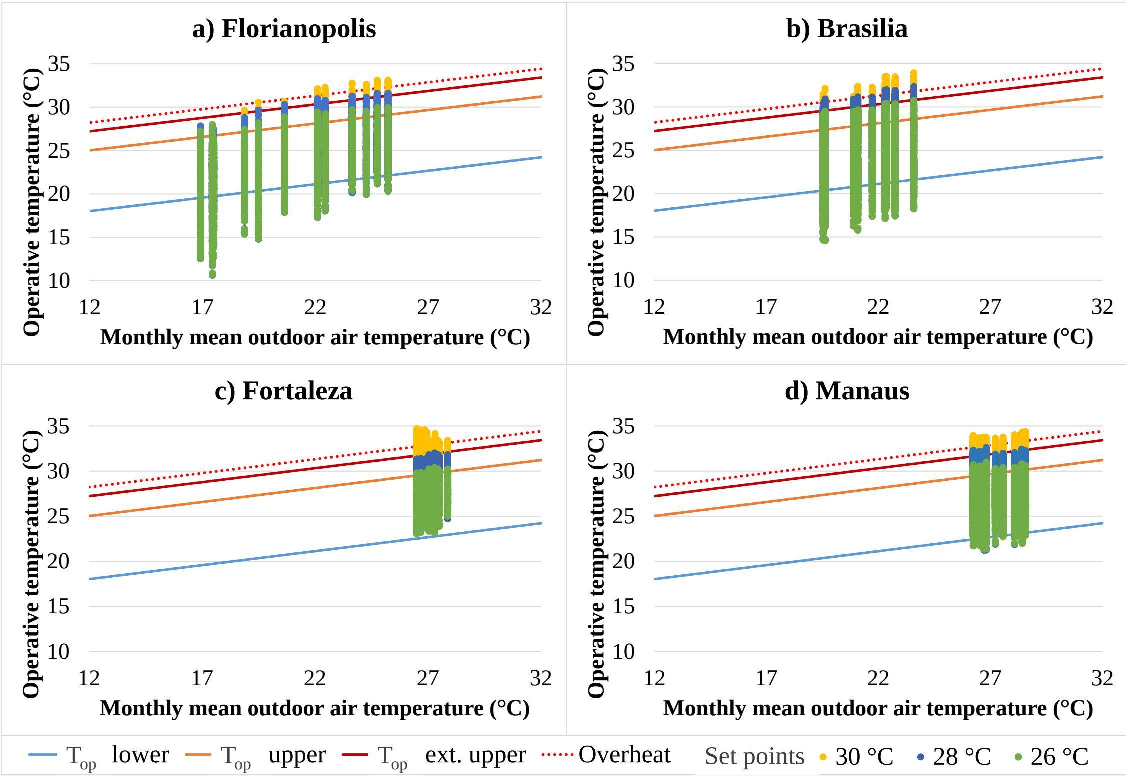

Fig. 17. Simulated operative temperature of the critical zones per city applied to the adaptive model with each set point – lower limit (T_{op} lower), upper limit (T_{op} upper), extended upper limit for high air speed (T_{op} ext. upper) and threshold for overheating analysis (Overheat)

Although Fig. 16 indicates that the set point of 30 ºC would be applicable to most cities, the overheating analysis gives another result. Fig. 17 shows the maximum limit of 3% of occupancy hours under higher temperatures (1 ºC higher than T_{op} ext. upper) is surpassed in Brasilia, Manaus, and Fortaleza with the set point of 30 ºC. Therefore, the maximum applicable set point is 28 ºC. On the other hand, in Florianopolis 30 ºC is applicable even though it only brings 2,5% more energy savings than 28 ºC set point.

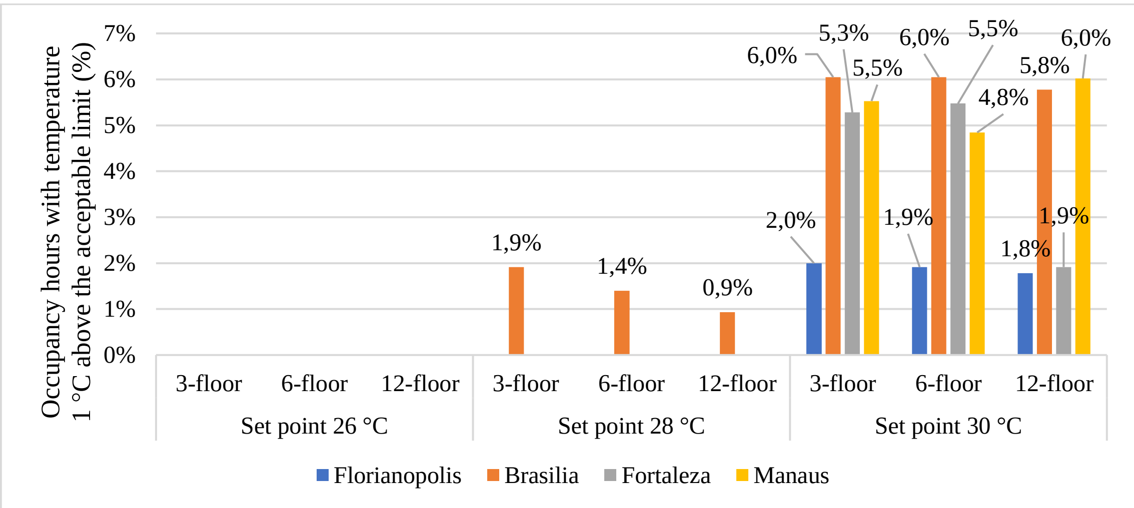

Fig. 18. Overheating evaluation – Percentage of occupancy hours with operative temperature 1 °C above the maximum adaptive limit in each city per set point temperature

3.4. NZEB and PEB potential evaluation

To analyse the potential of reaching a nearly zero energy building (NZEB) and positive energy building (PEB) the energy demand and photovoltaic (PV) production were compared on each simulated condition as shown in Fig. 19. The results show 3-floor buildings in mild-climate cities can be PEB with the implementation of photovoltaic energy production on their roof area without the proposed strategy. However, in warm-climate cities the proposed strategy enables 3-floor buildings to be PEB with the lowest set point proposed – 26 °C. In these cities, full conditioned buildings – at 24 °C – are NZEB with 77% and 93% of demand met. In all cities, the extension of set point to the limit identified in the last section – indicated in red in Fig. 19 – 3-floor buildings would have their met demand increased from 33 to 63 percent points. This would allow the surplus energy produced to be used by the owner for deducting it from the energy bill of another building registered in their name, according to local regulation [70]. Similarly, for 6-floor buildings, the strategy is needed to achieve NZEB in warmer climates, which is reached with 26 °C set point temperature. In the other cities, the fully conditioned case is already NZEB. The proposed strategy is not enough to make 6-floor buildings to become PEB. Though, by applying the highest applicable set point (indicated in red in Fig. 19), they are able to meet 80% and 84% of demand in Florianopolis and Brasilia, respectively. In Fortaleza, the suitable set point of 28 °C allows the 6-floor building to meet 66% of the demand. In Manaus, the same set point would allow the PV system to achieve 58% of the demand, which is lower than in the other cities, but almost 20 percent points higher than the fully conditioned building. For 12-floor buildings, unfortunately the proposed strategy is not enough to achieve NZEB nor PEB in any city. However, considering the extension of set points to the suitable values identified for each city in last section, the proposed strategy rises the met demand by around 10%.

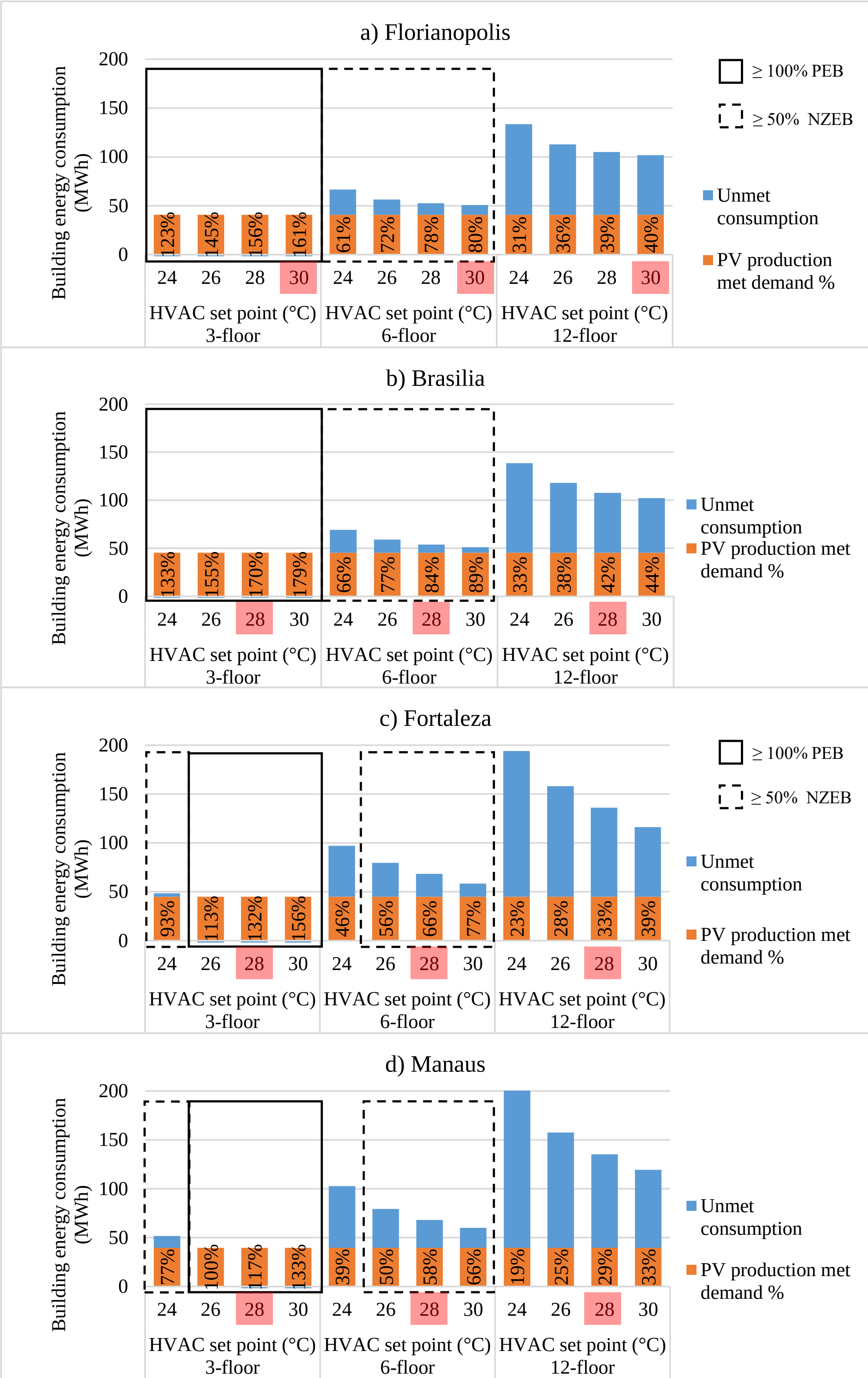

Fig. 19. Annual building energy consumption, the met energy demand (%) and unmet demand by PV production. Maximum applicable set point temperature in red.

Thus, for buildings with 12 floors or more to become PEB, it would be necessary to complement the energy production on other building or site surfaces. Opaque or translucent facade surfaces could be used [71,72] or other horizontal surfaces such as parking lots or pedestrian covered areas [73]. Assuming these possibilities, the remaining photovoltaic (PV) area necessary to meet 100% of the energy demand in each case was calculated and results are depicted in Fig. 20. The black dotted lines and percentage indicate the reduction in extra module area achieved by increasing the set point temperature to the highest applicable limit identified compared to the baseline – fully conditioned at 24 ºC. For 3-floor buildings in Manaus and Fortaleza the area needed is zeroed. For 6-floor buildings, the extra area needed can be reduced in at least 65% and up to 55% in Brasilia and Fortaleza, respectively. Finally, for 12-floor buildings, the extra PV area needed is reduced in at least 33% and up to 42% – in Brasilia and Manaus. In addition, for the highest buildings to become nearly zero energy buildings the strategy applied with the highest set point temperatures enables reducing the demand of extra modules area in 55% in Florianopolis, 65% in Brasilia, 56% in Fortaleza and 57% in Manaus.

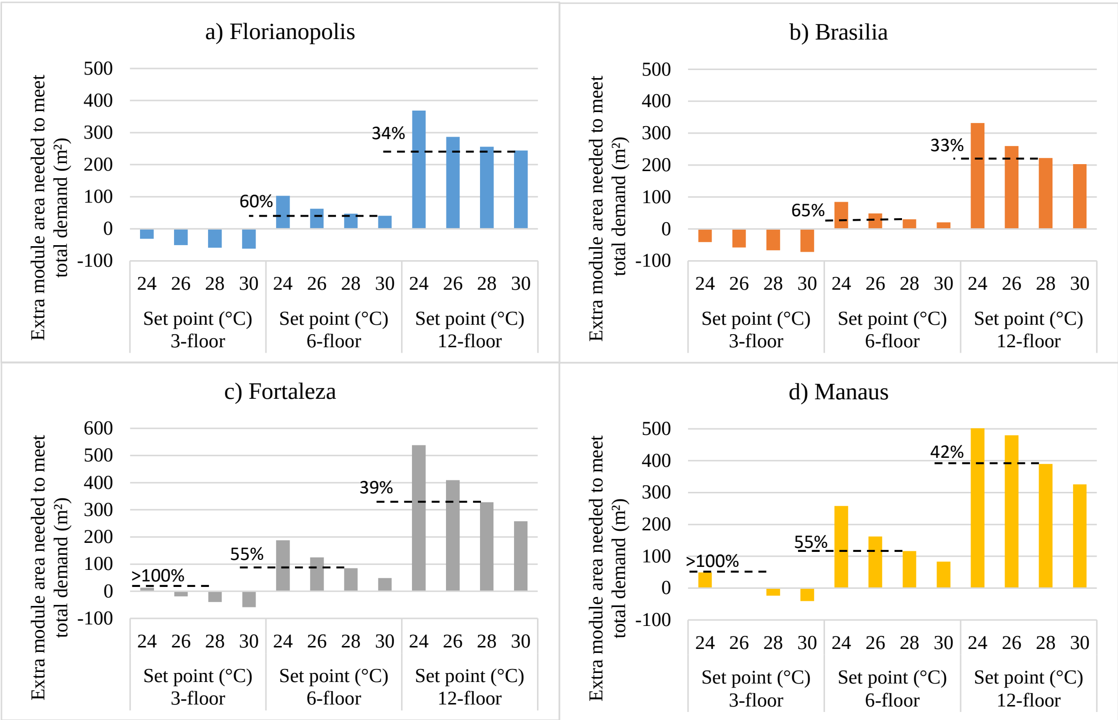

Fig. 20. Extra module area needed to meet total energy demand (in m²). The black dashed line and percentage highlight the impact of the proposed strategy over the need for extra area considering the highest applicable set point temperatures compared to the baseline condition

4. Discussion

Our results support that achieving NZEBs depends on several aspects and focusing on siloed issues may not be appropriate. As addressed by IEA-EBC Annex 53 [74] building performance is mainly influenced by six factors. Three of them are related to technical and physical aspects: climate, building envelope, and building services and systems; while the others are human-related: operation and maintenance, occupant activities and behaviour, and indoor quality. The proposed strategy focused mainly on the human-related aspects; however, the results also bring some insights on the physical aspects.

4.1. Technical and physical factors

Our results emphasise the influence of climate on achieving NZEB and PEB, as well as the importance of studying it in Brazil and other cooling-dominant climates, since the majority of built PEBs are located in cold regions [75]. Four case studies were conducted under varied climate conditions to have a broader understanding of this panorama. The Annex 53 activities indicated cooling degree days (CDD), in which ASHRAE climate classification is based, are important to quantify the influence of climate on building energy use [74]. However, when it comes to achieving NZEB and maximizing the use of natural ventilation, further climate indicators also play an important role. The 2A climate cities have similar CDD – Florianopolis = 4129 and Brasilia = 4454 – and the same is observed between the 0A climate cities – Manaus ($CDD_{10°}$=6443) and Fortaleza ($CDD_{10°}$=6405). However, the availability of solar irradiation had an expressive impact on the potential for photovoltaic production, which was higher in Brasilia and Fortaleza. Similarly, the analysis of internal operative temperatures indicated a higher probability of overheating occurrence in Brasilia than in Florianopolis. This aspect is also influenced by the difference in irradiance level which increases heat absorption by windows in Brasília. Thus, considering the proposed strategy based on mixed mode operation, it is important to consider that the cities present distinct potentials for maintaining thermal comfort by natural ventilation. In addition, photovoltaic potential was identified not to be proportional to CDD or latitude alone, so other climatic variables are important.

Furthermore, the results confirm that the restriction of roof area in highly verticalised cities can be a barrier to achieve NZEB or PEB. Regarding the climatic variations mentioned above, photovoltaic technologies should be applied on a case-by-case basis to better suit local conditions [76,77]. Moreover, the use of PV in facades can also be very cost-effective when used as a substitute for facade finishing elements of commercial buildings [71]. The performance of the photovoltaic facade could be improved if applied as a ventilated facade. This solution would allow the reduction of heat transfer to indoor spaces [78] and enhance the performance of modules by increasing its ventilation [79]. Besides, it would be possible to consider the adjustment of the type of energy production system based on the local climatic potential to maximize production [80]. For instance, Florianopolis was found to have lower photovoltaic potential than the other cities, however it has a great wind potential that could be further exploited [81]. From a policy-making standpoint, mapping multiple sources of energy production in each geographical region, or even favourable combinations of diverse sources would be very helpful to support an increment of renewable energy production.

The building envelope is also impactful in this aspect, as different parameters may boost the accomplishment of passive commercial buildings in cooling-dominant climates [82]. On defining the building envelope, it was observed that, to achieve level-A performance, the main aspects to be improved were window-to-wall ratio; and selecting a lower solar heat gain coefficient (SHGC) for windows and roof insulation. For further reduction of heat absorption by windows, the use of shading could be recommended. However, in the case of vertical office buildings with hybrid conditioning system, a previous study had indicated ventilation area has a greater impact than shading [16]. This study highlights the importance of taking advantage of cross-ventilation and windows with lower SHGC [16], which were applied to the building. These strategies help to reduce peak loads, while maintaining comfort by natural ventilation, and reducing cooling demand. Besides the envelope, another crucial aspect for achieving level A was the selection of an efficient cooling system. The cooling system used in this study is among those with the highest coefficient of performance in the Brazilian market (COP = 4.79 W/W). Most split systems have a performance between 3.22 and 3.02 which correspond to current level A and B of the national labelling for splits [83]. Compared to other countries and international standards the national labelling for these systems are outdated [84,85]. Fortunately, the revision of these criteria was approved recently and new limits will become mandatory at the end of 2022 [86]. Considering current market levels of efficiency, the proposition indicates the current level B – 3.02 EER – should become level F in 2022 and be completely outdated in 2025, when the lowest level will be higher than the current level A – level F in 2025 will be 3.50 [86]. The new requirement proposes the evaluation of Seasonal Energy Efficiency Ratio (SEER) instead of the current index – Energy Efficiency Ratio (EER) – that evaluates the efficiency in full load performance. This change sets the evaluation conditions closer to real-use conditions and encourages the purchase of inverter systems, which have higher partial load performance [87] and are more efficient.

Therefore, another issue for reaching NZEB or PEB in different countries is related to the efficiency requirements and corresponding levels of performance which set a standard for the manufacturing industry. The literature supports that energy use in buildings is related to several stakeholders during different phases of the building life cycle [88]. Besides the active role of building designers towards reaching efficient projects, technology developers and vendors, as well as policymakers, also play essential roles in the path for zero energy buildings. National energy efficiency policies should set higher standards for high-performance equipment to encourage the market to improve product quality, which would be reflected in energy performance of buildings in the future. Future work could also address the impact of climate change on the potential of the proposed strategy.

4.2. Human-related factors

This study shows mixed-mode operation associated with desk fans could be more widely implemented in warm climates, as it can maintain occupants' thermal comfort with lower energy consumption. Currently, in most office environments the use of air conditioning is favoured, even in cases where the climatic conditions allow the use of natural ventilation. The set point temperatures used vary little regardless of location, since they are based mainly on national standards. In Brazil, the 2008 standard is outdated in relation to international studies on thermal comfort and it is under review so that ASHRAE 55 parameters are adopted. The current standard defines that temperatures must be between 21 °C and 25.5 °C with a relative humidity of 60%, and air speed must not exceed 0.2 m/s [89]. In practice, the average temperature of 23 °C is more usual. Due to the restriction of air speeds, the application of ventilative cooling is hindered. Thus, a great potential for energy savings is wasted, as demonstrated in this study. In addition, the standard does not include natural ventilation or hybrid operation mode. Thus, it is expected that the incorporation of ASHRAE 55 parameters should represent a great step towards broader possibilities of conditioning operation in office environments. The results presented herein could also stimulate other warm climate countries to include these strategies in their national thermal comfort and energy efficiency standards, as a great potential was depicted.

Nevertheless, this study relies on the assumption that occupants would agree with the set point extension based on predictions calculated by adaptive thermal comfort model. Many studies show preferences may vary largely among different groups of people and organisation culture [90,91]. So, future studies should be carried out to validate occupants' satisfaction with the proposed set point extension. It is interesting to note that field studies conducted previously in Brazil suggest an acceptability to higher operative temperatures with the increase of air speed, as shown in Fig. 21. This figure was based on the Brazilian Thermal Comfort Database [92,93] and presents operative temperatures considered both acceptable and comfortable in the studied climates when occupants were under low (< 0.2 m/s) or higher (> 0.2 m/s) air speed. In 0A climates the temperature limit is higher than identified in this study, while in 2A the opposite occurs, the identified limits are lower than the studies indicate. However, the great effect generated by the increase in air speed and the possibility of extending the set point temperature by applying the proposed strategy is confirmed in this database.

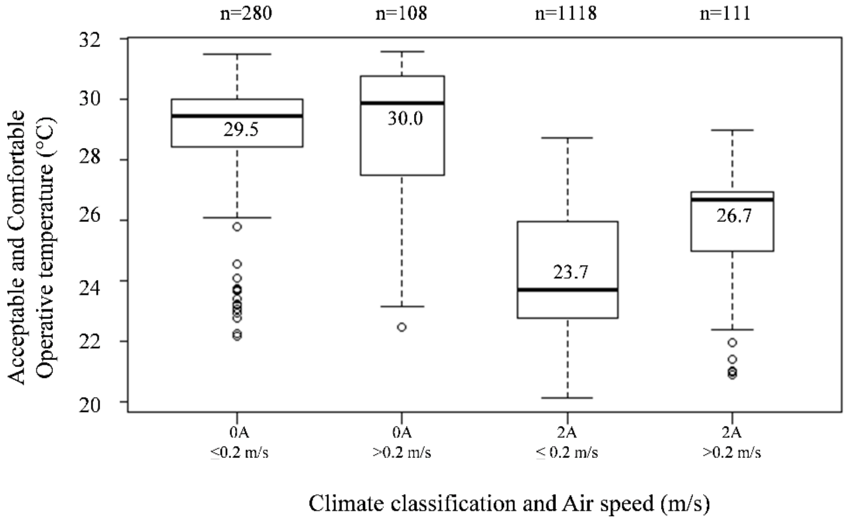

Fig. 21. Acceptable and comfortable operative temperatures based on the Brazilian thermal comfort database [92,93]

To enable the implementation of this control strategy, it would be necessary to identify the set point accepted by the occupants of a given office. Personal comfort models are a key tool to include occupants' preferences in the set point definition and control. When associated with sensors and environmental controls, it is possible to fine tune the set point including horo-seasonal and interpersonal demand variation [94–97]. This interconnection is possible with the Internet of Things (IoT) by including humans in the loop [98]. IoT is also essential for the proposed strategy as it allows an unitary split system to be automated [99]. This way the great efficiency potential of these small systems is exploited, while the advantages of central control can be provided. Automation is also important to avoid conflicts in shared office spaces, where occupants might be afraid to make adjustments due to the effect on colleagues [28,100]. Awareness campaigns could also be applied in order to occupants better understand their environmental impact and how controls work, so they become are more willing to accept variable conditions [101].

The percentage of high operative temperature – especially with the 30 °C set point – also highlighted the misalignment between the defined cooling set point and indoor operative temperature. Since operative temperature is more closely related to users' thermal comfort, the proposition of an environment control aiming at occupants' satisfaction should consider this difference. The present results indicate that without desk fans the maximum acceptable set point in Brasilia would be 26 °C because the percentage of comfortable hours with 28 °C set point would be 60% and overheating occurrence would surpass the 3% limit. In the other cities the comfortable hours at 28 °C would still be around 70% but overheating could also become a problem since it would be calculated based on the upper adaptive limit without extension. This difference between the air temperature and operative temperature is probably due to high percentage of window surfaces and small floor plan depth that cause the mean radiant temperature to have a great effect on operative temperature. One way to overcome this problem would be to use a set point adjustment that considers the measured or predicted mean radiant temperature [102,103]. This strategy could allow horo-seasonal adjustment of the set point, which could be relevant for mild climate cities. The use of operative temperature is not yet common and some of the problems related to this inclusion are discussed by Halawa et al. [104]. However, Simone et al. [105] states that with the appropriate sensor it is possible to achieve reasonable values of mean radiant temperature for inclusion in thermostat control.

Although this study was based on a simplified control operation method, with a fixed set point throughout the year, it was observed that the resulting cooling savings were higher than previous studies in similar climates, as shown in Table 9. The cooling savings presented in Table 9 are a comparison to full conditioned conditions in the MM and MM with ceiling fans (MM+CF) references. In the study of Lipczynska et al. [36] savings are calculated comparing 23 °C set point without fans to 26 °C set point with ceiling fans (CF). The high cooling savings achieved in this study highlight the potential for using desk fans, which present lower energy consumption than CF – 0,3 W/m² in this study and 2 W/m² in Bamdad et al. [35]. However, as shown in Table 9, higher set point temperatures were applied in this study, which also maximize cooling savings. However, as mentioned above, this extension would not be possible without the desk fans.

Table 9. Cooling energy savings of previous references and this study

Reference	**Study type**	**City**	**ASHRAE 169 Climate zone**	**Cooling savings or indicated index**	**Set point or operation temperature**
Emmerich [106]	MM	Miami	1A	70 to 50% of HVAC fan and 43% (winter) to 0% (summer) cooling savings	20-26 °C
Wang and Chen [107]	MM	Miami Phoenix	1A 1B	< 10% < 10%	Outdoor temp. 15-22 °C and Indoor air > 19 °C when occupied When unoccupied outdoor 10-22 °C
Wang and Greenberg [108]	MM	Houston	2A	20%	Monthly adaptive set point temperature
Ezzeldin and Rees [109]	MM	Alice springs El Arish Manama Madinah	2B 2B 0B 0B	35-70% 40-60% 45-60% 50-55%	Monthly adaptive set point temperature Chilled water set point = 6.7 °C
Daaboul et al. [110]	MM	Beirut	2A	31% annual savings	Cooling 21-26 °C MM Monthly adaptive set point

Bamdad et al. [35]	MM+CF	Darwin Brisbane	0A 2A	46% 52%	Heating 21 °C Cooling 24 °C MM monthly adaptive set point with extended upper limit for perimetral zones and core with AC always on Ceiling T_o > Adapt upper limit CF 2W/m²
Lipczynska et al. [36]	Extended set point from 23 to 26 °C including CF	Singapore	0A	30%	Cooling 26 °C Ceiling fans operated by occupants CF 30 W but consumed 1%
This study	MM+ DF	Florianopolis Brasilia Fortaleza Manaus	2A 2A 0A 0A	93-96% 75-85% 53-67% 54-71% (3, 6 and 12 floors)	30 °C 28 °C 28 °C 28 °C DF T_o > 26°C DF 0.3 W/m²

AC – Air conditioning
CF – Ceiling fans
DF – Desk Fans
MM – Mixed-mode operation

In addition, the impact of relative humidity could also be further investigated. Although the adaptive thermal comfort model does not include relative humidity (RH) restrictions, it is known that convection has a reduced effect when high temperatures are associated to high relative humidity [111,112]. Under these conditions, although they prefer greater air movement, the cooling effect is limited by the reduction of evaporative heat loss [111,113]. Therefore, Zhai et al. [111] indicate 30 °C with 60% RH as an acceptable limit when fans are available. However, these limits seem to vary [114,115], In conditions similar to this study, in a field study in Brazil, Buonocore et al. [116] identified thermal comfort votes to drop when operative temperature was 30 °C and RH higher than 70%. To evaluate the impact of this condition, annual distribution of RH for critical zones – west-facing rooftop zone – are presented in Fig. 22. It is observed that RH reaches almost 100% in all cities. Set point temperature increment impacts on RH when cooling is on (AC) as the number of conditioned hours becomes smaller. In addition, Fig. 22 shows RH is higher when the air conditioning is off (NV), which is expected, since the cooling process reduces the air temperature and air humidity. However, the frequency of occurrence of operative temperatures ≥ 30 °C that are within the adaptive comfort limit and coincide with RH ≥ 70% was found to be very low. This situation occurs mainly in Manaus, with a frequency of 2,3% at 28 °C set point and 4,8% at 30 °C set point. In Fortaleza, 1,8% of occurrence is also found under the 30 °C set point temperature, but in the other cities and set points the occurrence is lower than 1% of occupancy hours. Since 30 °C set points were not suggested for Manaus nor Fortaleza, the main impact on the presented analysis would be a reduction of 2% on predicted comfortable hours in Manaus under the 28 °C set point. However, as shown in Fig. 16, this would still result in more than 90% of comfortable occupancy hours for the most critical thermal zone of this city, thus no changes to the suggested maximum set point temperature are required. Anyhow, further field studies regarding RH acceptability limits with desk fans are encouraged to validate this statement.

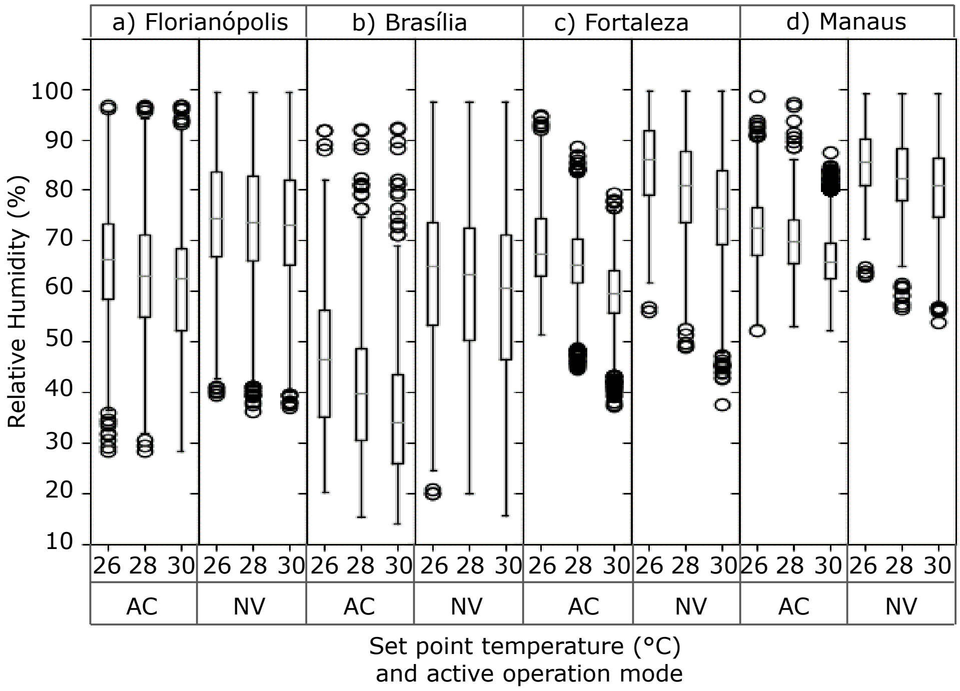

Fig. 22. Annual relative humidity distribution in the critical zones per city, set point temperature and active mode – air conditioning (AC) or natural ventilation (NV).

Finally, indoor environmental quality (IEQ) is another important factor regarding this study: along with reducing as much as possible the energy use, NZEBs should also guarantee satisfactory IEQ for occupants. The literature supports that requirements about indoor conditions could also become specific criteria for NZEB or PEB definition [117]. In this study, the most prominent IEQ parameters regard thermal aspects and evaluations were conducted. A consequent impact of this study's proposition is the use of natural ventilation as much as possible throughout the year. The literature recommends such mixed-mode operation as it can reduce HVAC consumption while also ensuring appropriate indoor air quality [118]. Hummelgaard et al. [119] concluded that occupants in naturally ventilated offices are slightly more satisfied with the indoor environment as well as have lower prevalence of sick building syndrome symptoms compared to those in fully mechanical ventilation. Thus, stimulating occupants to rely on PCSs combined with natural ventilation where possible is expected to improve indoor conditions from both thermal and air quality concerns.

5. Conclusion

The results highlight buildings are complex systems affected by several aspects like climate, technology availability, operation controls, and occupants' behaviour and preferences. There are still many steps ahead for NZEB and PEB expansion in Brazil and the inclusion of their classification in the national energy labelling system for buildings is a major step in this direction. The revision of national thermal comfort limits and changes in the way office spaces are conditioned is also needed. The revision of the Brazilian thermal comfort standard in progress incorporates the 2020 ASHRAE 55 parameters, which allow a greater variation in set point temperature and air speed values. This work highlights the advantages and possibilities involved in expanding these limits by applying mixed-mode operation and personal fans in office spaces to reduce cooling energy demand. Therefore, the results could help to extend the international goal of decarbonisation to under-developed warm climate countries, as the proposed strategy has a low cost and could help to increase NZEB financial and spatial viability in verticalised city centres. Regarding the goal of achieving NZEB mid-rise office buildings in vertical urban centres, the study presents some important outcomes and future challenges:

- The application of personal fans with mixed-mode operation strategy was demonstrated to be very efficient for open-plan offices. Fans could further extend thermal acceptable occupancy hours up to 30%, and occupants could accept higher set point temperatures.
- For this strategy, climate conditions have higher impact on energy consumption per area than number of floors. However, the difficulty in becoming a Positive Energy Building (PEB) with rooftop photovoltaic system for a building with limited projection area and more than three floors was confirmed.
- The proposed strategy allowed highly efficient 3-floor buildings in warmer climate cities to become positive energy buildings (PEB) with 26 °C set point temperature and desk fans.
- For 6-floor buildings in warmer cities, adopting at least 26 °C set point enables reaching nearly zero energy buildings (NZEB) based on the national labelling system parameter; however, PEB requirements are not met regardless of the location and increment of set point temperature.
- For taller buildings with 12-floors, the roof area was not enough to meet half of annual energy demand even with the highest proposed set point temperature.
- Nevertheless, it reduced from 33% to 65% the extra PV module area needed to meet the building annual demand, which could increase the economic and spatial feasibility of mid-rise buildings to become PEB.
- A set point temperature definition method was proposed based on adaptive thermal comfort limits, and overheating probability. This method allowed identifying that although 80% occupancy hours could be within operative temperature comfort limits with 30 ºC set point temperature, the probability of overheating was high in most of the cities. Therefore, this set point would only be applicable for the mild climate city with lower global horizontal radiation incidence – Florianopolis. For the other ones, 28 ºC maximum limits is recommended.
- The selection of the set point temperature extension should also consider the misalignment between air temperature and operative temperature, as the first is usually used to control cooling, but disregards the radiant effect impacting occupants' thermal comfort.
- Future studies are needed to find strategies to assure occupants' use of desk fans and thermal acceptability, including situations with high relative humidity.
- In addition, future work could be carried out to evaluate other control strategies like set point temperature control based on operative temperature and horo-seasonal temperature adjustment associated to desk fans.

Acknowledgment

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APPENDIX E – PAPER 4

TITLE

User-centered environmental control: a review of current findings on personal conditioning systems and personal comfort models

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ABSTRACT

Occupant-centric building design and operation has attracted recent research efforts in many countries, as building occupants are being more recognized as the main drivers in planning and operating safe, comfortable, energy-efficient indoor environments. In this matter, the role of building managers and operators is crucial to capture the needs of occupants and to adapt the response of the building accordingly. IEA EBC Annex 79 participants conducted 72 interviews with operators and facility managers across 7 countries (Brazil, Canada, Germany, Italy, Poland, Singapore, and USA) covering a wide range of ASHRAE 169 climate zones (from 0 to 5 in the climate classification). This paper presents a qualitative cross-case analysis of operators' perspectives and experiences to identify regional differences. Therefore, the analyses are based on the hypotheses that climate or other country-related aspects would be the main drivers of building operation procedures differences. Results show climatic differences have little influence on building management, while occupants' complaints are very influenced by them. Moreover, operators are lacking clear tools, like guidelines and standards, on how to optimize building management in a climatic-adaptive and occupant-centric manner. Therefore, the development of operation protocols for building sustainable operation respecting climatic context and occupants' control is recommended.

Key words: Building operation, Interview data, Occupant satisfaction, Regional Differences, HVAC control, Energy efficiency

1. Introduction

In pursuing energy efficiency strategies it is important to remember that it is not buildings that use energy, but people [1]. This is evident from the so-called energy performance gap, which shows the deviations between designed and real performance of buildings [2], as well as from the high variance of energy consumption due to individual occupant behavior [3]. In commercial and public buildings, where environmental control is assigned to specific individuals, the impact of human behavior on the building environment is a direct consequence of the actions of occupants and operators. Occupants use the building space to reach comfortable environmental conditions for their activities, while operators — in charge of controlling different aspects of the buildings like HVAC systems, lighting, openings, etc. — focus on the high performance of buildings. Thus, building operators and building managers significantly influence energy performance and comfort on a day-to-day basis through their operational decisions [4,5]. In theory, the two objectives of high energy efficiency and high occupant comfort levels should be consistently and simultaneously targeted. However, occupants' needs and control of building systems are sometimes in conflict [6]. In these situations, operators could consider occupants' needs not as operational guidelines, but as interference that, in extreme interpretation, should be reduced by restricting occupant control. This issue is highlighted in the International Energy Agency's Energy in Buildings and Communities Programme (IEA EBC)- Annex 79 - Occupant-Centric Building Design and Operation project [7], which serves as the motivation for our analysis:

> Despite the fact that buildings are designed for occupants in principle, evidence suggests buildings are often uncomfortable compared to the requirements of standards; difficult to control by occupants; and, operated inefficiently with regards to occupants' preferences and presence [7].

The reason for this situation is that, considering the complex and diverse nature of the needs of occupants in commercial and public buildings, building managers and operators often lack the knowledge and tools to operate buildings optimally [8]. ASHRAE developed fundamental guidelines for building operation [9], however, shifts in operation (and design) paradigm are required to involve occupant-centric operation: occupants should not be considered as passive recipients satisfied with so-called fixed ideal environment conditions described by the PMV index [10]. Instead, built environments should be adjustable so that they can be customized with respect to climate, building characteristics, performed tasks, and occupants’ social factors [11,12].

Importance of occupant control over the indoor environment has been reported extensively in scientific literature [13]. For example, Karjalainen [14] and Oseland [15] find that people feel more comfortable indoors if they have higher adaptation possibilities or if surroundings are more personalized to their needs. These observations can be explained in three ways: adaptive opportunities enable occupants to adjust indoor environment parameters to their needs; occupants can change their clothing or activity to feel more comfortable; and adaptive opportunities lower occupants’ stress and increase their physiological adaptability to given environmental parameters [16].

However, it should be noted that users do not always prefer to have full control over building systems. They would rather have experts or control algorithms handle domains that are too sophisticated or time-consuming for occupants or that do not directly influence their comfort levels [17]. Thus, control algorithms, although often perceived by occupants as unwanted limitations of control, could also be tools that increase people's work performance, by decreasing their adjustment efforts/time [18,19]. Therefore, levels of automation in buildings and operator tasks are topics of interest in the scientific community.

Operators of buildings and their points-of-view have been investigated in various contexts. As the building operator profession started to become established, Gazman [20] and Putnam et al. [21] studied their education levels. Balaji et al. [22] interviewed 10 operators to diagnose weaknesses of the Building Management System (BMS). These flaws make the work of operators more difficult, leading to lower comfort and productivity in buildings and worse energy efficiency. There is also deeper research on the connection between operators' work and building performance / performance gaps. Zhang and Gao [23] analyze the building operation process and propose a framework for optimization of facility management procedures. Craig Roussac and Huang [4] investigate the role of feedback information for operators' engagement toward energy efficiency of their buildings. Based on observation of five case studies of nonresidential buildings, Aune et al. [24] analyze operators' work as mediation between occupants' needs and technological systems. Min et al. [25] present the case study of higher education campuses to prove the potential of operators to work for improvement of energy performance. An interactive model between building operators and occupants has been developed and used by Liu et al. [26] to investigate the role of communication strategy to meet energy performance gaps in green office buildings.

The above-mentioned studies are connected to single countries or even one building analysis. To the best of our knowledge, research conducted from cross-country perspectives in this domain have not been published, unlike other aspects of building use. Chien-fei et al. investigate multi-country and multi-cultural differences in heating and cooling practices, adaptive strategies, energy saving intentions, and social interaction using an international survey [12,27]. Jeong et al. [28] focus on variation in the design of smart-home interfaces based on American and Korean cognitive styles. However, as illustrated by the red arrows in Fig. 1, aspects related to building operation have not yet been covered in studies comparing multiple countries. Therefore, the purpose of this work is to help fill in these gaps about regional differences in operators' decision-making, procedures, and their relation to building control technologies and occupants.

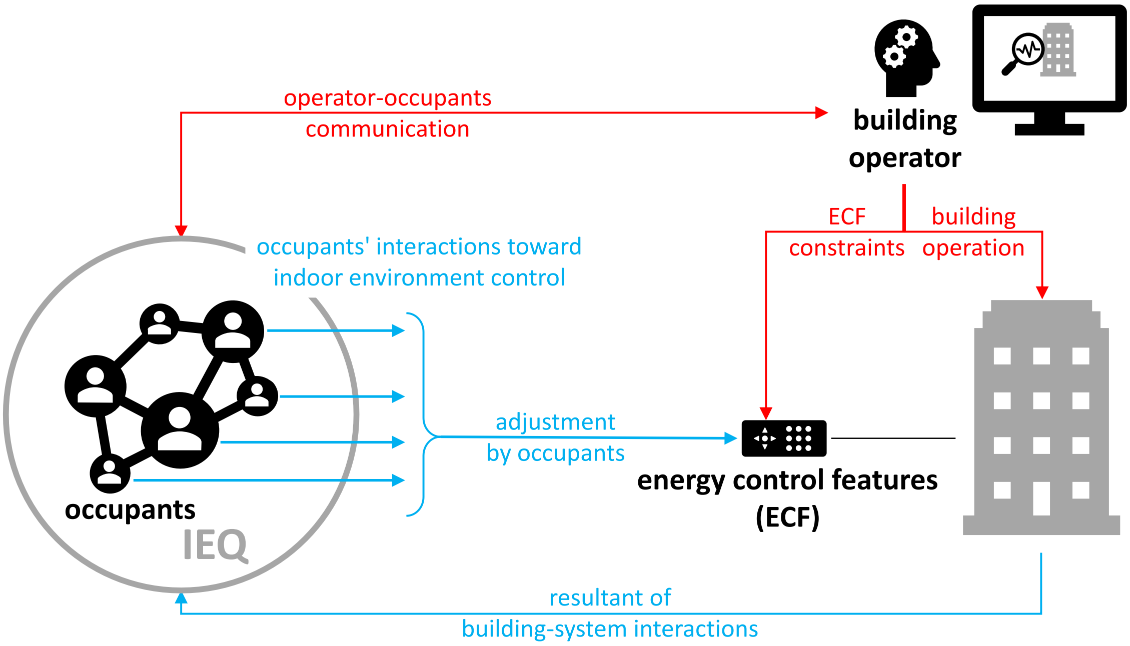

Fig. 1 - The scope of our analysis in the context of human-building interaction. Red arrows are our topics of interest, while blue arrows represent topics that have been covered in some way by other papers (ECF - energy control features). For proper visualization of figure colors please see the online version

2. Methodology

2.1. Hypotheses

Building operations regional differences could be influenced by many aspects, like country policies, market structure [29] and local economy, technical and development levels [30] and climate. Climatic differences are manifested in variations in both building and HVAC design for distinct climates [31,32]. Climatic and seasonal variation influences human thermal perception [33–35] as well as human personality [36] (which mediates interhuman communication). Moreover, culture plays a significant role on ethical standards [37] which are important in communication between operators and occupants, and can potentially influence occupants' behavior. Sociocultural aspects may also affect people's trust in automation [38], which is important for building control and operation. Therefore, considering the cross-case comparison methodology [39], the analyzed aspects are separated based on two hypotheses:

I. Building operation and procedures are influenced mainly by local climate.

II. Other country-driven aspects, like economic, sociocultural, and technological differences are more influential to building operation and procedures.

2.2. Interviews and Limitations

To enable the evaluation of this hypothesis, an interview guideline was developed by expert researchers from the IEA EBC- Annex 79 [40]. Interviews were chosen as an investigative method to allow follow-up questions and to integrate open-ended questions to enable additional insights. Subsequently, the results could be used for broader (online) surveys.

The questionnaire consists of 23 questions (see [41]) aimed at covering the multiple operation aspects that would be related to the two hypotheses as depicted in Fig. 2.

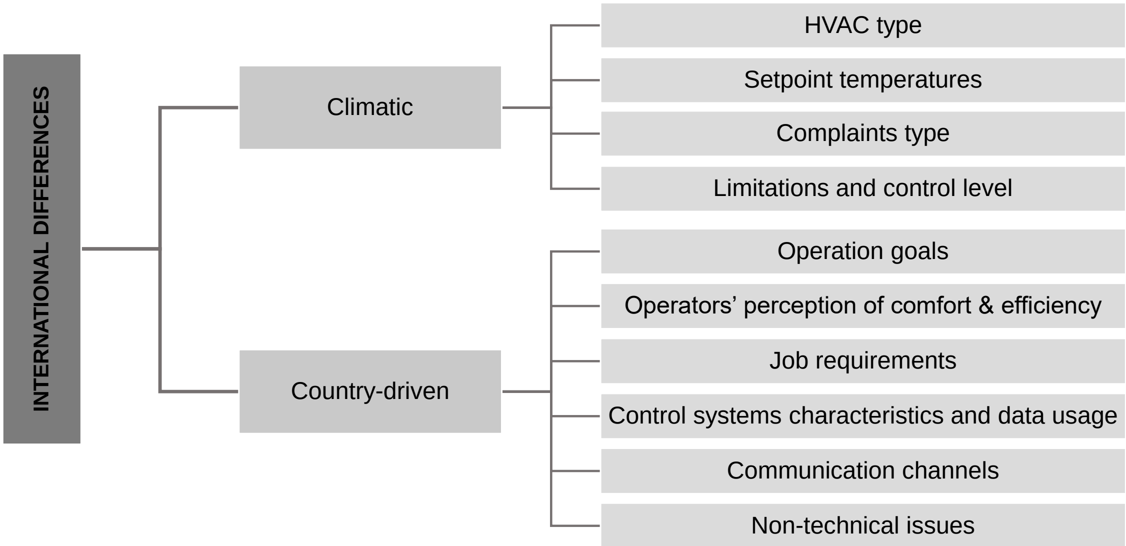

Fig. 2 - Initial correlation between hypotheses and operation procedures aspects

The semi-structured interviews were conducted from January to November 2020 with building management professionals by researchers online, or by phone call or in-person in each country's language. The translation procedure of questions and responses from different countries and languages follows a predefined procedure to ensure the proper translation as described in detail by Hahn et al. [41]. The interviews conducted in English speaking countries were transcribed directly into the analysis software. To meet data privacy requirements, the interviewees were anonymized, and no personal identification or sensitive data were collected. This human-subjects research initiative initially received the research ethics approval at Northeastern University in Boston, MA, USA (IRB # 20–01-01). Additionally, ethics approval was sought at each subsequent participating institution and country that required such approval.

Some limitations and biases of the proposed method have been identified. Initially, the samples were obtained through personal contacts by the scientists. This resulted in a significant number of responses, nevertheless, the sample by country is not evenly distributed or generalizable. The numerical analysis presented in this study does not aim to generalize the results for the national panorama of each country, but to facilitate the comparison of the sample results highlighting tendencies and differences in building operation. Indeed, since the present study is rooted in a qualitative perspective, a naturalistic approach was adopted to better interpret the results. In other words, the primary aim of this study is not prediction or generalization of findings, but rather, exploration of real-world phenomena to build knowledge on the field and likely extrapolate it to similar situations [42]. Further influencing factors result from a rather broad spectrum of job positions of interviewees (technicians to managers) and a concentration of high degree employees given the contacts available. Finally, the operator perspective might already include inherent biases of the topics considered. As already explained in [41] the interviews revealed a so-called saturation rate, which confirms the sufficient number of samples. This means that increasing repetitions (trend) of similar answers lead to a clear picture of the study subject.

2.3. Methods of data analysis

To analyze interview content information, qualitative approaches are the most appropriate [39]. Thematic analysis was chosen as the main analysis method, as it allows the assessment of data characterized by the input of both implicit and explicit ideas into themes according to the proposed lines of investigation [43]. It was applied by extensive reading of the transcripts to systematize and structure the data from textual transcripts, coding was selected as the main approach. Codes were created to represent the identified themes and categorize the answers. To structure the framework of expected categories and report such information graphically, content analysis was selected as the main approach to data analysis [39].

NVivo 10 software [44] was adopted to aid in qualitative data management and analysis throughout the study. The interviews were uploaded into NVivo and underwent two processes: automatic coding of transcripts and manual coding. In automatic coding, NVivo sorted the heading variations into dialogue by question, interviewer, and respondent categories. In addition, it was programmed to sort by country, date, interviewer name, memos and interview pseudonyms. Manual coding was conducted after reading and rereading the interviews to create the themes (identified by nodes in NVivo). Nodes were defined and redefined as needed in this process, which included tools available in the software such as word frequency and text search queries. Matrix coding and crosstabs were adopted to report the information from nodes numerically, based on cross-case methodology [39].

3. Sample characterization

3.1. Climate characteristics

In order to conduct climate-driven analyses, the climate zones from ASHRAE Standard 169 [45] were adopted in this paper and a climate zone was assigned to each interview according to its location. The set includes 0 to 5 climate zones, defined based on the criteria depicted in Table 1. For some analyses, the climate zones were grouped based on heating degree-days (HDD) and cooling degree-days (CDD). Warmer climates with prevalent CDD and low HDD (≤ 2000) will be referred to as “cooling dominated (CD)” in this paper, while those with HDD above 2000 as “heating and cooling dominated” (HCD) [46]. This classification is applied to highlight what would be expected as the prevalence of cooling and/or heating demand in the buildings from the climatic perspective.

Table 1 - ASHRAE 169 thermal zone classification

Climate zone	Name	Interval
0	Extremely hot	6000 < CDD10 °C
1	Very hot	5000 < CDD10 °C ≤ 6000

Climate zone	Name	Interval
2	Hot	3500 < CDD10 °C ≤ 5000
3	Warm	CDD10 °C < 3500 and HDD18.3 °C ≤ 2000
4	Mixed	CDD10 °C < 3500 and 2000 < HDD18.3 °C ≤ 3000
5	Cool	CDD10 °C < 3500 and 2000 < HDD18.3 °C ≤ 4000
6	Cold	4000 < HDD18.3 °C ≤ 5000
7	Very Cold	5000 < HDD18.3 °C ≤ 7000
8	Subarctic/arctic	7000 < HDD18.3 °C

In total, 72 interviews were conducted in 7 countries and 5 climate zones, including more than 18 cities, as shown in Fig. 3. Fig. 4 shows almost half of the sample corresponds to data from climate zone 4 and 3/4 of the set represents heating and cooling dominated (HCD) climates. The set does not include heating dominated climates, which limits the analysis of climate-related trends.

Fig. 3 - Interviewees' locations across countries and climate classification from ASHRAE 169-2020. For proper visualization of figure colors please see the online version

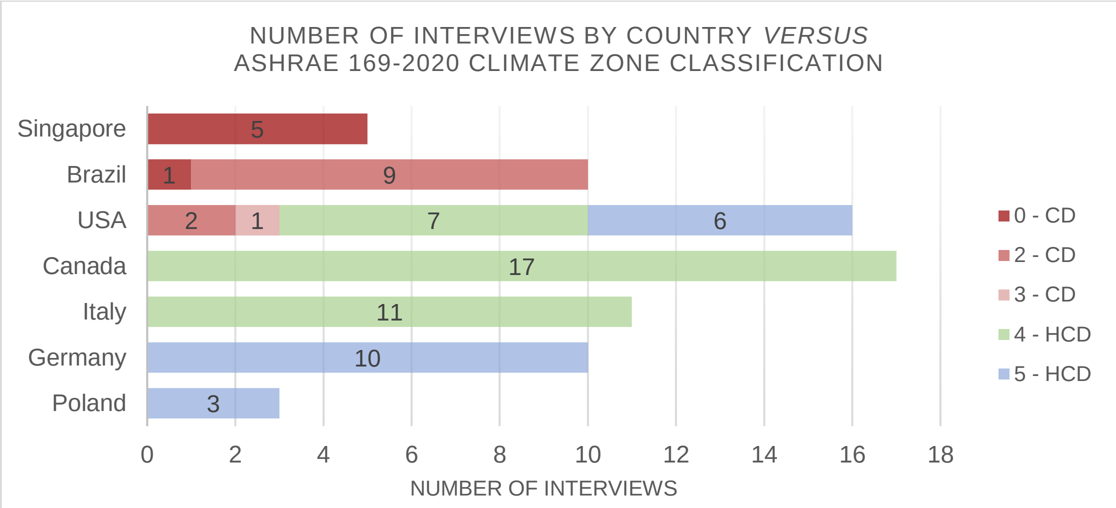

Fig. 4 - Number of interviews by country *versus* ASHRAE 16-2020 climate zone classification. For proper visualization of figure colors please see the online version

3.2. **Building typologies** and participation in operation

A great proportion of the interviewees indicated they operate more than one building. Therefore, to deepen the analysis, they were asked to choose one building to answer most of the questions so they could be more specific about daily issues. Thus, the typology of buildings was not predefined for the selection of interviewees, creating a varied sample. Fig. 5 shows the building typologies included by country. As can be observed, the variety of typologies is different by country, but in general there is a predominance of office and university campus buildings.

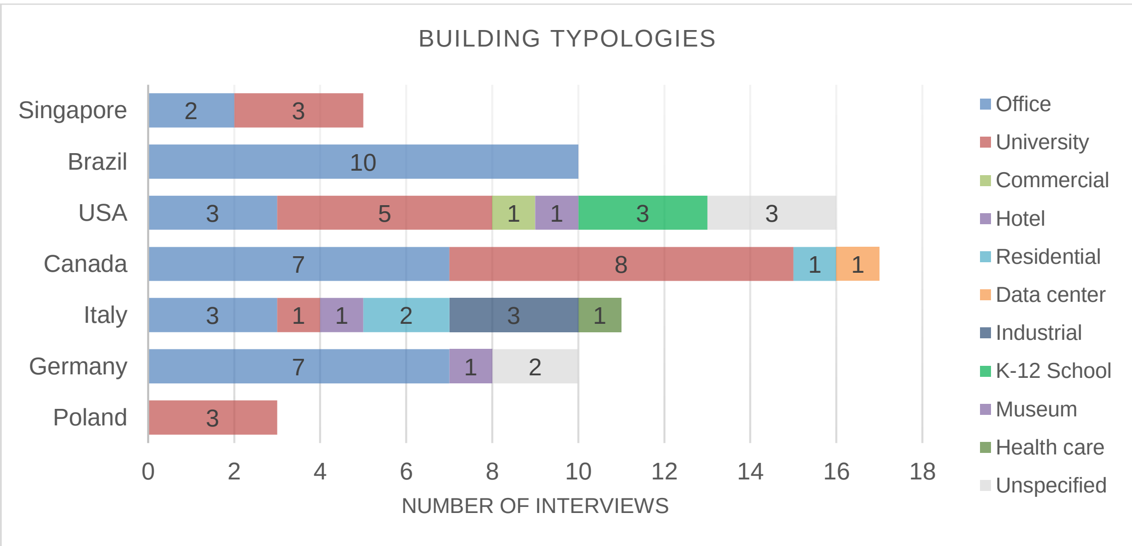

Fig. 5 - Building typologies addressed in the interviews by country. For proper visualization of figure colors please see the online version

The terms used in this paper to refer to the interviewees are managers and operators because only three interviewees (from Canada) referred to their job titles as *building operator*, while most of them used the word *manager* associated with *building*, *energy*, or *facility*. The majority (49 out of 72) indicated they occupy at least one of the operated buildings during part-time of the day or more, as shown in Fig. 6. In some countries the presence upon request is related to a remote operation, but only one interviewee (from Germany) indicated they are never in the building. Therefore, this superficial difference in the job title did not affect their involvement in daily building operations, which is also reinforced by their answers and knowledge about the procedures.

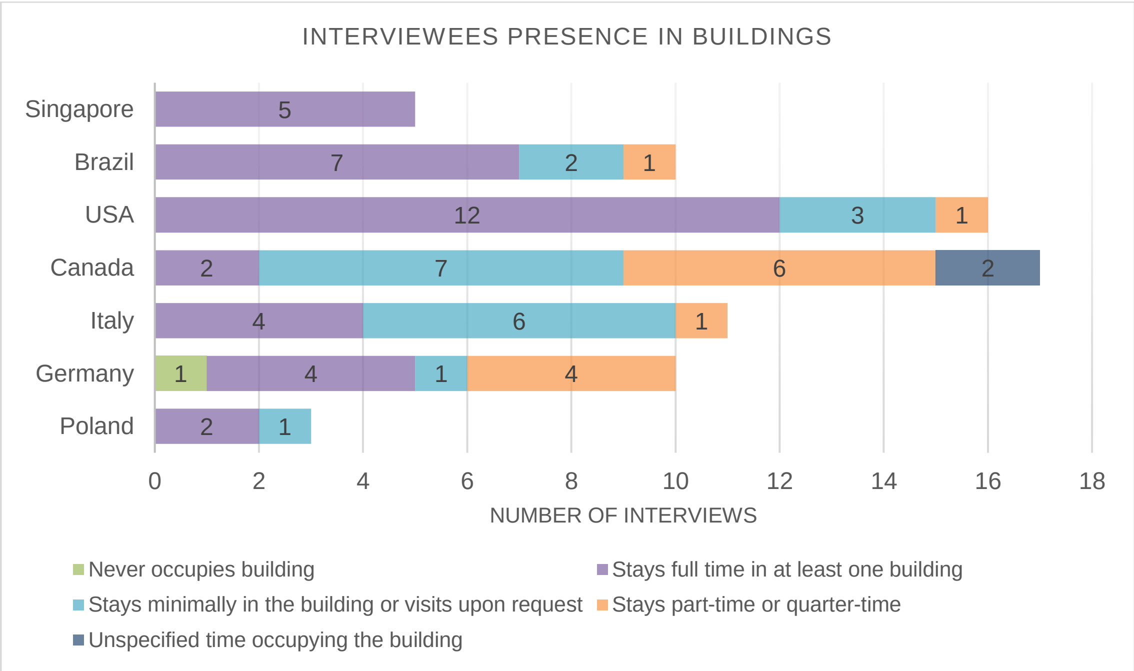

Fig. 6 – Interviewees' presence in the buildings by country. For proper visualization of figure colors please see the online version

3.3. Building system types

Heating, ventilation, and air-conditioning (HVAC) systems available in the buildings operated by the interviewees were classified according to the type of primary conditioning equipment. Not all interviewees comprehensively described the HVAC systems. Therefore, this analysis is based on the main terms identified in their descriptions. Primary equipment types are quite variable among the buildings. However, in CD, cooling equipment is mostly present, namely chillers (mentioned in 8 out of 30 CD total responses), Variable Refrigerant Flow (VRF) systems (mentioned in 4 of CD interviews), and split systems (mentioned in other 4). On the other hand, in heating and cooling dominated (HCD) places, the types of primary equipment were harder to be defined based on interview answers, since the reported types are more heterogeneous (e.g., boiler, heat pump, VAV, CAV, district heating and cooling, AHU, etc.).

In this set, more than half of the buildings were equipped with a Building Management System or a Building Automation System (BMS/BAS). BMS/BAS is an overarching computer-based control system that is used to monitor and automatically control the operation of building systems, i.e. their functionalities and the parameters they regulate [47]. Fig. 7 shows the presence of BMS/BAS by country.

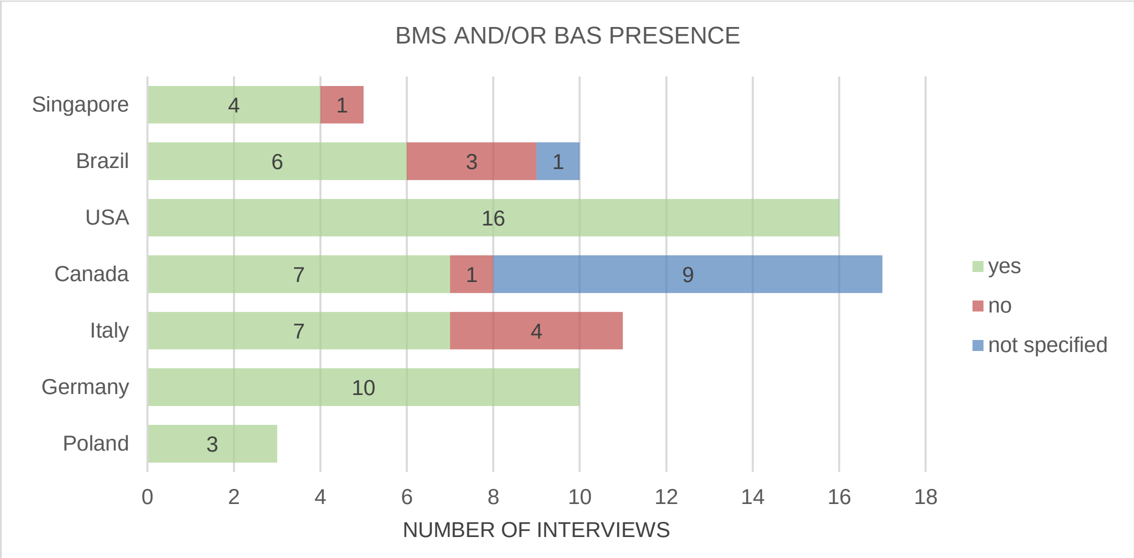

Fig. 7 - Presence of BMS and/or BAS in the buildings addressed in the interviews by country. For proper visualization of figure colors please see the online version

4. Results and Discussion

4.1. Hypothesis I. Climate characteristics and their influence on building operation

4.1.1. HVAC system type vs. climate

HVAC systems were analyzed in this set according to the type of terminal devices. Terminal devices were expected to be related to climate characteristics as the climate classification is defined based on cooling-degree days and heating-degree days. Findings show that terminal device types are more consistent among cooling dominated (CD) climates (Fig. 8), where two main types are identified: fan coils (mentioned by 4 interviewees) and split condensers (mentioned by other 4). Conversely, higher variability is observed in HCD locations, namely radiators (mentioned in 4 out of 17 HCD total responses), radiant floor or ceiling (in 5 interviews), and fan coils (mentioned in other 4). The results indicate the predominance of air terminals in CD climates, which could indicate cooling systems are more frequent. While in HCD, radiant heating systems are more frequent than other system types, but convectors and fan coils are also mentioned, indicating the presence of cooling and heating in some interviews. This confirms the climate-driven relation between HVAC system type and climate classification. Nevertheless, country-related trends were also identified. In Brazil, only splits and fan coils were mentioned. In general, split systems are only mentioned in a few interviews from Brazil and Italy, therefore, it could be deemed that most of the sample includes central cooling systems, when it is present. Also, in places with more varied climate conditions throughout the year (HCD climates), HVAC solutions seem to be more diverse. However, this may stem from other local factors such as availability, costs, and knowledge of the technologies.

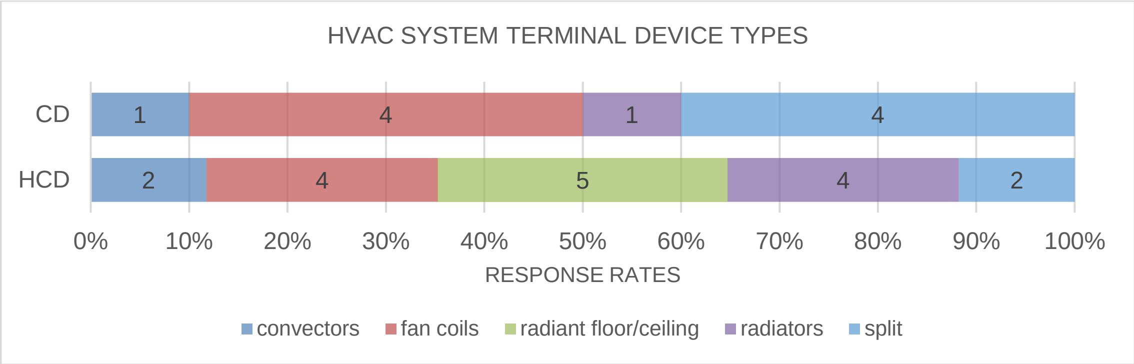

Fig. 8 - HVAC system terminal device types by climate group. For proper visualization of figure colors please see the online version

4.1.2. Setpoint temperatures vs. climate

Following the same line of reasoning, setpoint temperatures were expected to vary with climate, resulting in higher cooling temperatures in warmer climates and lower heating temperatures in colder climates, to take advantage of occupant adaptation. Furthermore, it would be expected that countries in the same climate zone would present similar setpoints, with cooling setpoints indicated for CD climate locations and both cooling and heating for HCD.

Fig. 9 and Fig. 10 show the setpoint temperatures indicated by operators by climate and country, respectively. In many interviews (29 out of 72) the setpoint temperatures are not mentioned by the interviewees, although all buildings have at least one of these conditioning systems. As expected, in the warmest climate (zone 0) only cooling temperatures are indicated as shown in Fig. 9. However, this correlation to climate zones is not reflected in all countries. Poland and Germany, despite referring to climate 5, indicate only heating temperatures, while in the USA, the same climate zone includes cooling and heating. Also in the USA, climate 2 includes cooling and heating temperatures, while interviewees in the same climate from Brazil only refer to cooling setpoints. Although cooling temperatures were not mentioned, the buildings in Poland have cooling systems. So, the answers may indicate that operators are more concerned with the heating system. The relationship between climate and the available system (cooling or heating) is observed in few locations, indicating climate is not the only driver.

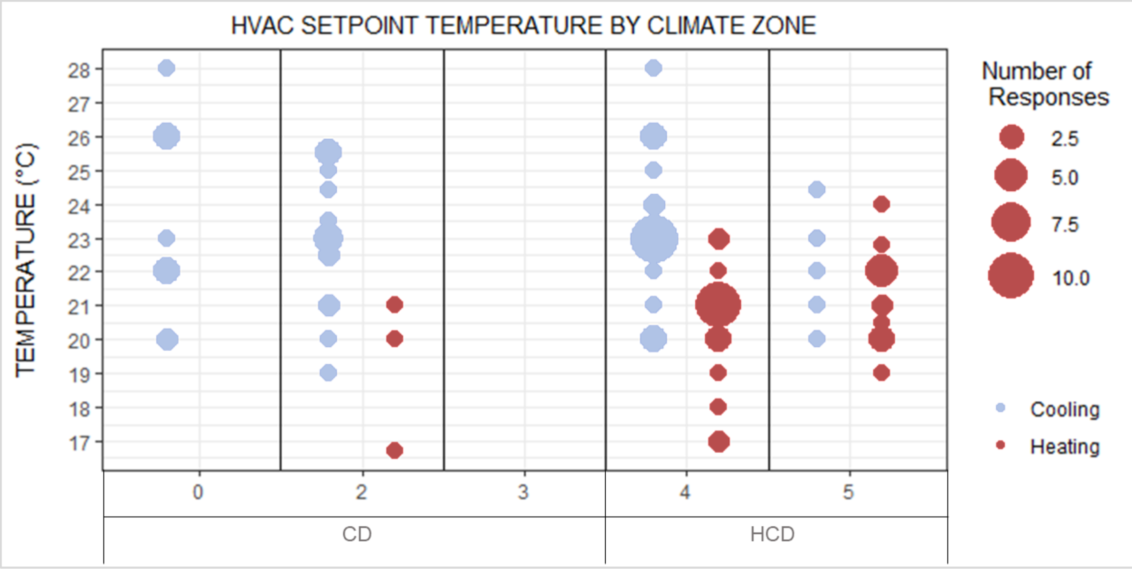

Fig. 9 - Setpoint temperature ranges mentioned by operators by climate zone. For proper visualization of figure colors please see the online version

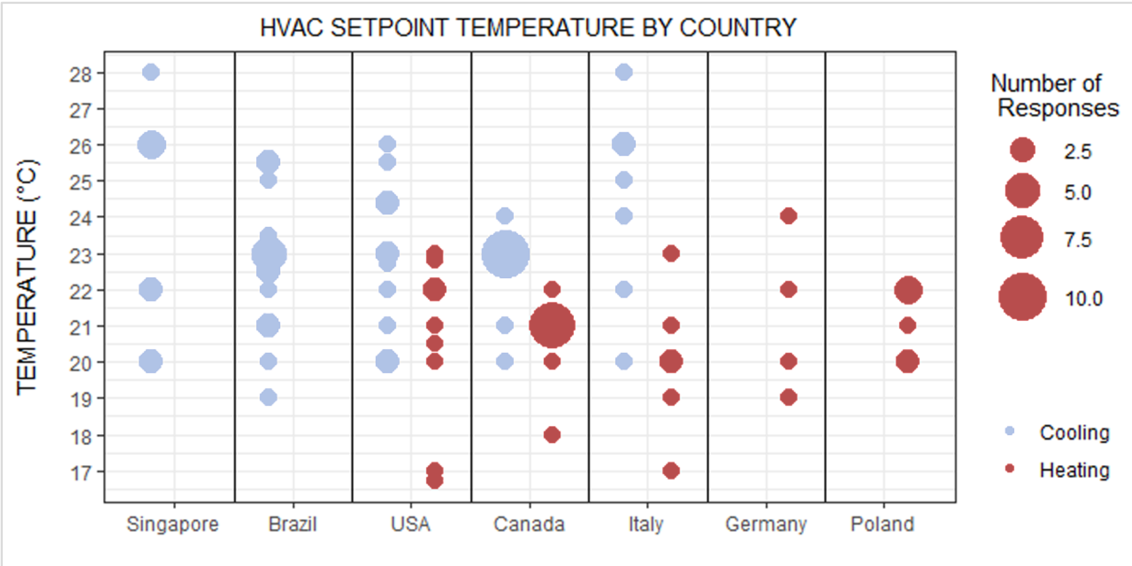

Fig. 10 - Setpoint temperature ranges mentioned by operators by country. For proper visualization of figure colors please see the online version

Similarly, the setpoint range amplitude seems not to depend only on the climate zone, showing a country-driven variation (Fig. 10). Despite the different climates, the cooling setpoint temperatures in Singapore and Italy are very similar, reaching the highest cooling values of the set. On the other hand, Brazil, which includes climates 0 and 2, indicates the lowest cooling temperature (19 °C). The predominant cooling setpoint in Brazil and Canada is 23 °C, despite the climate differences. Regarding heating temperatures, in Germany the highest temperature (24 °C) is mentioned in one interview, while the lowest is mentioned in the USA (16.5 °C). In Poland, the heating setpoint range is narrower, between 20-22 °C, which might be related to the smaller sample size. On the other hand, Canada, which has the greatest sample size, shows very uniform results, with the predominance of 23 °C for cooling and 21 °C for heating (see Fig. 10).

Although a clear relationship between the climates and the setpoint range has not been verified, it is worth noting in Fig. 9 that the cooling and heating ranges in climate 5 are closer to each other, with a difference of 1-2 °C. And, despite the expected similarity between zones 4 and 5, zone 4 shows a broader variation between cooling and heating temperatures, reaching a difference of 11 °C. The US is the only country where cooling setpoints were indicated in climate 5, and the only country with results from more than 2 climate zones. The tendency mentioned is confirmed when the information from the US only is analyzed, as shown in Fig. 11: setpoint ranges become more restricted in colder climates. This result could indicate lower adaptation capability in colder climates, where heating and cooling are used to maintain a similar temperature. Overlap between minimum cooling and maximum heating setpoints are observed in three answers from the US, just one from Canada, and one from Italy. This indicates less concerns about possible activation of cooling and heating simultaneously in the US, as the ranges allow it. It also indicates the temperature has some influence within the same country, but when comparing multiple countries, other factors seem more influential, causing the setpoint between locations with the same climate in different countries to diverge. Further analysis of possible influential factors is presented in section 4.2.1.1.

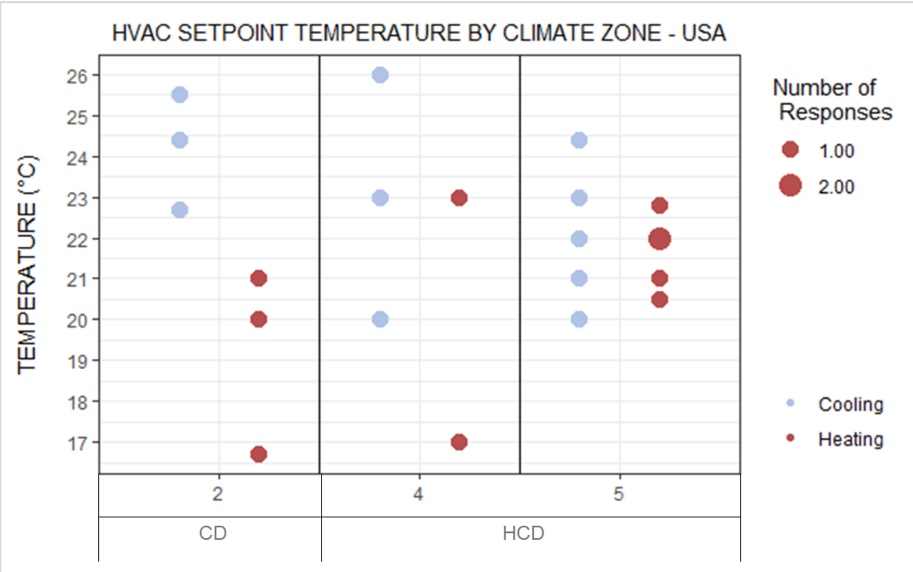

Fig. 11 - Setpoint temperature ranges mentioned by operators by climate in the USA. For proper visualization of figure colors please see the online version

4.1.3. Complaint types vs. climate

Regarding the most frequent type of occupants' complaints, it is assumed that climate would be the main driving factor since they mainly refer to heating, cooling, and air quality. Thus, complaints regarding warm sensation were expected to be more frequent in CD climates, while cold sensation to be more frequent in HCD climates. The analysis of the occurrences of “too hot” and “too cold” complaints was associated with the season in which they occur to verify if they could be caused by system fault. Therefore, the occurrence of “too hot” complaints during summer, when cooling activation was expected, was deemed as insufficient cooling, and “too cold” in that season as overcooling. The same was applied to heating activation during winter, “too cold” complaints were considered an indication of insufficient heating and “too hot" complaints of overheating. Fig. 12 shows the results per climate zone and climate zone group.

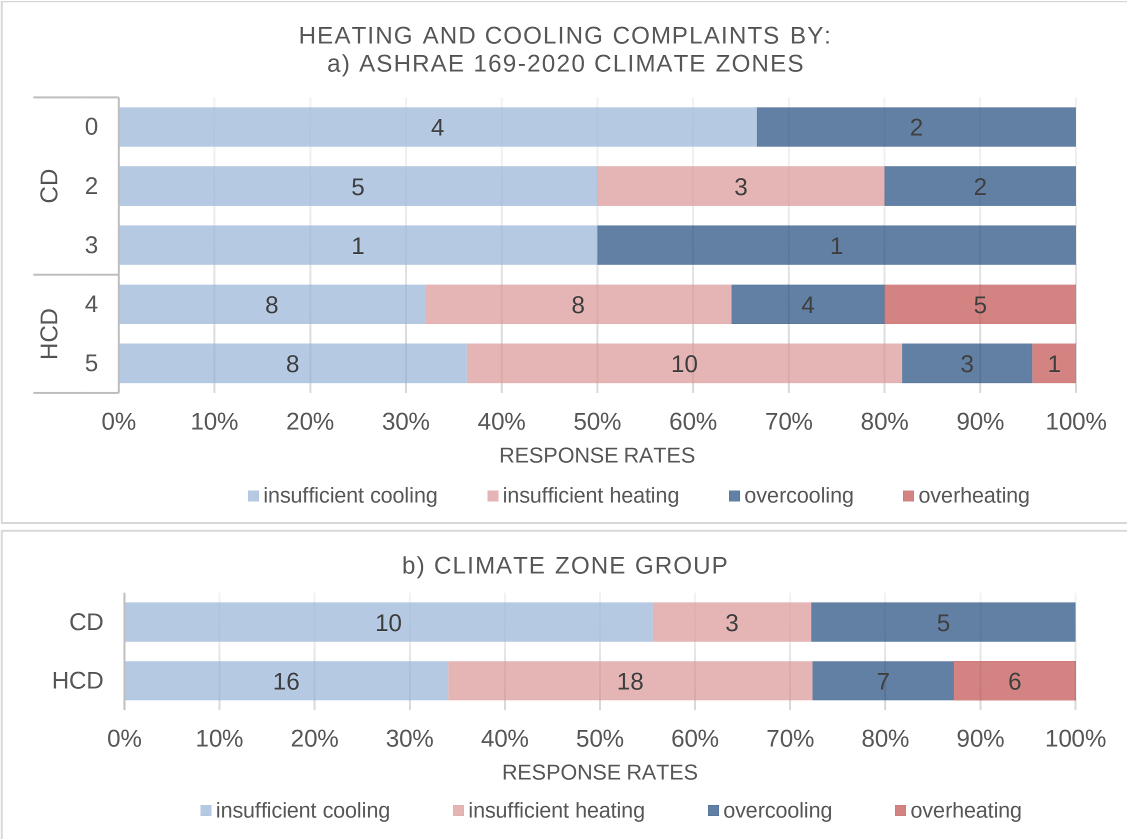

Fig. 12 - Complaints regarding heating and cooling depicted by a) ASHRAE 169-2020 climate zones and b) climate zone group. For proper visualization of figure colors please see the online version

Fig. 12a shows a trend of increasing issues with insufficient cooling towards climate 0 and insufficient heating following the opposite trend, increasing towards zone 5. An exception to these trends is observed in the German sample (Zone 5): half of the complaints were about feeling "too hot" during the summer season (insufficient cooling). This could result from the buildings not having cooling systems. In general, HCD locations show a more balanced proportion of cooling and heating issues (Fig. 12b). The few insufficient heating issues observed in CD climates came from the Brazilian sample in zone 2, where heating systems are not available. Because of this variation in system availability, overcooling could occur in all climate zones, while overheating only in HCD climates.

Insufficient cooling/heating are predominant in this study (47 out of 65). Although it might be related to undersized HVAC, it could be also driven by high expectations of the occupants regarding the indoor environment, as pointed out by some operators. Moreover, operators suggest the complaints to be related to yearly or daily dynamics of heating/cooling loads, or to inaccuracies of system control algorithms, causing problems such as long HVAC response time. Those events corroborate the predominance of insufficient cooling/heating, which lead to complaints, as depicted in the present analysis. The results show climate plays an important role in shaping most frequent types of occupants' complaints, but it also depends on system availability, which does not depend only on climate characteristics as shown in Section 4.1.1.

4.1.4. Limitations imposed to occupants and level of control vs. climate

It was hypothesized that the control limitations imposed on occupants, and the respective reasons to do so, would be driven by climate, since their complaints were mostly related to heating and cooling as indicated in the previous section. Thus, limitation types and reasons were analyzed by climate groups (CD and HCD) as shown in Fig. 13.

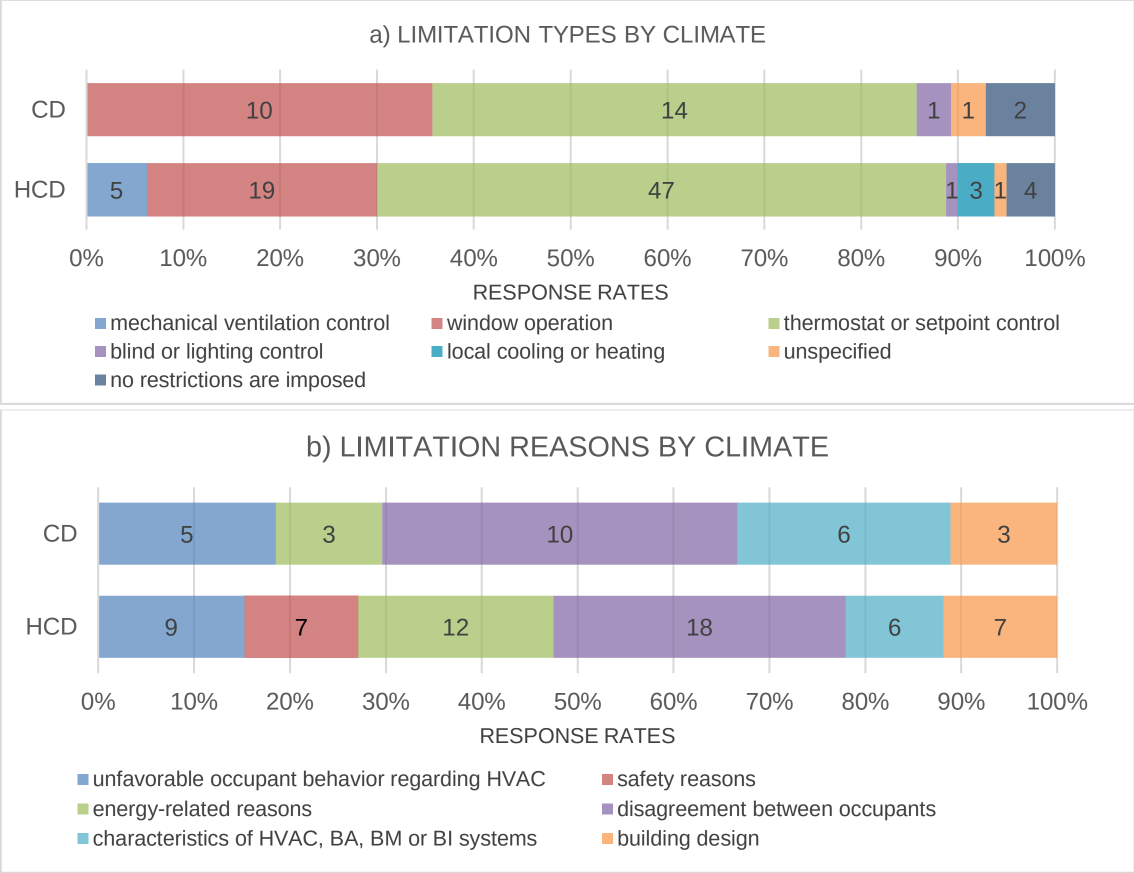

Fig. 13 - Analysis of answers distribution of limitation a) types and b) reasons imposed on occupants' control by climate group. For proper visualization of figure colors please see the online version

Fig. 13a shows no clear trend concerning limitation types, as thermostat or setpoint adjustment and window control predominate in both climate groups. Most operators indicated occupants have partial control of the setpoint temperature, as they can control it within a predetermined range. And something similar is indicated regarding system schedule. Most interviewees from both CD and HCD climates indicated HVAC operation schedules to be adjustable in some level to occupants' needs when requested or according to season, day, and/or time of the day only. However, 6 interviewees from HCD (out of 54) indicated not to be able to do any possible schedule adaptation, while the same did not occur in CD location. Conversely, as regards overall start-up and turn-off times, they were indicated to be fixed in most cases, suggesting a low flexibility for this specific aspect. This type of restriction is more likely to be influenced by other country-driven aspects, like economics or cultural norms. Exceptions exist in the USA and Brazil, where the number of variable and fixed operation times are rather balanced indicating no clear trend.

In 10 of all interviews, operators mention occupants do not have direct control of the setpoint temperature. Four of those are from the USA, and the restriction is related to automatic temperature adjustment according to external conditions. Another 3 are from Brazil, but in this case the operators mentioned that fixed values are used because they consider the users would not or do not control it in an "appropriate" way, disregarding standard procedures and collective comfort. Indeed, human-related factors are indicated as the main reason for limitation in both climate groups (see Fig. 13b), and all countries, except for Singapore and Poland. Fig. 13b shows disagreement among occupants corresponds to around 1/3 and unfavorable occupant behavior around 1/6 of the responses. The use of personal conditioning systems like local heater and fans could help to reduce the human-related issues indicated as it increases individual adjustability with low energy consumption [48]. However, as shown in Fig. 14, the use of these systems is also limited in the USA and Poland. Operators explained heaters were not allowed because their operation could lead to energy waste as they are not integrated to the central system control. This lack of integration could lead to the activation of central cooling during winter. For this reason and for safety, the use of local heaters is usually forbidden. Fans, on the other hand, were allowed in most of the cases; probably because the increment of air motion would not affect the cooling control. Fig. 13b also indicates that energy-related reasons seem more relevant in the HCD zone, especially for the European countries. This trend could be related to local regulations, energy costs, as well as cultural influence, which are correlated to operators' goals addressed in the following section.

The limitations regarding window operation were expected to be more frequent in CD climates as natural ventilation would be adopted as a cooling strategy in warm climates. But this limitation is the second most recurrent in both climate groups, showing low correlation to climate differences. Still, the share of responses indicating limitation of window control is proportionally greater in CD climates. However, the absolute number of responses is higher in HDC countries, especially in Canada, as shown in Fig. 14. Lighting controls limitations were mentioned only in 2 of all interviews, one from Germany and another from Brazil, despite the difference in climatic characteristics, which thus cannot be considered as drivers. In general, the observed trends could be related to local regulations and energy costs, as well as to cultural norms, being more related to country-aspect than to climate.

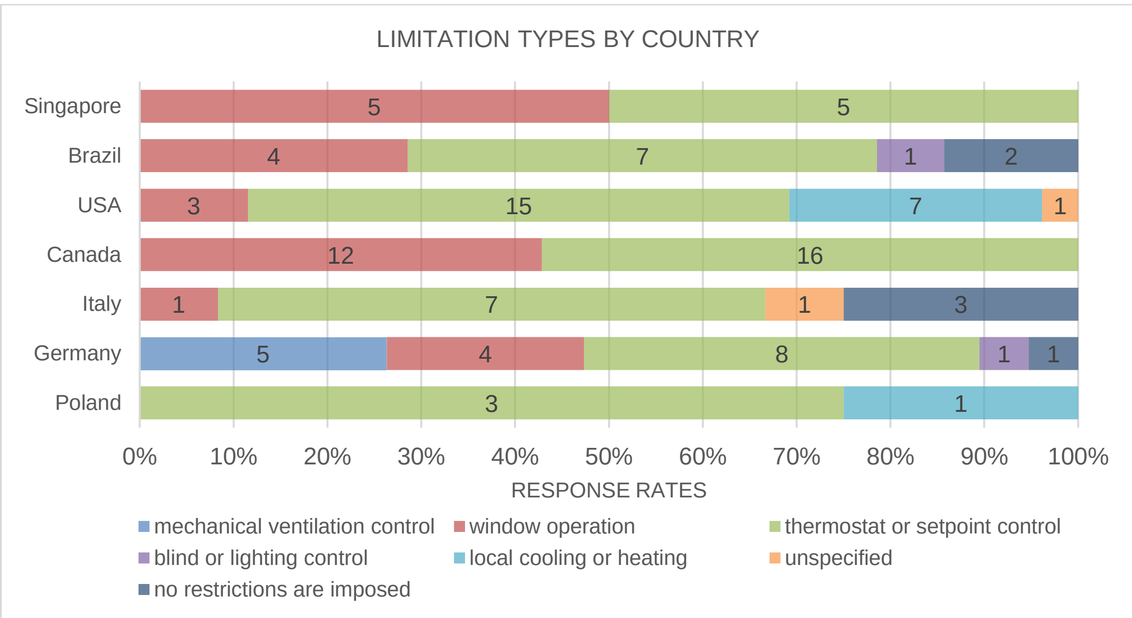

Fig. 14 - Analysis of answer distribution of limitation types imposed on occupant control by country. For proper visualization of figure colors please see the online version

4.2. Hypothesis II. Other country-related differences and their influence on building operation

4.2.1. Operation goals vs. country

The operation goals would guide and drive operators' decision making. Operators were asked to indicate their two most important goals. Most of the goals were expected to be related to country differences, like economic factors and local regulations, more than climatic differences, which would affect occupants’ comfort and complaints.

Despite what was expected, Fig. 15 shows occupant comfort and complaints together are the most mentioned goals (49 total votes). However, the total responses indicating the main goal to be energy cost or savings received a similar amount of votes (44 votes). Fig. 15 shows that comfort and energy concerns are more balanced among answers from Poland, Germany, Italy, Canada, and the USA. In Brazil the operators are much more concerned about occupants’ comfort than energy related issues; the latter was not even listed as a reason for imposing limitations to occupants (see Section 4.1.4). Meeting standard requirements and ensuring the system lifespan and the reduction of maintenance demand are considered more important. In contrast to Brazil, operators in Singapore are mostly concerned about energy costs and savings. Occupants’ comfort, meeting standards and reducing greenhouse gas (GHG) emissions received the same number of votes (2 votes each). It is interesting to verify that GHG emissions received more votes proportionally to the country total in Singapore and Canada, which were the only countries to have carbon taxes implemented by 2020 [49], when the interviews were performed. More recently, at the beginning of 2021, Germany also implemented a carbon pricing for buildings [50]. However, when this study was performed, one of the main concerns of Germany operators, in addition to comfort and energy, was meeting local standards and regulations, as shown in Fig. 15.

By these results it is possible to conclude that operation goals are not mainly correlated to climate differences as no trend can be drawn from CD and HCD climates. Other aspects, like economic factors and policies, seem to play a very important role as they relate to energy cost and GHG emission. Ensuring occupants’ comfort could also be analyzed as an economical influenced factor, since pleasing the clients is a job requirement, as some of the operators mention. Responding to complaints and being demanded by occupants is also time consuming, which implies a cost for building operators in terms of time expenditure. In addition, it could also have sociocultural influences, as favoring building energy efficiency could be seen as acceptable in some places and not in others. In addition, favoring standard requirements over other aspects, like observed in Germany, could be seen as a way to achieve thermal comfort, less complaints by the occupants as well as energy efficiency by operators. Some operators, from different countries, refer to regulatory standards and Standard Operation Procedures (SOP) to justify some procedures, and said that following them also give them arguments to contest occupant requests when considered inappropriate.

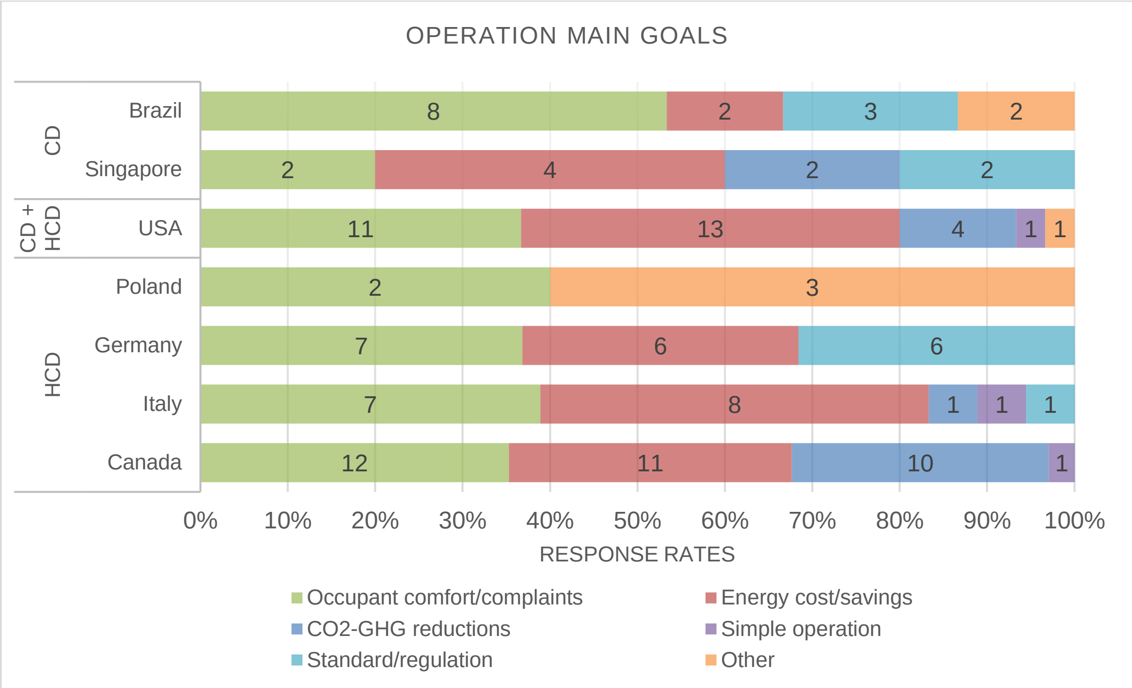

Fig. 15 - Operational main goals. For proper visualization of figure colors please see the online version

4.2.1.1. Setpoints vs. goals

Considering the setpoint temperature to have a high impact on occupants' comfort and building energy efficiency [51], operators' goals regarding these aspects were expected to be correlated to the setpoint temperature range. Also, concerns about meeting standard requirements and energy efficiency should indicate the chosen temperatures to be aligned with local regulations. For this reason, the values were compared to national operation standards and regulations. However, few documents were found specifically for operation, as shown in Table 2. This means operators usually rely on guidelines and requirements from other domains, such as design and energy calculation.

Operators from Italy and Singapore indicated the highest cooling setpoints among the set and it seems to be consistent with the number of votes indicating energy efficiency as their main goal. In Fig. 15, Singapore shows twice as many votes for energy as for comfort, so it is possible that operators are not as concerned about the impact on occupants when adopting high setpoints. On the other hand, in Italy, similar temperatures are associated with balanced votes regarding energy and comfort, which leads to the interpretation that operators consider these high cooling setpoints not to jeopardize occupants' comfort. As shown in Table 2, operators from both countries indicated to use the maximum standard temperature for cooling and in some cases to exceed that limit.

In contrast, the lowest cooling setpoints indicated by Brazilian operators seem to be associated with their low concern about energy efficiency. The results suggest lower to mean standard values to be considered appropriate to maintain occupants' comfort (see Table 2). Nevertheless, occupants from Brazil and Singapore mainly complained about feeling hot during summer (Fig. 12a, climate 2), so the lower setpoints used in Brazil might not be solving this issue. This may stem from the inability to compensate for radiant heat gain, or the thermal expectation of occupants who prefer to feel colder indoors [52]. Table 2 also shows that operators from the USA, even though indicated to be concerned about energy efficiency and occupants' comfort, also use cooling temperatures lower than the standard. As many Brazilian and American operators indicate their main reason for restricting occupants' control was the disagreements among them, the selected setpoints might be the ones identified to please most occupants.

Operators from Germany mentioned 'meeting standard requirements' (SOPs) as their main goals more than other countries. The only 2 interviews that indicated direct values also suggested heating temperatures higher than the standard. However, in most interviews, instead of indicating a temperature, interviewees indicated to follow the standards.

Table 2 - Standard and applied setpoint temperatures

Country	Operators' interview: 1) Predominant value (°C) 2) Total indicated range (°C)		Standard/regulation setpoint operation ranges (°C)		
	Cooling	Heating	Cooling	Heating	Reference document type and domain
Singapore	1) 26 2) 20-28	-	24-26	-	Health and comfort standard [53]
Brazil	1) 23 2) 19-25.5	-	21-25.5	-	Design standard, Health regulation [54,55]
USA	1) 20 2) 20-26	1) 22 2) 17-23	24-26	20-22	Energy Codes regulations [56–59]*
Canada	1) 23 2) 20-24	1) 21 2) 18-22	24	22	Energy Code regulation [60]
Italy	1) 26 2) 20-28	1) 20 2) 17-23	23-26	19-21	Energy performance calculation standard, Design and

					operation regulations [61–64]
Germany	-	1) none 2) 19-24	25.5-28	18-21	Energy performance calculation standard, design and energy performance assessment standard [64,65]
Poland	-	1) 22 2) 20-22	23-26	16-20	Building regulation, design standard [66,67]

* These are common values found in open-access regulations from some states of the USA

4.2.2. Operator's perception of occupants' comfort and building efficiency vs. country

Although climate influences the type of occupant complaint, the operators' perception of the level of occupants' comfort was expected to be not only related to climate, but also influenced by other local factors, such as sociocultural differences. The same was expected regarding operators' perception of building energy efficiency. In addition, their perception of occupants' comfort and building efficiency was expected to be correlated.

Fig. 16 and 17 present the answers to both topics and show only operators from HCD climates evaluate the buildings as having low energy efficiency and uncomfortable occupants. However, from the HCD climate group, Italian and Polish operators are more optimistic about occupants' comfort – none of the interviewees indicate the occupants to be uncomfortable. Generally, in both climate groups, operators seem to be more critical about energy efficiency than occupants' comfort. Only in the set from Singapore the opposite occurs, and energy efficiency is better rated than occupants' comfort. CD climate countries (Singapore and Brazil), seem to be more optimistic about both energy efficiency and comfort. Therefore, having to deal with one operation mode (cooling) seems to facilitate reaching optimal control. For instance, many operators from Canada highlighted the hot and cold complaints received during transitional seasons, which would require a faster action in response to variations of outdoor conditions.

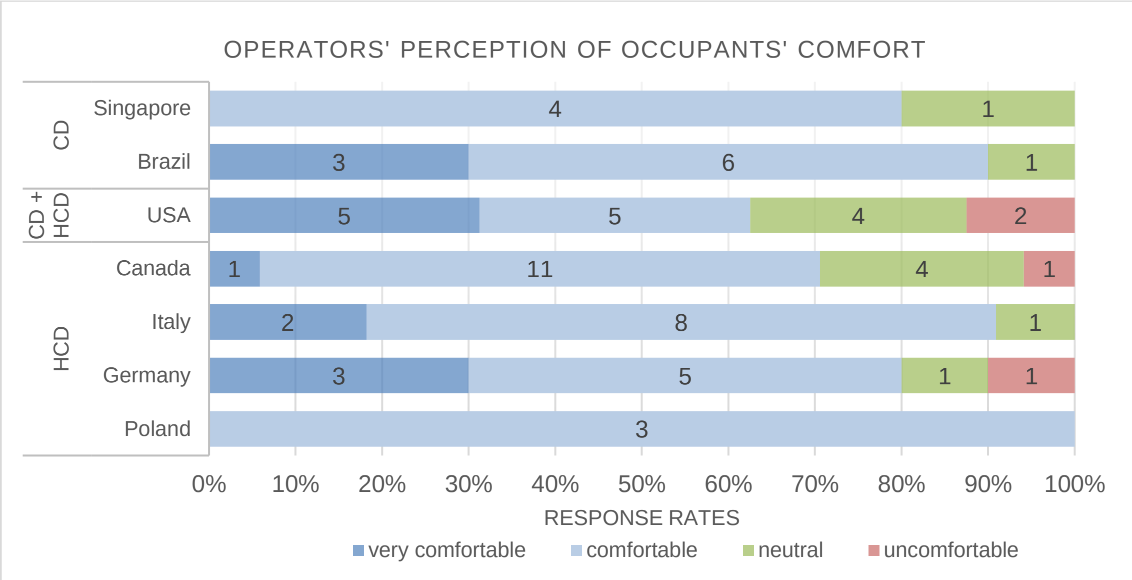

Fig. 16 - Operators' perception of occupants' comfort by country and climate group. For proper visualization of figure colors please see the online version

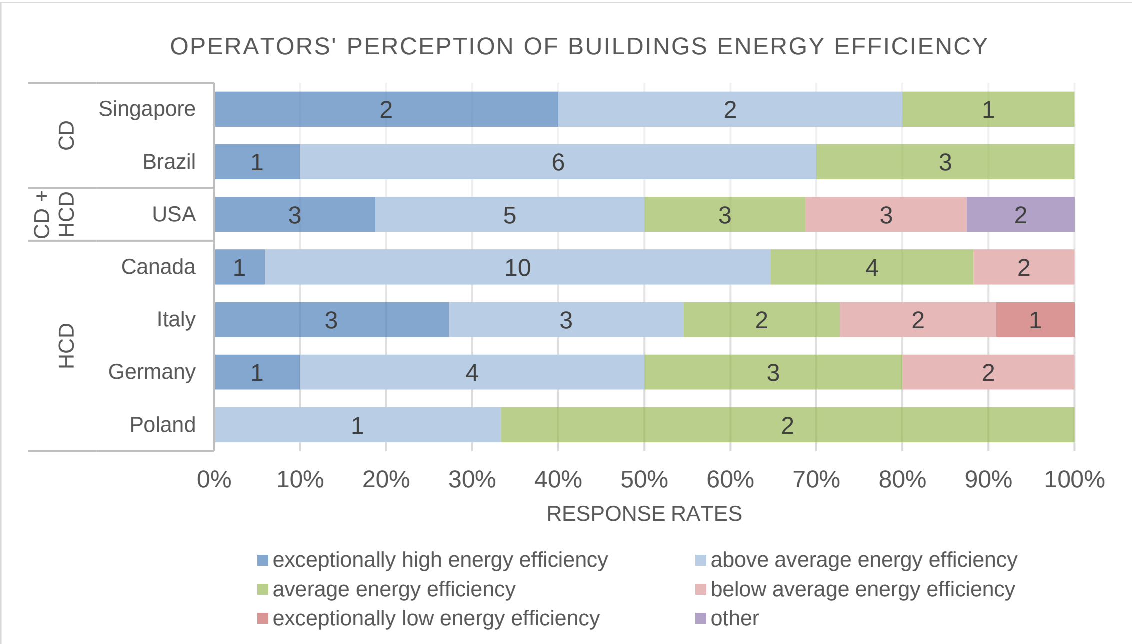

Fig. 17 - Operators' perception of building energy efficiency by country and climate group. For proper visualization of figure colors please see the online version

By crossing each answer on operators' perceptions about energy efficiency to their perception of occupants' comfort, a correlation is verified. In general, average to exceptionally high energy efficiency buildings are more often considered from very comfortable to neutral comfort. Also, those perceived as "below average energy efficiency" are more correlated to uncomfortable spaces. This relationship was found to be clearer among answers from the USA. However, an opposite situation was observed in interviews from Germany and Canada: buildings perceived as uncomfortable were associated with "exceptionally high" and "above average" energy efficiency levels. This could be related to operators prevailing energy over comfort. However, Fig. 15 indicates operators from these two countries to be as concerned about energy as to comfort. Therefore, it could be inferred they are aware that actions taken to save energy might jeopardize occupants' comfort. Many respondents mentioned that a balance between energy efficiency and occupant comfort would be ideal, but reaching this optimal point is very challenging. In general, this analysis shows that operators seem to be aware of the correlation between efficiency and occupants' comfort.

4.2.3. Operators' training and job requirement vs. country

Educational qualifications, training and job requirements of building operators were expected to vary by country due to governmental regulations, local building codes, technologies available/used, cultural norms, etc. However, the research group was able to find little information on local standards regarding operator training requirements. Likewise, the analysis of job titles and type of training the interviewees consider most relevant for their daily work revealed no clear trend or strong difference among countries. In the USA and Singapore operators had more specific training related to green certification and sustainability. A significant number of interviewees from Germany, Italy, Canada and all the Polish operators were engineers. On the other hand, Brazilian and American interviewees held a wide variety of degrees. Despite these variations, practical experience was indicated to be one of the most important types of knowledge for the job, and most interviewees had at least 5 years of experience.

The operators' job titles varied greatly from one to another. However, those that held an energy manager or analyst title were more concerned about energy-related aspects. All the Italians, most of the Canadians (9/17) and some Singaporeans (2/5) interviewees held this title and indicated energy cost/savings and emissions to be their main goals. On the other hand, a small number of German operators held this title (2/10), which explains their tendency to rely more on standards to address those matters, as they are less specialized in the subject. None of the Brazilian operators held this title, which is coherent with their lack of concern for energy. However, American, and Polish operators are an exception to this trend as a few held this title, but most of them indicated energy cost and savings as their main goals.

4.2.4. Control system characteristics and data usage vs. country

The characteristics and usage of BMS/BAS were expected to be correlated to country-related aspects like technological development level. Therefore, this hypothesis includes two domains: system configuration as well as data collection (sensors) and usage.

The analysis shows that control system configuration appears to be climate influenced as, in HCD, the most frequent configuration is the centralized control of the HVAC system, including the setpoint and other thermal control variables, while in CD it involves HVAC and lighting control. This result shows how lighting system operation appears relevant especially in contexts characterized by high solar radiation and natural lighting availability all year round, which provides a non-negligible effect also in terms of thermal loads.

On the other hand, there are country differences in data collection and usage, e.g., occupant counting sensors in any technical system (e.g., HVAC, lighting etc.) and its integration in the control systems. In Canada and the USA, a large proportion of the buildings considered have CO_2 (15 out of 33) and occupancy (22 out of 33) sensors installed for direct measures, whereas in Brazil it seems to be less common. In addition, alternative occupancy and counting technologies are applied, especially in Italy and Germany. Turnstiles (at the entrance of buildings or for each unit), badge card access (some even per zone) and energy monitoring of plug loads, and lighting were mentioned. The occupancy sensors are either “hard-wired” in the electrical installation to control, for instance, the lighting without any connection to the BAS, or integrated in the overall control system to support further technical systems control such as ventilation rates or heating and cooling operation. The results of the interviews show that the first case is still much more common. This is especially the case in the USA, Canada, Singapore, Germany, and Italy. The use of occupancy sensors for HVAC systems control was only mentioned in the USA, Canada, and Singapore, which have mainly air driven HVAC systems (as shown in Section 4.1.1). Generally, the presence of sensors is rather influenced by technological differences between the various countries in which the interviews were conducted. The reason for this might be the difference in regulations and standards as well as the predominantly used type of systems (e.g., air systems vs. radiator heating or other water systems) also identified previously in Section 4.1.1.

The use of monitored data – in real time and recorded in databases – is also associated with country-related aspects. It turned out that in Brazil some respondents mentioned that external companies are contracted to analyze and evaluate the collected data, indicating possibilities of optimization or fault prevention/correction. On the other hand, in the USA there were reports of additional 3rd party software being used for data analysis regarding energy and comfort. Wider use of monitored data in Canada, Germany, and the USA related to fault identification, alarm setting (threshold-based), and malfunction were named. Data is used to create trends based on complaints, and to run pilot tests of automated fault detection and diagnosis, as mentioned in a few interviews. Another group of responses from the USA, Germany, and Italy stated that the data is used to adjust schedules, setbacks and setpoint temperatures of the HVAC system. In relation to the technical systems, they support the routine inspection and maintenance requests.

4.2.5. Communication channels and frequency vs. country

The frequency of communication between occupants and operators is a relevant factor in assessing occupants' perception of comfort. However, it could also be related to the mode of communication. The mode of communication and its frequency were expected to be driven by country-related aspects like cultural norms, available technology, and contract issues.

In this set, the most used communication channel was online portals, especially in the USA, Brazil, and Germany, as indicated in Fig. 18. These were also the countries with the highest frequency of communication indicated to be “daily” and “as-needed”, as shown in Fig. 19. These results may indicate that such systems are considered an effective way of frequent communication between operators and occupants. On the other hand, this communication channel seems to be less common in Canada, as none of the interviewees mentioned this option. In Canada, Italy and Poland direct types of communication appear to be more common. Among direct communication modes, “phone calls” and “in-person” were indicated in all countries, and “e-mails” was the least stated option. This result may be less related to sociocultural and technological differences among the countries and more likely to be related with the speed of response, which influences the effectiveness of the communication. Online portals may be more practical and faster to assure discomfort issues are identified the right way. Surveys, on the other hand, can be interpreted as a tool to obtain broader occupant feedback about operational aspects, and could be applied with a lower frequency. In this regard, they would be less characterized as a way to communicate a specific problem – such as a momentary discomfort that would demand immediate action from the operators – and more as a tool for continuous improvement of the overall operation procedures and system performance. Surveys were mentioned to be applied in all countries, except Italy and Germany.

It is worth noting that, even where online portals are most frequent, many operators indicate they communicate with occupants daily, as in Brazil and Germany, rather than as needed, like in the USA – which would be the expected frequency. In any case, both indicate frequent communication, either by occupants' or operators' initiative. Most of the countries with higher communication frequency ("daily" and "as needed") are also those where operators could identify occupants to be uncomfortable as stated in Section 4.2.2. On the other hand, in Italy, Singapore and Poland, the frequency of communication is lower than monthly in some cases, which is identified as "other" in Fig. 19; and none of the operators indicate occupants to be uncomfortable in those countries (see Section 4.2.2). "Other" category includes a number of possible answers, either matching with "only limited to certain phases", or other unlisted answer options, corresponding mostly to poor communication (e.g., occasionally, not very often, seasonally, annually, etc.). These results show a correlation between frequency of communication and identification of uncomfortable conditions, which indicates that more effective communication could improve the understanding of occupants' comfort and the identification of discomfort.

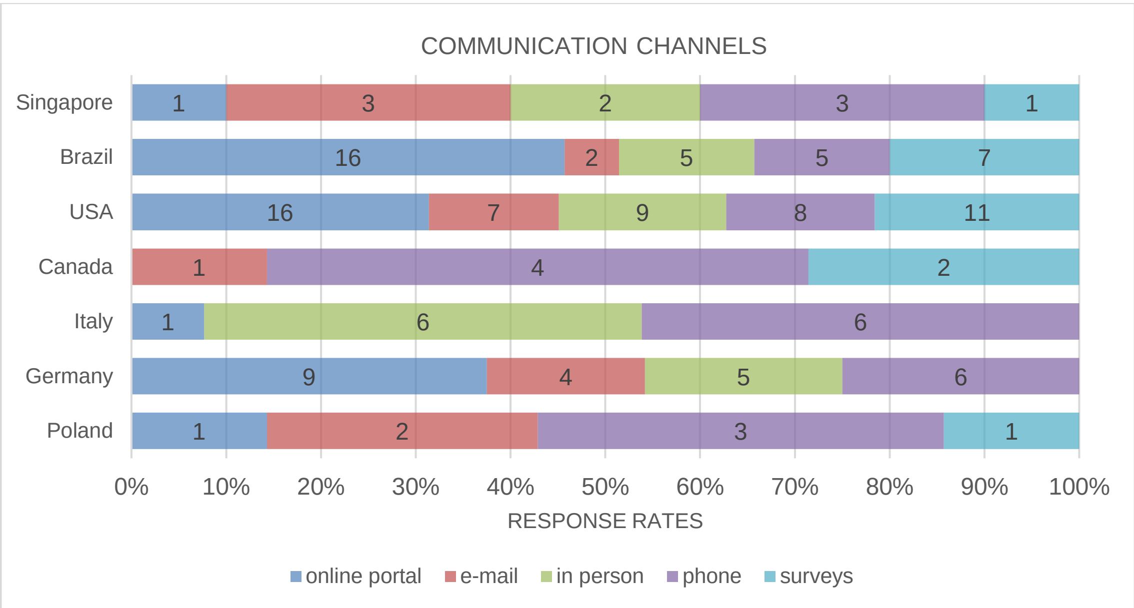

Fig. 18 - Communication channels by country. For proper visualization of figure colors please see the online version

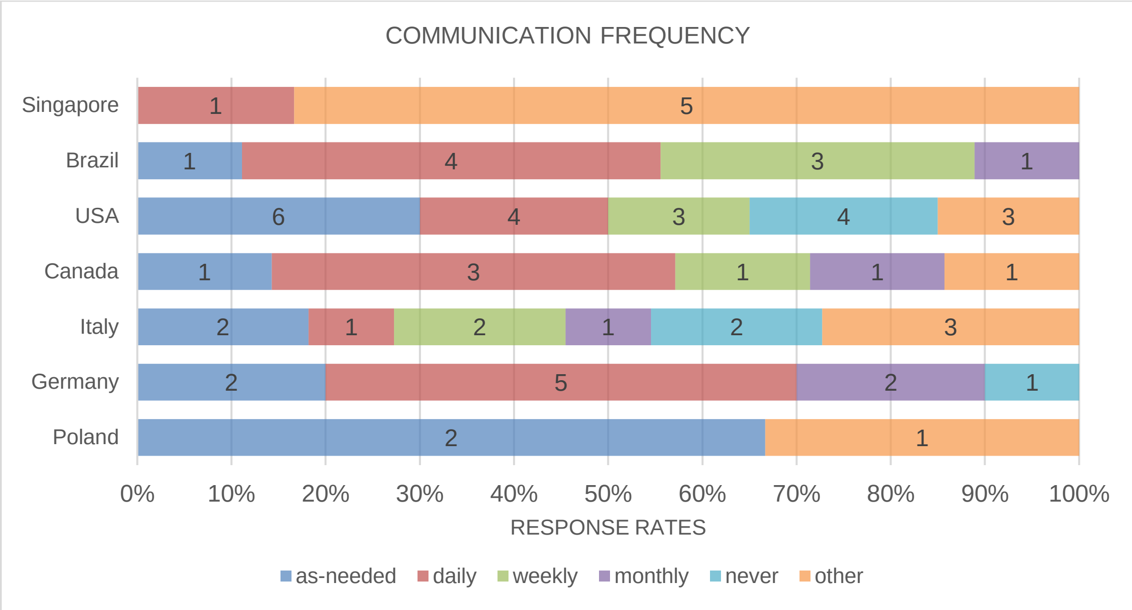

Fig. 19 - Frequency of communication by country. For proper visualization of figure colors please see the online version

4.2.6. Non-technical issues vs. country

Another question from the interview addressed the main non-technical challenges operators face in improving the energy efficiency of the building. These issues were expected to be related to country-driven issues, like sociocultural and economic aspects. Five main non-technical challenges emerged from the answers.

Fig. 20 shows that bureaucracy to get funding or financial assistance is the main non-technical issue indicated in all countries but Poland. Similarly, user operation or engagement also hinders the operation of the systems for many operators in every evaluated country. Except for Singapore, operators from all countries reported this non-technical issue, which is in accordance with two of the main reasons to restrict occupant control discussed in Section 4.1.4– disagreement among occupants and unfavorable occupant behavior in Fig. 13b. Finally, internal communication, planning or execution of organizations is also a concern in many countries and high response rates were observed for this issue. On the other hand, it is interesting to verify that some operators mentioned reaching optimal operation to find a comfortable condition for most occupants as a non-technical issue. This could indicate they consider not having enough tools to achieve this balance, or that they believe this is not achievable because it depends on a subjective aspect. Considering that most buildings in this set have central control systems, this result may indicate that the automation systems, where they exist, do not include the occupants' perspective in the loop. Hence, some of the buildings could benefit from smart occupant-centric automation controls [68].

Similar non-technical issues were found to be the most recurrent in most of the countries, so the correlation to country-driven differences seems low. As bureaucracy to get funding for retrofits or sensor installation seems to be a big challenge throughout the world, clear and concise proposals should be provided to best clarify the importance and opportunities related to this extra cost. Better internal communication among the actors involved in this role, and higher education and engagement from the users' side are key aspects along these lines. Consequently, it might be easier to assess the positive impact of investments on system improvement, and to enrich even more the proposals. With more robust proposals, it is expected that public and private funding organizations understand the benefits more easily and the bureaucracy involved in providing funds for retrofits or sensor installation to be reduced. The repeated application of satisfaction surveys can be an interesting strategy to support the demand for investments and to prove the benefits generated after an intervention. In addition, the publication of case studies that quantify the impact of these interventions is also very relevant to support estimates of future projects.

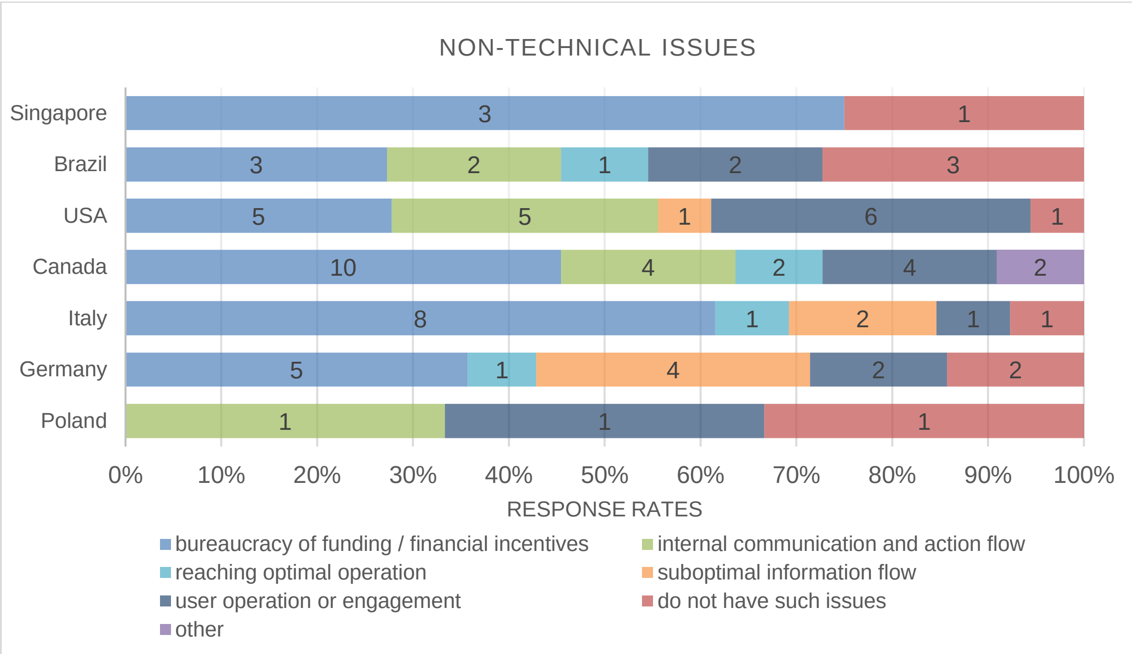

Fig. 20 - Non-technical issues faced by building operators by country. For proper visualization of figure colors please see the online version

5. Conclusion

5.1. Interpretation of the results

The results show that most operators find the buildings they operate generally comfortable (56 out of 72) and efficient (42 out of 72). However, a more careful analysis of the frequent complaints indicates that in many cases there could be situations of inadequate heating or cooling (insufficient or excess). These issues are more recurrent in HCD climates, as well as the indication of low efficiency and discomfort. Some operators mentioned that dealing with the indoor environmental conditions in shoulder seasons is quite difficult due to the variability of climate conditions that may be unexpected. Therefore, the evidence obtained from these interviews led to the hypothesis that operation adjustments are easier in cooling dominated climates, because it would mean to deal with a single operation mode. To verify this hypothesis, occupants' perception of comfort and building energy efficiency measurement data should be collected and analyzed.

Among the topics addressed, the complaint types were the aspect most strongly associated with climate characteristics, the others included in hypothesis I turned out to be mainly influenced by other factors. Setpoints are not only correlated to climatic conditions.

Sociocultural aspects, standard values, and probably economic factors, such as energy savings/cost play an important role, since this is the second main goal of operators. In addition, from this research, there is no evidence that HVAC systems are suited to climate characteristics. However, within the same country the correlation between climate and setpoints is observed, although different from what was expected, showing closer ranges of heating and cooling in colder climates. Additionally, an association is noticeable for terminals, which are air-based for CD and mostly radiant-based for HCD. The presence of heating and cooling systems varies per city located in the same climate zone, like Texas in the USA that includes both heating and cooling, while Brazilian cities in the same climate zone (2) include only cooling. Concerning the motivations to limit occupants' control, no clear climatic-based trends are found; thermostat and window control are limited in most countries. Appendix A presents a synthesis of the expected versus observed trends regarding the two initial hypotheses.

As mentioned, economic factors such as energy costs, equipment maintenance, and time spent on building management seem to have a great influence on the way buildings are operated. On the other hand, sociocultural factors are important to understand the operators' willingness to follow regulations, or to trust the occupants and to solve conflicts. In addition, the technological development of the country can also influence the type of HVAC installed and the feasibility of applying a particular technology. Each of these aspects could give rise to new hypotheses, and an interdisciplinary study could be carried out to identify the drivers influencing the differences found among countries. To do so, additional information through interviews, questionnaires or focus groups should be collected.

5.2. Practical implications and other contributions

The study points out that there are important differences in how operators in each country operate their buildings and that these could be the focus of further research. In addition, the results show that there are some opportunities to optimize the operation of buildings. On the one hand, it was observed that the setpoint temperatures could be wider if adjusted according to climatic characteristics, which would save energy by taking advantage of the occupants' adaptation potential. On the other hand, providing thermal conditions that please all occupants without leading to unnecessary energy consumption seems to be the main challenge for operators. Although a large part of the analyzed buildings has BMS/BAS that allow control and have access to data that could solve these problems, they seem to be underused. This may be due to the lack of information available on how to use this data and apply efficient strategies.

Results show operators rely on standards, procedures, and guidelines to drive decisions, but optimizing energy efficiency and occupant comfort is a very challenging task, even for highly educated operators, and it is accomplished through trial-and-error methods generally. This indicates the need for the inclusion of adaptive strategies and occupant-centric controls in international protocols and building operation guidelines. These documents should indicate, for example, how to:

- include weather forecast and measurements in the setpoint control system
- include window operation in control algorithm
- use applications (apps) to collect real-time occupant comfort votes to provide operators with decision support or to automatically enhance BMS/BAS control

- include predictions of user preferences in the setpoint adjustment control and operation mode setting
- include local cooling and heating systems (personal conditioning system) activation in the central systems setpoint automation control

Given the differences found among countries, the guidelines should be adjustable to the local context by including practical measures applicable to different conditions. In addition, more studies are needed to show the benefits of implementing such strategies and to demonstrate their cost-effectiveness. This information would be very helpful to facilitate the access to funding and other financial incentives, which were key non-technical constraints reported by operators. In addition, it could be used in awareness campaigns targeted at occupants to increase their understanding of operation procedures helping to engage them on using building controls efficiently.

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Appendix E.1

Table E.1. 1 - Conclusion Synthesis

Analyzed aspect		**Hypotheses**		**Justification**
		Initial expectation	**Observed trend**	
HVAC type (cool/heat)	Terminal type	Climate	Climate	Air terminals are more common in CD climates while radiant terminals only appear in HCD.
Setpoint temperatures	Ranges and cooling/ heating availability	Climate	Both	Countries in the same climate group have very different setpoint ranges. So, cooling/heating availability is not only influenced by the climate. But within the same country differences among climates are observed
Complaint type	Cooling and heating issues by season	Climate	Climate	Insufficient cooling / overcooling issues were predominant in CD climates.
Limitations and control level	Limitation types	Climate	None	Thermostat control limitation predominates, and window control is the second most recurrent in all climates and countries.
	Reasons to limit		Country	Human-related reasons seem to be the most important drivers in both climates. Some country trends are clear. In European countries, operators seem more influenced by energy efficiency concerns.
Operation goals	Main goals	Country	Country	Comfort/complaints are the main goals, but also energy aspects stand out. The balances between these goals vary per country and can be influenced by economical aspects and trust towards regulations.

Operators' perception	Occupants' comfort & building efficiency	Country	Both	HCD operators are less optimistic about comfort & efficiency, but the correlation between these aspects varies per country.
Job requirements	Training	Country	None	Training varies, but practical experience is common and important to all countries and climates.
System control and data usage	Controlled aspects	Country	Climate	CD locations include light sensor to take advantage of natural lighting.
	Sensors and data usage		Country	Sensors and BAS correlates to HVAC technologies, but also to the age of the systems. Monitored data is underused, and its application varies by country.
Operator-occupant communication	Channel	Country	Country	USA, Brazil, and Germany include more online portals, while in Canada, Italy and Poland direct communication types are more common. Results seem to be more related to communication effectiveness than technological readiness.
	Frequency			Communication frequency is diverse, but daily and as-needed communications are the most frequent. Results suggest more effective communication could improve the understanding of occupants' comfort.
Non-technical issues	-	Country	None	The main challenge is bureaucracy to get investments.

APPENDIX F– PAPER 5

TITLE

Implementation of Desk Fans in Open Office: Lessons Learned and Guidelines from a Field Study

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ABSTRACT

Desk fans allow individual adjustment in shared spaces, increasing occupants' thermal satisfaction. They can also reduce energy use when associated with the extension of room conditioning system setpoint temperature. In comparison to other Personal Comfort Systems (PCS), low-power desk fans can be very efficient in warm climates. Nevertheless, previous studies identify some barriers to their implementation and show no clear guidelines on how to overcome them. Therefore, this study presents the results of a field implementation of desk fans in an open office in Brazil and based on the lessons learned, proposes guidelines for future implementation. In the intervention, one desk fan was provided for each occupant, and the setpoint temperature progressively increased. Indoor thermal conditions were recorded simultaneously with occupants' thermal perception, using sensors and surveys. Results show fans increased thermal satisfaction by 20 % and when fans were available the preferred indoor air temperature increased by 1 °C. Nevertheless, many constraints affect the results. Based on this experience we emphasize the need to understand the HVAC system, engage operators, and apply gradual temperature modification. Occupants' expectations had a great impact on the possible temperature extension; therefore, we suggest a way to limit temperature extension in future implementations.

Keywords: field study, desk fans, intervention, thermal comfort, setpoint, personal comfort system

1. Introduction

Personal comfort systems (PCS) are devices "under the control of the occupant, to heat and/or cool individual occupants directly, or heat and/or cool the immediate thermal environment of an individual occupant, without affecting the thermal environment of other occupants" [1]. Desk fans are small equipment that increase the air movement around an occupant producing, a cooling effect of 3K [2]. They can be especially efficient in warm environments when able to provide high and controllable air speed with low power [3]. By providing local control, interpersonal preference variation can be met and occupants' satisfaction enhanced in shared spaces [4–9]. Simultaneously, this local control generates a microclimate that can meet occupants' demands while the room temperature is extended. This extension could be applied to setpoint temperature offset, generating substantial energy savings [10,11].

Despite these benefits and the extensive research on the topic in recent years [12], there are still many gaps related to PCS implementation [13]. The main challenge in shared spaces is finding a common setpoint and controlling it throughout the year to satisfy multiple occupants' demands. For instance, if the most sensitive occupants are the reference for central system control the potential energy savings are reduced [14]. On the other hand, an acceptable temperature can produce more savings but not match the preferred temperature [15] and that could, in the long term, affect occupants' satisfaction. To account for the known interpersonal preference variation [16], many studies propose predictive personal comfort models [17] to control HVAC. However, few present a solution for how to combine individual model responses into a single temperature [18,19]. As these solutions are tested in small settings or controlled environments, their applicability could be questioned from a practical point of view as being too complex and time-consuming for a real building.

Previous studies indicate that the optimal cooling and heating setpoint vary according to weather conditions. However, the dead band does not vary, the broader the values, the bigger the energy savings [10]. Personal comfort systems allow the extension of the dead band. Therefore, in cooling-dominated, like the ones found in Brazil, in which buildings have no heating systems, a simpler setpoint change can be proposed by increasing the cooling setpoint as much as possible within occupants' thermal comfort limits. For this climate, some studies indicate desk fans can be one of the most efficient PCS as they produce a high cooling effect with low energy power (2-3W) [3,20]. Climate chamber experiments indicate acceptable temperature limits up to 30 °C with small types of fans [3]. However, field experiments show lower acceptable limits in real conditioned office spaces, between 26 °C and 27 °C [21–24]. Even during the 'Coolbiz' campaign in Japan, which promoted a long-term use of 28 °C setpoint temperature with adaptive opportunities like the use of fans, the comfort temperature was 27 °C [25]. Previous studies show occupants used to cooled environments may prefer a lower setpoint than using a fan [14]. In addition, fan characteristics can compromise usability [26,27]. Although desk fans are available in many countries, we can see there are few observation field studies including them [28]. This highlights that the implementation of desk fans involves many challenges that need to be further comprehended to find appropriate ways to overcome them. Therefore, this paper has two goals. The first is to present the results of an intervention field study on the implementation of desk fans and extended setpoint temperature. The second consists of presenting guidelines for the implementation of desk fans based on the lessons learned from this study and the literature. These guidelines could be used by practitioners and researchers interested in implementing this strategy.

2. Method

2.1. Experiment Location and Building Characteristics

The implementation took place in part of an open plan office of a utility company in Florianopolis, in the southeast of Brazil. The local climate is subtropical hot-humid, Cfa [29] and 2A [30]. The study area was on the second floor of this three-floor building. The envelope is made of reinforced concrete and single-glazed panels shaded by horizontal external louvers. The building HVAC is a chilled water-cooling system that includes four fan-coil units (FCU) per floor. Figure 1a shows the location of the two FCUs that supply the selected areas. Both areas and other nearby occupied spaces are open or separated by low partitions, allowing air exchange. Two water chillers supply all the building's FCUs. Outdoor air is constantly supplied directly to each FCU room (without pre-cooling or heat recovery systems).

Figure 1a shows the location (red dots) of the data loggers used during the experiment to record indoor air temperature (T_a) and relative humidity (RH) every 5 minutes (HOBO® MX1101). The data loggers have a temperature accuracy and range of ±0.21 °C from 0 °C to 50 °C, and of RH ±2 % from 20 % to 80 % and ±6 % for other ranges. The studied spaces had low exposure to outdoor conditions as the included occupants were sitting far from the facades or being shaded by the balcony. Nevertheless, the measurement of the mean radiant temperature occurred in two days at two locations (indicated by red crosses) to check the variation, using a black globe and air temperature probes (Testo® 400), which have a measurement range of 1°C to 120 °C and ±0.3 °C error for the measured interval. The results of those measurements indicated a median difference between air temperature and mean radiant temperature (calculated according to ASHRAE 55 [1]) of 0.4 °C in one day and 0 °C in the other. Therefore, the difference between the air temperature and the mean radiant temperature during the period can be ignored, which is common in conditioned office spaces [31]. The measurement of overall air speed also occurred in two representative spots with a hot-wire probe attached to the Testo® 400 with a measurement range of 0 m/s to 5 m/s and accuracy of ±0.03 m/s + 4 % of the measured values. The results showed that 95 % of the time, on both days, the air speed was lower than 0.2 m/s, showing that air conditioning produced a low air speed.

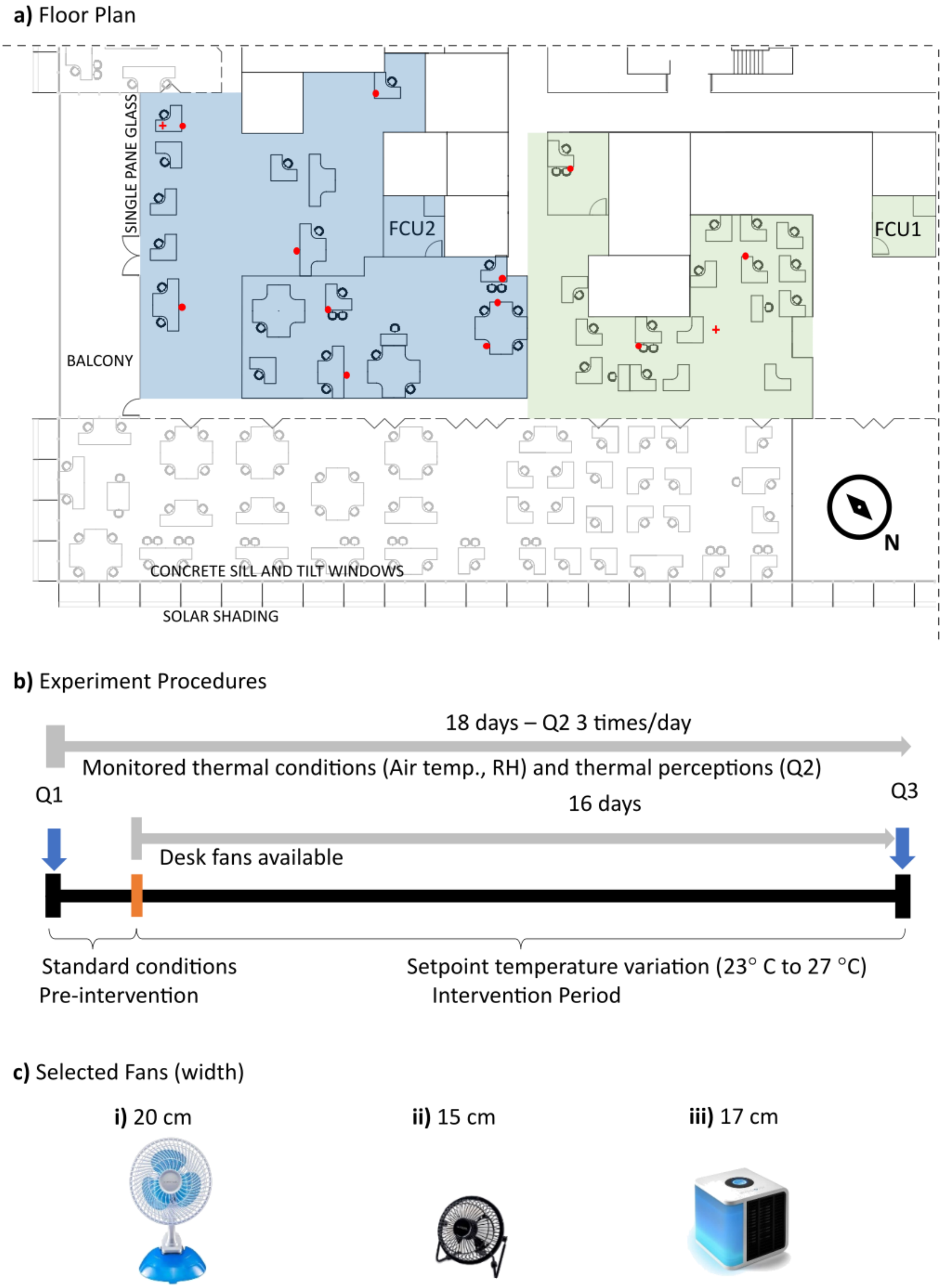

Figure 1. a) Experiment floor plan – studied areas hatched with two colors to indicate supply fan-coil units (FCU1 and FCU2). The red dots indicate the location of measurement data loggers and the red crosses the sensors used for measuring the mean radiant temperature. The light grey layout indicates occupants not included in the study. The symbol in the bottom right indicates the north. b) Experiment procedures scheme and questionnaires – personal information (Q1), snapshot (Q2), experience feedback (Q3). c) Selected fans with respective width sizes – characteristics described in [32].

2.2. Experiment Procedures

The experiment lasted 18 days from January to February 2021, which are the warmest months of the year in Florianopolis. Figure 1b shows the experiment procedures. The questionnaire Q1 had personal and background information questions and occupants answered it once. We recorded indoor air temperature and relative humidity during the whole experiment. The second questionnaire (Q2) was applied three times a day during the entire experimental period. The Q2 was a snapshot questionnaire containing 5 questions about occupants' presence at their workstation, clothing, right-now thermal comfort (on a 4-level scale), right-now thermal prefer (on a 3-level scale) and, the status of the fan (on, off, or not available). The experiment started under standard operation and the intervention started two days after, by providing a desk fan to each participant. During the intervention, participants could freely control the fans. Questionnaires Q1 and Q2 are presented in Appendix A.

Participants chose between two types of fans selected in a previous study [32], options i and ii in Figure 1c. Option iii is an evaporative cooling fan used by only two participants – one manager and a participant who was feeling too warm during the experiment. One day after the fans were available, we increased the setpoint temperature by 1 °C and monitored the responses. On the following day, the setpoint temperature increased another 1 °C, and so on. The initial strategy was to raise the temperature progressively from one day to another and maintain the same temperature throughout the day. However, when there were more than three "very uncomfortable" votes, we lowered the setpoint. After "very uncomfortable" votes ceased, we tried to maintain a higher setpoint during the mornings and a lower one in the afternoon. The default setpoint was 23 °C, and the experiment ended after having at least 60 responses per setpoint temperature. After that, we applied a third questionnaire (Q3) to get feedback on the experience and help interpret the results. All questionnaires included a field for a pre-defined code to correlate answers per occupant while maintaining anonymity.

2.3. Data Processing and Statistical Analysis

The data from occupants and environmental variables were interconnected and analyzed using Rstudio with *tidyverse, metrics, ggpubr, lme4, extrafonts, effsize, and scales* packages. To test the intervention's impact on occupants' thermal perception and to answer the questions presented in the objectives we grouped the data by different variables and applied statistical analyses. To compare the significance of differences between means we used t-test. To evaluate the influence of environmental variables on occupants' perception we used multiple coefficient regression analysis. The threshold for statistical significance was $p\text{-value}<0.05$. To verify the effect size over the results the Spearman coefficient (rho) was calculated considering negligible values <0.2, low between 0.2-0.5, moderate for 0.5-0.8, and strong for >0.8 [33]. In the case of the probability of "no change" and comfort (grouping very comfortable and just comfortable) Cliff's delta test was applied to assess the size of the difference, considered negligible values <0.15, medium between 0.15-0.47, and large for >0.47 [34].

3. Results

This section presents the main findings organized in the following sections: 1) Participants, 2) Temperature control and indoor conditions, 3) Thermal perception, and 4) Influencing factors.

3.1. Participants

In total, 34 people participated in the experiment, 65 % male and 35 % female. The average age was 43 years old with 11.2 standard deviation (sd) and the average body mass index (BMI) was 26 – classified as pre-obese [35] – sd is 5. Mean clothing insulation was 0.5 clo. The dress code for men is stricter, they cannot wear shorts or light shoes. So, women's clothes showed greater variation (sd. 0.12 versus 0.02 for men). The absolute difference of means is small – 0.04 clo, which corresponds to underwear insulation. The average metabolic rate was estimated at 1.2 met with 0.2 sd, indicating occupants to be in sedentary activity. The votes in which participants indicated not to be in their workstation. BMI, age, or estimated metabolic rate showed no statistical difference between genders. Gender was asked instead of sex to account for diversity, but none of the participants indicated "other" gender different from "male" or "female".

3.2. Temperature Control and Indoor Conditions

As indicated above, during the experiment, the setpoint temperature changed from 23 °C, which was the standard temperature, to 27 °C. Both systems (FCU1 and FCU2) received the same setting, simultaneously. However, as shown in Figure 2, setpoint and indoor air temperature presented a great mismatch. The median temperature during the experiment was 25.1 °C although 23 °C was the setpoint on most days (40 %). This means the HVAC was not able to maintain the setpoint most of the time. In addition, Figure 2 shows this control limitation was more critical during the afternoon when indoor temperatures tended to be higher.

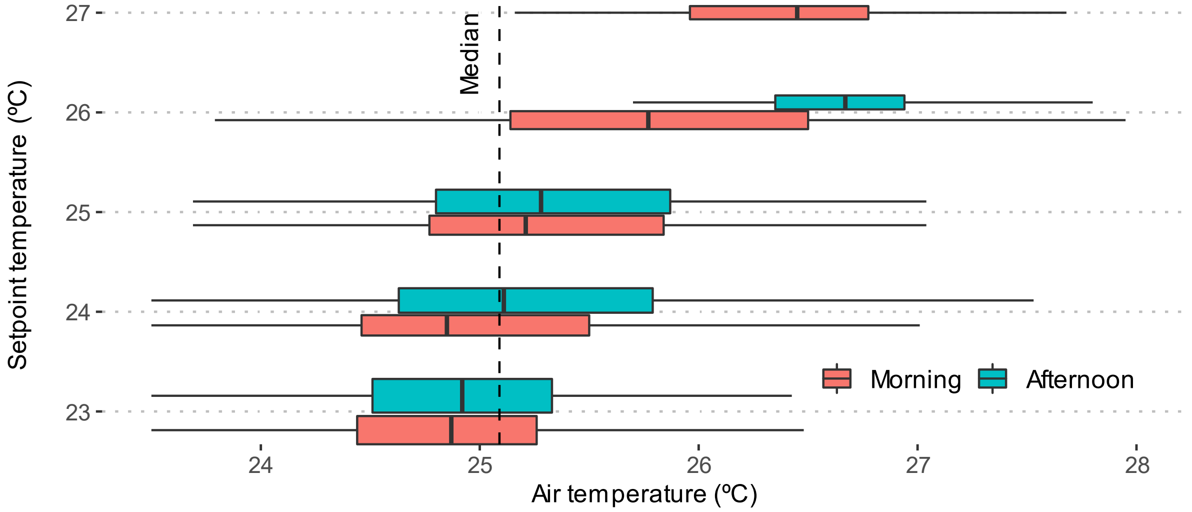

Figure 2. Setpoint temperature vs. indoor air temperature in the morning and afternoon. The thickness variation of the boxplots represents sample size variation. The median of each boxplot is represented by a solid line and the dashed line represents the overall median indoor air temperature.

This issue relates to the HVAC system design and control. During summer, the cooling runs from 6 am to 7 pm, but outside air runs from 6 am to 9 or 10 pm, when all equipment are turned off. Occupancy usually starts between 7 am and 8 am, but the HVAC starts 1h before to prepare the space for occupancy. The whole HVAC system runs with constant airflow, and to address the variable demands, each floor has 8 fan-coil units (FCU) with individual control to maintain the conditions of small areas. The duct size and pressure balance are used to determine the airflow in each zone inlet, there is no variable air flow boxed or local reheat. Each FCU is inside a room connected to ducted outdoor air, and the return air comes through the room door vents directly from the zone. Each FCU constantly mixes outdoor air with the return air, cools down the mix, and distributes it to each zone. The chiller capacity should meet a typical summer day demand with high outdoor temperatures, as this is the usual design condition. However, there is no dedicated air handling unit nor a heat exchange to pre-cool the outdoor air, which makes the heat load in the fan-coils vary greatly due to the variation in outdoor air conditions. During the experiment, it was not possible to change the chiller's supply temperature because it would affect other building areas not included in the experiment. The setpoint temperature change affected only one parameter – the position of the valve that controls cooled water circulation inside the FCU. These electronically controlled valves modulate the chilled water flow through to FCU to provide enough cold to maintain indoor air temperature close to the setpoint temperature based on the thermostat response.

Few buildings in Brazil have variable air volume or reheating, so this is a common design strategy for office buildings. However, results show the setpoint control precision was very low. Figure 3a shows there is a significant correlation between indoor air temperature and outdoor air temperature when outdoor air temperature surpasses 24 °C ($p<0.01$), and the effect size is low (rho=0.35). This relationship is clear when the 23 °C setpoint is observed, for example. On the other hand, the system maintains a maximum of 27 °C indoor air temperature, even when outdoor air temperature reaches 34 °C. Indoor relative humidity (RH), in Figure 3b, shows a smaller variation, staying mainly between 60-70 % through the experiment. Nevertheless, higher than standard design conditions, which are usually 55-50% RH Therefore, the HVAC can control indoor conditions up to some level but with low precision, especially under high outdoor conditions.

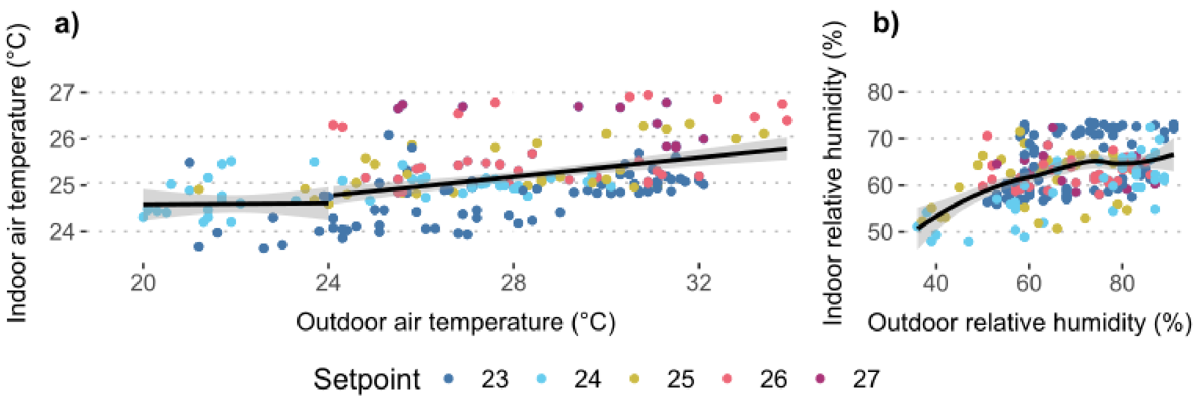

Figure 3. Indoor vs. Outdoor conditions: a) temperature, b) relative humidity. Colors indicate setpoint temperatures.

Consequently, the experiment results were affected and the setpoint did not correspond to indoor air temperature. Because of this mismatch, the results were analyzed based on indoor air temperature.

3.3. Thermal Perception

Figure 4 shows the comparison of occupants' perception in pre- and post-intervention, first without fans and later with fans available. Figure 4a shows the availability of desk fans increased the percentage of preference for "no change" at every temperature bin. Cliff's test indicates a large difference between the probability of "no change" with and without fans (delta= -48%). For both with and without fans, the higher percentage of "no change" occurs between 24 °C and 25 °C, and the availability of fans increased satisfaction by 19%. Figure 4b shows the mean preferred temperature (corresponding to no change votes) increased by 0.8 °C and the standard deviation reduced – from 24.2 °C (sd. 0.85) to 25 °C (sd. 0.68). However, the interval between the 1st and 3rd quartiles shows a 1°C increment between periods – from 23.6-

24.6 °C without fans to 24.6-25.5 °C with fans. Therefore, fans' availability had a positive impact on occupants' thermal preference leading to the acceptance of a higher room temperature.

Regarding occupants' thermal comfort, Figure 4c also shows a higher percentage of very comfortable votes in the period with fans. However, at the same time, the amount of just uncomfortable votes increased at 24-26 °C and few very uncomfortable votes appeared in this period. This could indicate a decreased perception of comfort when fans were available, and the air temperature was higher than 24 °C. Nevertheless, when the comfortable (just and very comfortable) temperature ranges are compared in Figure 4d we also observe a higher interval when fans were available – from 23.8-24.8 °C to 24.6-25.5 °C. The mean comfortable temperatures are closer than the preferred temperature, 24.5 °C (sd. 0.86) without fans and 24.9 °C (sd. 0.74) with fans. Therefore, Cliff's test showed the probability difference of comfort to be negligible (delta= -5%).

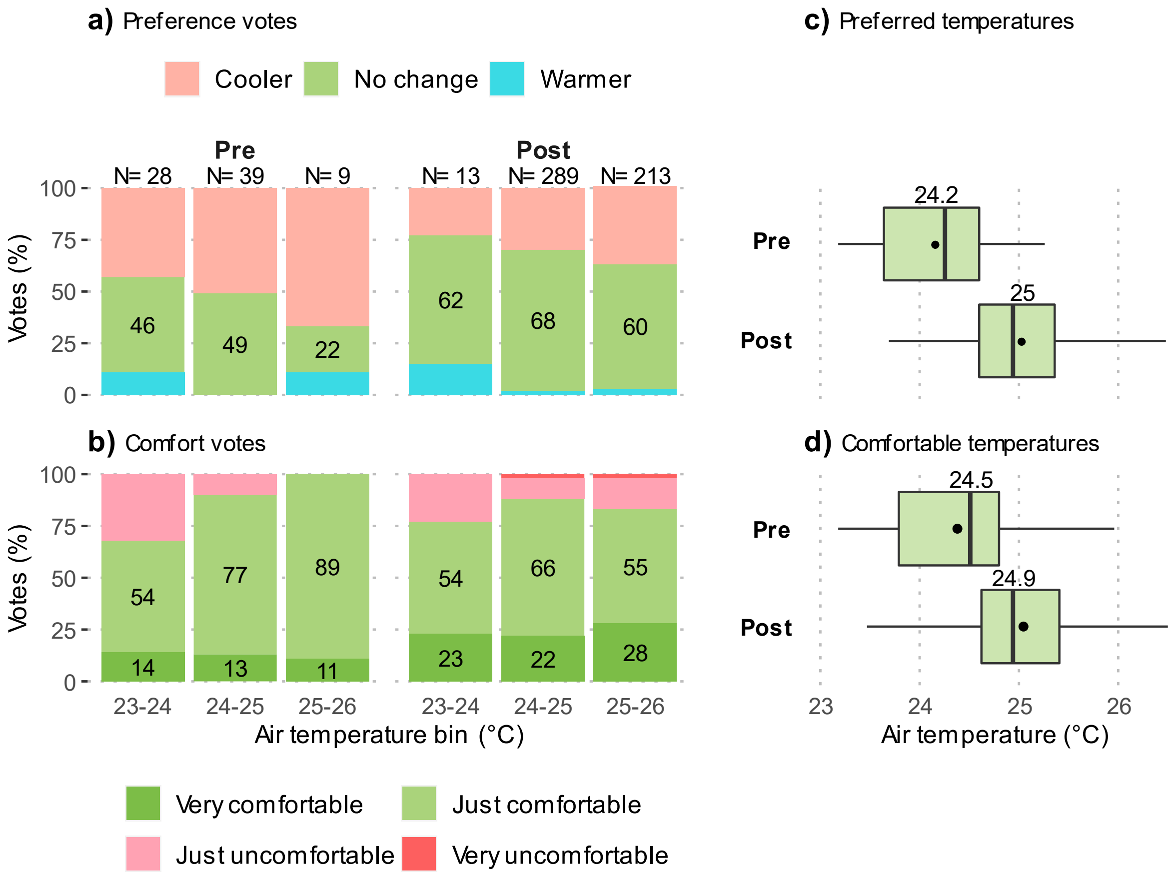

Figure 4. Thermal perception a) preference votes and b) comfort votes by temperature bin and, c) preferred temperatures (no change) and d) comfortable temperatures (just and very comfortable) in the pre (without fans) and post (with fans) periods

This could stem from the high percentage of comfortable votes during the experiment resulting in a smaller difference between periods. The sum of just and very comfortable votes was higher than "no change" votes for all air temperature bins comparing Figure 4a and c. These indicate fans met occupants' preferences but seem not to significantly affect the less restrictive occupants' comfort. To further understand this result, Figure 5 the daily percentage of comfort is presented in Figure 5 (bar plot) and compares it to the indoor (boxplots) and mean outdoor air temperatures (T_{out} in dashed line). Figure 5 also shows the setpoint of each day (triangles).

In the first week, comfortable votes increased gradually after the intervention (as of January 12) following the increase in setpoint temperature. However, in the second week, although the setpoint on January 17 was the same as January 14 (25 °C), the indoor air temperature increased a lot due to high outdoor temperatures (T_{out}). That abrupt increase generated very uncomfortable votes. In the next day, the recording of three "very uncomfortable" votes prompted the reduction of the setpoint back to default, 23 °C. However, the "very uncomfortable" votes did not disappear, and operators received complaints. Although the setpoint was 23 °C, the very uncomfortable votes lasted five working days, showing persistent discomfort. After one day without very uncomfortable votes, the setpoint was raised again – on January 26. Finally, in the last three days of the study (week 4), the mean indoor temperature was 1 °C higher than the pre-intervention period – 24 °C and 25.2 °C, respectively – and the percentage of comfort was almost the same (~75%). This indicates the acceptance of a 1 °C increment by the end of the experiment.

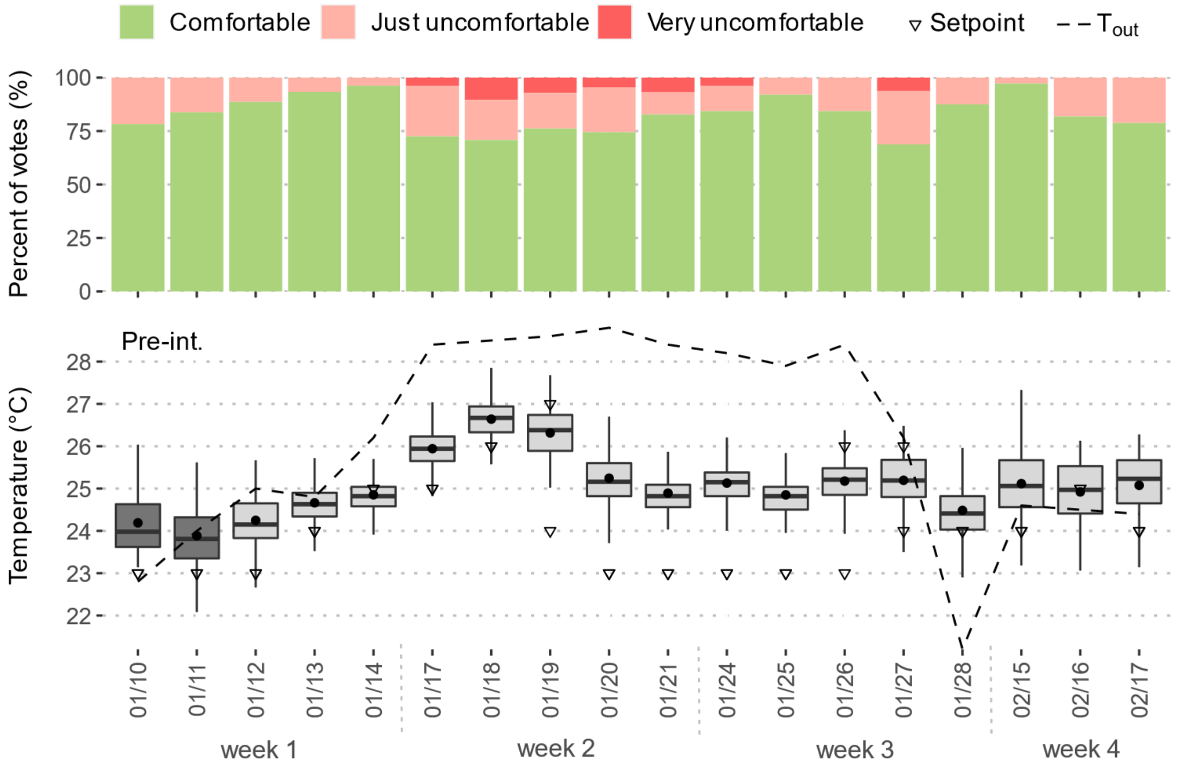

Figure 5. Percent of daily thermal comfort votes compared to daily indoor air temperature variation (boxplots). Very comfortable and just comfortable votes grouped as "comfortable". The dashed line indicates the daily mean outdoor air temperature (T_{out}). Pre-intervention (Pre-int.) period indoor air temperature boxplots are in dark grey. Dates are grouped by week.

3.4. Influencing Factors

Figure 5 shows outdoor temperature seems to have influenced besides indoor air temperature, occupants' thermal comfort during the experiment. The multiple regression probability analysis indicated mean outdoor air temperature significantly influenced occupants' comfort but was not their thermal preference. In contrast, indoor air temperature was found to influence significantly thermal preference but not thermal comfort. The experiment period (pre or post intervention) was a significant factor to preference and comfort, while fan status (on/off) at answering time was not significant to either.

A great difference was found on fan activation period among occupants, some of them maintained the fan on most of the time when available, while others indicated it to be on only in one response. Additionally, the temperatures corresponding to “no change” votes were very different for each participant and the range was broad for most of them. The maximum air temperature difference between the experiment areas (supplied by FCU1 and FCU2) was 0.9 °C. However, the mean preferred and comfortable temperatures between both groups were the same in the intervention period. Therefore, the regression analysis showed that the system identifier was not significantly correlated to the probability of comfort or preference. Therefore, the same temperature could be set for both building areas, not demanding different adjustments.

4. Discussion

In this section, the results are discussed based on the answers to the main questions that we believe professionals or researchers interested in implementing office fans should have. Nevertheless, the study limitations are also discussed at the end of the discussion.

4.1. Why Implementing Desk Fans in Shared Office Spaces?

As shown in this study, desk fans increased the number of occupants’ “no change” votes by ~20 % and increased the very comfortable votes by ~10 %. Like in a previous study [26], some occupants did not foresee fans as helpful equipment but that changed after the experiment. Before the intervention (in Q1), only 3 participants out of 25 – who answered Q1 and Q3 questionnaires – preferred air conditioning (AC) with fans as a conditioning mode for hot days. Most of them (13 people) preferred AC without fans. However, after the experiment, 12 people indicated to prefer AC with fans. This highlights not only the effectiveness of desk fans in meeting occupants’ demands but also the positive impact of increasing occupants’ controllability. Moreover, this before and after comparison hints that we should provide a desk fan to occupants because having the opportunity to use them exceeded their initial expectations of use. Additionally, this experiment showed desk fans can increase occupants’ thermal satisfaction.

The association of fans with setpoint extension has the potential to generate energy savings. In this study, results show indoor temperature could be extended by 1 °C. Increasing temperature setpoints saves energy as the cooling demand is reduced. The impact would be greater if the HVAC’s compressor is tuned for it [36]. In this study, we were not able to change the chiller setpoints because this would affect the entire building beyond the intervention area, where occupants did not have access to desk fans. Additionally, the fan coils would save energy if the fan power and air flow were not constant and/or the outdoor air was pre-cooled [21]. Unfortunately, we were not able to measure energy consumption during the experiment due to technical limitations. Nevertheless, changing the setpoint by 1 °C – from 24 °C to 25 °C – in a 2A climate location, like Florianopolis could produce around 9 % energy savings [10]. At the same time, based on previous studies [36,37], by adding 3-10 W desk fans, like the ones used in this experiment – detailed in [32] – the building energy consumption is expected to increase by less than 2 % provided all occupants used them.

Additionally, desk fans enhance perceived air quality and space air mixing. Fan only recirculates air, not directly renewing the air. However, by increasing air movement it can dilute CO_2 and other pollutants concentration in the breathing zone [38] and it is perceived by users to increase air quality [8]. This experiment did not measure this effect because, as indicated by [38], the ambient concentration level that could be more easily measured on the field would underestimate the effect on the breathing zone.

4.2. How to Prepare for the Implementation?

The pre-intervention period is very important. This period should be used to collect data about the standard operation and to diagnose and understand the HVAC system design, operation, and control capability. Different from previous studies [21,23], in this experiment HVAC showed poor control of indoor temperature when outdoor air temperature increased. Probably a longer pre-intervention period could have helped to identify this issue. In case of similar issues, additional tests can be proposed to understand how much and under which conditions indoor temperature can be better controlled. Unoccupied periods, weekends, for example, can be used to perform some tests avoiding disturbing occupants and helping to prepare for the intervention.

Additionally, building operators are a great source of information, as they deal with the system daily, and their experience is valuable [39]. Therefore, they can help to review and define an experiment protocol and should participate in and/or lead the intervention to avoid common mismatches between researchers' expectations and the building reality [40]. To do that, operators should be informed of the goals and benefits of the intervention, to engage in the process. Similarly, occupants should be aware of the intervention goals and benefits before any change is applied and understand their role in the success of the campaign should also be exposed.

4.3. What is the Necessary Sample Size of Occupants' Votes?

For statistical analysis or generalizing the results we usually need large sample sizes. For academic purposes, a power analysis should be performed to define the sample size [41] and the possible variations along the experiment should be considered. In this experiment the pre-intervention period was too short and showed a lower variation of temperature, making it more difficult to properly compare pre-post intervention results. Therefore, a longer pre-intervention period could have helped in the comparison, and repeating the survey application was important to follow occupants' perception during temperature variation. On the other hand, in a real-life implementation of a new system or operation strategy in an existing building, the focus should be on gathering the information you need, bothering occupants as little as possible. Therefore, the survey should be short and the application frequency as low as possible. An automatic system that sends the survey only when the new data point would substantially increase the information gathered should be implemented [42]. Another option is sending surveys based on procedure changes. For example, if the pre-intervention period has a very stable temperature, occupants can be surveyed once, because the result will represent well their overall perception. Then, they can be surveyed again upon implementing an intervention, for example, after making fans available and before changing the temperature. The next survey application would be after the first temperature increment, and so on. Nevertheless, when considering an adaptation period, which will be discussed in the following sections, it is better to apply surveys by the end of a test period, so occupants are used to the new setting or condition. The size of the questionnaire derives from the next question.

4.4. What Thermal Perception Scale to Use?

In this study, we used two thermal perception questions and scales – 3-level preference and 4-level comfort. As discussed before [13,17], there is a great variation of scales used among studies. This study showed people tend to be more restrictive when asked about their preferences [15], therefore, this scale gives more information about occupants' desires. On the other hand, this experiment partially met the expectation of using two scales to weigh annoyance as "very comfortable" votes fulfilled this purpose for some participants. However, we believe that idea was not clear to all occupants. In Q3, we asked occupants what they would expect to be used as an indicator for automatic setpoint change if the surveys had that purpose. The responses were not as expected, 40 % would expect a temperature adjustment when they indicated to prefer a cooler or warmer environment. Another 44% indicated a preference for change and "just uncomfortable" votes together would be a good indicator. Only three individuals expected a change based on their preferences for change and a "very uncomfortable" vote. This result is in line with previous studies that indicate the comprehension of the thermal perception scale may vary greatly among people [43] and that preference is usually more restrictive [15]. Therefore, the first highlight is that scales should be explained to occupants and any expectations about their responses should be revealed. Especially when using these votes to automatically predict their satisfaction and to control the temperature, like in these studies [44–47]. Second, results showed using only one scale would be enough to understand occupants' and the use of a 3-level preference scale is the most recommendable, bringing sufficient information and reducing answering time.

4.5. How Much Can the Temperature Be Extended?

The results from this study indicate the temperature extension for comfort would be of only 1 °C – from 24 °C to 25 °C but that was probably affected by the length of the experiment and the system controllability. Previous studies found 26 °C to be a feasible temperature when desk fans [23] and ceiling fans [21,48] are available. Therefore, in the future, 26 °C can be considered as a reference, but not a universal value applicable to any location and building. This and previous intervention studies used a similar approach to define the temperature limit, increasing it until receiving too many complaints or occupants getting too dissatisfied [21,23]. This approach has the big disadvantage of disturbing occupants and can generate persistent discomfort as observed in this experiment. Occupants' annoyance lasted 4 days after the setpoint reset to the default value. To avoid this issue, we tried to identify some referential limits that could be established based on the results considering the hypothesis that the discomfort was triggered by expectation disruption. To do that, we tested different indicators from previous studies related to adaptation and expectation.

The adaptive model indicates indoor operative temperature accepted by occupants is mainly influenced by prevailing mean outdoor air temperature (T_{pma}). This correlation is stronger for naturally ventilated buildings [1,49]. However, in this building, since mean outdoor air temperature (T_{out}) showed a significant correlation to thermal comfort and influenced indoor air temperature, this model could be applicable to this study. Other indexes tested were the 80th and 90th upper percentile (Q80, Q90) temperature of the pre-intervention period. This is inspired by Peixian et al. [15] who identified occupants' comfort votes as mainly correlated to the 80th percentile (Q80) of indoor temperature. This means, a broader temperature than the usual range that occurs 80 % of the time, can lead to discomfort. We also tested other indexes, indicated in

Table 1, to verify if the problem was the magnitude of the change, delta temperature variation impacting the nest day (D indexes), or the magnitude associated with a rapid change (the Q indexes). The Q80-2 and Q90-2 are a moving percentile, considering that along the week there could be some adaptation, causing people to accept a new reference value.

Table 1. Linear correlation to percentile of comfort and preference votes. The * indicates significant values ($p<0.05$).

Name	Meaning	Correlation to (rho)	
		Comfort	Preference
T_{pma}	Prevailing mean outdoor air temperature	-0.48	-0.39
Q80	Freq. T_a higher than 80th value of pre-int.	-0.32	-0.27
Q90	Freq. T_a higher than 90th value of pre-int.	-0.79*	-0.75*
Q80-2	Freq. T_a higher than 80th value of 2-3 prev. days	-0.4	-0.39
Q90-2	Freq. T_a higher than 90th value of 2-3 prev. days	-0.58*	-0.52
D80	Delta 80th T_a of the day before	-0.26	-0.13
D_{mean}	Delta mean T_a of the day before	-0.19	-0.008
D_{max}	Delta maximum T_a of the day before	-0.11	-0.11

Table 1 shows that, different from [15], only the 90th percentile (Q90) of the pre-intervention period is significantly correlated to comfort and preference. The Q90-2 is significantly correlated to comfort but with a smaller effect size (0.58 in comparison to 0.79). T_{pma} correlation is not significant. The 90th percentile temperature was 25.2 °C, 1.2 °C higher than the mean pre-intervention temperature, which occupants were used to. Therefore, when this usual upper limit was exceeded, occupants' thermal satisfaction decreased significantly. Although the 90th percentile of a pre-intervention period needs further validation, it could be used to limit the temperature extension to avoid occupants' discomfort in future interventions. This result highlights gradual change is beneficial to account for occupants' adaptation period. This leads to the next question.

4.6. How Long Does It Take for Occupants to Adapt to Temperature Change?

In almost one month, occupants adapted to a 1 °C average increment, which highlights adaptation period might be long. The literature does not indicate what is the minimum adaptation period for sedentary occupants under long-term exposure. The human body can reach neutrality within 37-47 minutes when exposed to a thermal overshoot in a transitory environment [50]. For longer exposures, the literature only presents periods for participants under high-intensity exercises [51,52]. However, the adaptation during low metabolic rate and under long exposure can be expected to be longer because human thermal regulation is less in demand [53]. Therefore, this is still a literature gap, but based on our experience and previous studies [21], at least two weeks under a stable air temperature are necessary for physiological, psychological, and behavioral adaptation.

4.7. Is it Possible to Automate the HVAC Temperature Control After Identifying Satisfaction Limits?

Considering temperature adjustment automation strategy, a previous study suggested occupants' preferences could be predicted based on personal comfort system operation [54]. In this study, the probability model based on air temperature and fan activation presented a Mean Absolute Error (MAE) of 0.68 for comfort votes and 0.28 for preference. Meanwhile, the probability model based only on indoor air temperature showed the same MAE for comfort and reduced the error of preference prediction to 0.25. Despite the similar values, we can see in

Figure 6 that the percentage of activated fans shows no clear trend to occupants' comfort or preference vote. The same percentage of votes relates to any percentage of fan activation, from 0 % to 100 %. Meanwhile, air temperature alone showed lower MAE for preference and would be easier to measure and implement as a prediction model. Therefore, in this case, including the fan status in an automation scheme would not be beneficial.

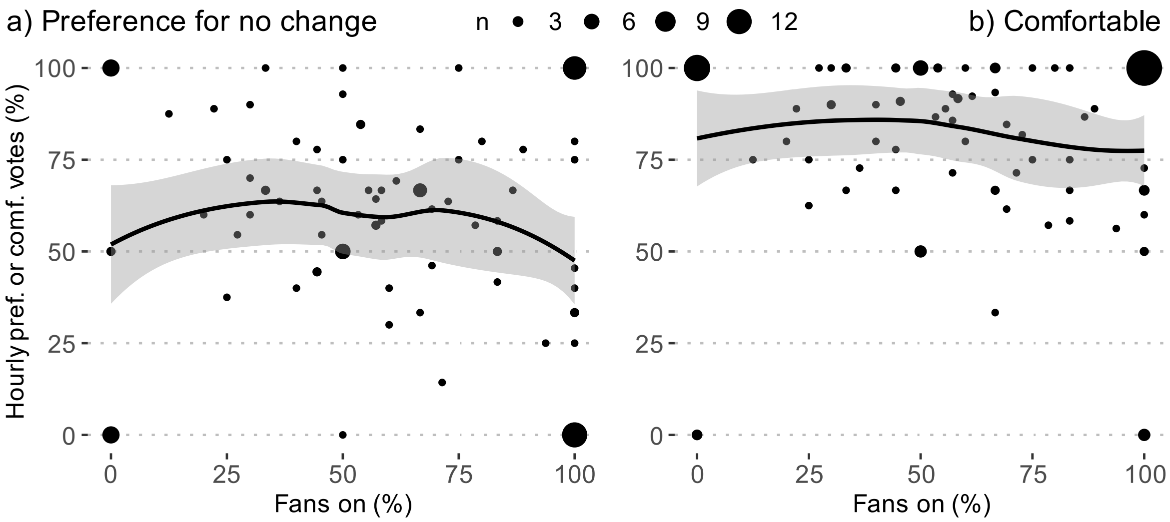

Figure 6. Percentage of fans on by a) votes of preference for no change, and b) comfortable votes (just comfort and very comfortable). Individual differences: percentage of fan usage on the left and preferred temperature on the right, by participant organized by AC supply system (FCU1 and FCU2)

Indoor setpoint temperature could be automatically controlled, however, to allow that, data from a yearlong is necessary so seasonal variations are considered. Previous studies showed occupants forgot they had the possibility of using desk fans [26], and, automatic activation according to occupancy would be beneficial if occupants can overwrite settings [36]. For PCS that supply cooling or heating, integration into the central system is crucial so conflicts of activation and energy waste [39,55] are avoided. Nevertheless, desk fans do not affect cooling setpoint, like other cooling PCS that produce cold (e.g., personal ventilation), therefore this integration is not necessary, and a simpler implementation procedure can be proposed. Determining cooling seasonal setpoints would be sufficient for office spaces in hot climates.

4.8. Study limitations

Many constraints affect the results of this study limiting the possibility of generalizing the outcomes. The first one was the HVAC control issues, which affected the stability of indoor air temperature and its correlation to the setpoint temperature. In other buildings, with better controls, the results would probably be different. The control issue associated with the great outdoor temperature variation in the post intervention periods considerably affected the results. The pre-intervention period was scheduled to be short because indoor air temperature was expected to be constant. However, that was not the case, and the sample size imbalance hindered the analysis. Extending both periods and repeating the experiment in a different order, i.e., taking off the fans and giving them back to occupants, would allow assessing the intervention impact and extending the sample sizes to increase statistical power. Additionally, it would be important to assess occupants' thermal perception in other seasons to define a year-round strategy for setpoint control when fans are available. A suggested strategy would be to use the setpoint identified through summer but survey occupants at the beginning and end of each month/season depending on the expected indoor temperature variation, and to keep an open communication channel in case there is a need for a daily adjustment. Another limitation relates to space restriction. Only by implementing this strategy in the whole building would be possible to evaluate the variation among building areas and necessary local adjustments of setpoints, which might be more relevant between floors and facades. These are case-dependent variables that should be considered to identify the most suitable control granularity and influencing factors. For instance, in this study, relative humidity (RH) was not an influencing factor because it presented a low mean variation, which is related to the local climate characteristics. However, in other conditions, RH could hinder fans' effectiveness [56,57].

5. Conclusions

This study presented the results of a practical implementation of desk fans in an open office during summer. Despite some limitations, the implementation increased occupant thermal satisfaction under slightly higher temperatures, which has the potential to save energy. Occupants' preference for no thermal change increased by 20 % with the use of fans the preferred indoor air temperature increased by 1 °C. In addition, based on the lessons learned, we suggested some guidelines for the successful implementation of desk fans associated with room temperature extension, and the main ones can be summarized:

- Pre-intervention period should be used to diagnose occupants' thermal perception during standard operation and to understand the HVAC system design and operation. Building operators should be involved and validate intervention procedures.
- The survey should be short and applied as few times as possible. Consider applying it in a pre-intervention period for diagnosis and 2-3 weeks after any intervention or change for comparison. Adopting the 3-level thermal preference scale is recommended.
- Provide desk fans to all participants and inform them of the intervention benefits and procedure, including their participation role.
- Modifications of indoor air temperature should be gradual. Small temperature variations can be applied to avoid discomfort, followed by survey responses. Two weeks is the minimum expected period for adaptation. The 90^{th} percent temperature range of the pre-intervention period is suggested as a limit reference for initial temperature extension.

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APPENDIX G – PAPER 5 QUESTIONNAIRES

Table G. 1 -Personal information (Q1)

N°	Question	Answering options
1	Write your initials followed by your year of birth (e.g. AR85)	Open-ended
2	How do you identify? (gender)	female/male/other
3	What is your age? (in years, e.g. 40)	Open-ended only numbers
4	What is your weight? (in kg, e.g. 70)	Open-ended only numbers
5	What is your height? (in m, e.g. 1.70)	Open-ended only numbers
6	How long have you been working in this building?	“Less than 1 year”, “more than 1 year”, “other”
7	How do you usually come to work?	"On foot", "by car", "by bus", "by bike", “other”
8	Do you exercise regularly?	"No", "Yes, once a week", "Yes, two or more days a week", "other"
9	Are you used to turning on the air-conditioning in your house or car during warm days? If yes, indicate in which places:	"Yes, in my house", "yes, in my car", "yes, in my house and car”, "no, neither", “other”
10	Do you have or would like to have a fan at your workplace during warm days?	“I like and use fans”, “I don’t have it, but I think I would like it”, “I don’t have it, but I think I would not like it”, “I don’t have it and do not know if I would like it”, “other”
11	Imagine you work in an IDEAL ENVIRONMENT. On warm days what would you prefer:	"air-conditioning", "natural ventilation", "natural ventilation with fan", "air conditioning with fan"
12	In your workspace do you usually feel:	“Always warm”, “warmer than colder”, “warm on hot days and cold on cold days”, “neither cold nor hot, usually I am comfortable”, “colder than warmer”, “always cold”, “other”

Table G. 2 - Snapshot (Q2)

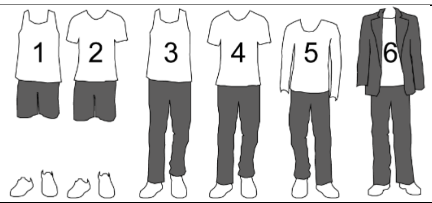
N°	Question	Answering options
1	Write your initials followed by your year of birth (e.g., AR85)	Open-ended
2	How long have you been in your workstation?	“More than 20 minutes”, “less than or equal to 20 minutes”
3	Which of the images better describes your clothing now:	
4	How would you assess the thermal conditions right now?	"Very comfortable", "just comfortable", "just uncomfortable", "very uncomfortable"
5	How would you prefer the temperature to be now?	"warmer", "as it is", "cooler"
6	Right now, your fan is:	“On”, “off”, “I don’t have a fan”

Table G. 3 - Feedback about the experience (Q3)

N°	Question	Answering options
1	Write your initials followed by your year of birth (e.g., AR85)	Open-ended
2	Overall rate the experience of having a personal fan on a 5-number scale:	1= “Very interesting”, 5= ”very uninteresting”
3	Rate the following characteristics of your fan: aesthetics, size, noise, air flow sensation, adjustability, cooling effect	“Very good”, “good”, “neither good nor bad”, “bad”, “very bad”
4	Would you like this fan to be better in some aspect or have any additional features?	Open-ended
5	Do you think the fan helped to maintain your comfort during summer?	“Yes, it helped in most of the days”, “Yes, it helped in the warmer days”, Yes, but it was not enough in the warmer days”, “It did not make much difference”, “No, I did not use it much”, “other”
6	Did you change the fan position during the experiment?	“Yes, often”, “Yes, sometimes”, “No”
7	What were the reasons for changing the position?	“To put it closer to me”, “To put it away from me”, “to get it out of the way not to affect my work”, “other”
8	Imagine you work in an IDEAL ENVIRONMENT. On warm days what would you prefer:	"air-conditioning", "natural ventilation", "natural ventilation with fan", "air conditioning with fan"
9	Imagine the answers from the questionnaires were used to adjust the temperature of the air conditioner in this space. When would you expect a change to occur?	“When I prefer cooler or warmer”, “when I prefer cooler or warmer and to be just uncomfortable”, “when I prefer cooler or warmer and to be very uncomfortable”, “other”
10	Considering your preference affects your colleagues, when do you think a temperature adjustment should happen?	“When most of the people (80%) is just uncomfortable”, “when more than half (51%) is just uncomfortable”, “when one person is just uncomfortable”, “when most of the people (80%) is very uncomfortable”, “when more than half (51%) is very uncomfortable”, “when one person is very uncomfortable”, “other”
11	Would you be willing to accept the setpoint temperature rise if you had a fan?	“Yes”, “yes if it would save energy”, “yes if my colleagues were more comfortable”, “no”, “other”

APPENDIX H – TERMS OF AGREEMENT TO ALL PAPERS

This document attests all the co-authors of the article entitled "User-centered environmental control: a review of current findings on personal conditioning systems and personal comfort models", AGREE with the use of this article in the Doctoral thesis of Maíra Afonso de André (first author), supervised by Professor Roberto Lamberts from the Graduate Program of Civil Engineering (PPGEC) at the Federal University of Santa Catarina (UFSC). Published in Energy and Building: https://doi.org/10.1016/j.enbuild.2020.110011.

Florianópolis, February 23th, 2023.

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Luiza de Castro: GOV.BR

This document attests all the co-authors of the article entitled "Achieving mid-rise NZEB offices in Brazilian urban centres: A control strategy with desk fans and extension of set point temperature", AGREE with the use of this article in the Doctoral thesis of Maíra Afonso de André (first author), supervised by Professor Roberto Lamberts from the Graduate Program of Civil Engineering (PPGEC) at the Federal University of Santa Catarina (UFSC). Published in Energy and Building: https://doi.org/10.1016/j.enbuild.2022.111911.

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Florianópolis, November 10th, 2022.

Karol Bandurski: ______________ Arkasama Bandyopadhyay: ______________

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Jakob Hahn: ______________

Michael Kane: ______________ Carola Lingua: ______________

Benedetta Pioppi: ______________ Cristina Piselli: ______________

ANNEX A – Paper 4 Interview Script

Occupant Centric Building Design and Operation

An Interview Regarding Occupant Sensing Technologies and their Usage

Developed by IEA EBC Annex 79 – Occupant-Centric Building Design and Operation

This interview questionnaire is intended for facility managers, energy managers, and building operators. The goal is to identify common occupant sensing technologies for energy management, determine how these technologies are used and supplemented with operator expertise, and define white space for future R&D. This questionnaire is intended to guide an in-person or phone interview. Questions in **green** are intended for later quantitative analysis. The responses from these interviews will then guide the adaptation of the questions into an online survey to engage a broader audience.

1. Introduction
   - ✓ Review and sign consent form. Every question is optional.
   - ✓ Identify and start any recording equipment.
   - ✓ Record interview metadata:
     - Country and city of interviewee
   - ✓ Discuss the purpose of this interview:

     "You were selected for this interview as an operator of building energy systems. This interview is part of an international series of interviews conducted under the International Energy Agency's Annex 79 – *Occupant-Centric Building Design and Operation*. The goal of these surveys is to understand how you, and other operators, understand the needs of the building occupants, and adapt the response of the building accordingly."
2. Operator Information

Questions	Possible Answers
1. What is your title?	• Facility manager • Energy manager • Building operator • General manager • Other: ________

Questions	Possible Answers
2. Please describe your experience/credentials that you find most relevant to this job.	• Union training • 2-year degree • X years of experience
3. How often are you personally occupying (each/the) building(s) you manage?	• All working hours • Less than half of each business day • Less • Upon request, which occurs daily/weekly/monthly
4. Do your own personal demands for comfort effect how you manage the building.	• No. I'm not in the building enough to care. • My office is in poorly conditioned basement, so I feel separated for the work I do to make others comfortable. • I regularly change the setpoint, setbacks, and schedules to meet my own demands for comfort because I can detect an irregularity before a complaint call comes in.
5. What are the top 2 goals that drive your operational decisions?	<u>Dropdown list</u> • Occupant comfort • Energy savings • Energy cost savings • GHG reductions • Ease of operation • Reducing equipment cycling • Reducing occupant complaints • Standard operating procedure / legal requirements
6. What two sources of information help you most in achieving these goals?	• Conversations with occupants • Case management system • Sensor data from X • Gut feeling • Utility bills • 3rd party contractors • My boss • My subordinates

Questions	Possible Answers
7. Describe the building(s) you manage in terms of number of buildings, use, size, and number of occupants. HVAC system type: CAV, VAV, hydraulic. (photo)	• I manage 5 schools across town varying in size from 10k sqft to 100k sqft and 100 ppl to 2,000 ppl. • I only manage one building, a 20 unit apartment building with about 30 ppl.

If the interviewee manages more than one building or facility, then have them **focus on one building** in their portfolio that best characterizes a typical building.

3. Building Occupants

Questions	Possible Answers
8. How comfortable do the building occupants seem to be?	Dropdown list • Very comfortable • Comfortable • Neutral • Uncomfortable • Very uncomfortable • Don't know/care
9. How well do you feel that you understand the needs of building occupants?	Dropdown list • Very well • Well • Neither well or poorly • Poorly • Very poorly

Questions	Possible Answers

10. Describe the most typical ways users make their space a more comfortable?
 	
(photo)
	• Users have no way of changing the indoor temperature.
	• Thermostats:
	  ○ There is a thermostat for every two offices, so they can work out what temperature works for them.
	  ○ In most areas, there’s only one thermostat for every 20 people, so we just put a lock box over the dial.
	  ○ Most of the thermostats are broken (pneumatic system?)
	• Phone calls – I get phone calls all the time and try my best to remember them when I’m back in the mechanical room adjusting settings.
	• Online forms/apps
	  ○ The new case management app is great. I see the complaints right away and can often quickly fix issues.
	  ○ There’s an online form, but I only really check it once a month.
	• Word of mouth – if things get really bad in the spring, people eventually walk up to me in the halls and complain.
	• Windows – they can open windows, but it really messes with the system.

11. In what ways do you restrict how users can adjust the indoor temperature?	• Locking windows • Locking thermostats • Thermostats changes are limited to ±2° • Their only input is through phone calls
12. If so, why? Can you provide a relevant anecdote?	• We had to lock the thermostat when two users kept fighting over the setpoint causing our compressors to cycle too much. • We gave up on occupancy sensors when most of them were covered in masking tape. • Restrictions were part of the design, e.g., non-operable windows and no/locked thermostats

Questions	Possible Answers
13. Does your building have occupancy sensors or CO_2 sensors? If so, how many are there and how are they used?	• Lighting vs HVAC • Motion detectors – used for occupancy driven setback schedules (and ventilation rates) • WiFi-based occupancy sensors • People counting cameras • Submeters for plug and lighting loads • CO_2 sensors – used by BMS to automatically determine ventilation rate. • Badge access cards
14. What is the most frequent complaint type you receive regarding the heating, cooling, and air quality of the facility?	• too hot in the summer, too cool in the summer • too hot in the winter, too cool in the winter • discomfort in spring and fall • Air draft • Stuffiness, lack of adequate ventilation
15. When do these complaints typically occur?	• morning, afternoon, evening • fall, winter, spring, summer • the week of switchover to cooling where conditions are miserably hot, and people can't even open windows. • After or during vacations
16. How often do you communicate (e.g., in-person or surveys) with building occupants about your job?	Dropdown list • Daily • Weekly • Monthly

4. Building Control Systems and Sequences

Questions	Possible Answers
17. Please describe the building automation system (BAS)**, if applicable. What features are most important to you? How old is it? Does it manage lighting and/or plug loads? Is data archived?** **(photo)** **If there is no BAS, skip Q18.**	• There is no BAS • I don't know much about the BAS. The installer set it up, so I try not to change things. • The BAS makes my job so much easier. I can see which zones are occupied, make sure the schedules are set correctly, and adjust everything from setpoints to the condenser temperature.

Questions	Possible Answers
18. How *could* you use 'real-time' or archived information from the BAS to make occupants more comfortable? Which of these methods do you utilize?	• The BAS automatically adjusts setbacks and ventilation rates based on the occupancy sensors. • Once a month I look over the data from the occupancy sensors and try to fix the setback schedules • I think the BAS keeps track of the occupancy sensor data, but I've never really looked. • Anticipating complaint tickets
19. Describe the typical start and stop schedules of temperature setpoints and ventilation rates? How are these schedules changed for occupant schedules, seasons, or special events?	• We use setbacks from 7pm to 7am based off, off conservative schedules, but we can't control ventilation rates. • The BAS takes care of everything based on the thermostats and occupancy sensors. I don't understand it well enough to change anything though. • We don't use any schedules.
20. How would you rate the energy efficiency of the building?	Dropdown list: • Exceptionally high energy efficiency • Above average energy efficiency • Average energy efficiency • Below average energy efficiency • Exceptionally low energy efficiency

5. Conclusion

Questions	Possible Answers
21. Describe non-technical (e.g., inter-personal, organizational**) challenges in improving energy efficiency in your facility?**	• Too much bureaucracy to get funding to install useful occupant sensors • Organizational challenges inhibiting information flow
22. What is the most important information that you wish you had access to regarding occupants and occupant comfort? How would you benefit from having access to this information?	• E.g., Occupancy counts, data for typical arrival / departure times, temperatures that minimize thermal complaints, etc. • Occupancy sensors are just too noisy. We need sensors that accurately measure occupancy to set schedules better. • Would it be possible to better predict when rooms are occupied? We need it to set schedules better.