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CONFORTO TÉRMICO HUMANO EM EDIFICAÇÕES DE ESCRITÓRIOS LOCALIZADAS NO CLIMA SUBTROPICAL ÚMIDO DE FLORIANÓPOLIS/SC

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Esta Tese foi julgada adequada para obtenção do Título de "Doutor em Engenharia Civil", e aprovada em sua forma final pelo Programa de Pós-Graduação em Engenharia Civil.

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RESUMO

O objetivo deste trabalho é estudar a percepção térmica de ocupantes nos diferentes modos de operação de edificações de escritórios com ventilação híbrida e com sistema central de condicionamento artificial, localizados no clima subtropical úmido de Florianópolis/SC. Estudos de campo sobre conforto térmico foram realizados durante dois anos em quatro edificações de escritórios localizadas em Florianópolis. Três edificações operaram com a estratégia de ventilação híbrida, equipadas com sistema de ar-condicionado para resfriamento e janelas operáveis, ambos controlados pelos ocupantes de acordo com suas preferências. A quarta edificação operou com sistema central de ar-condicionado. Por meio de estações microclimáticas foram realizadas medições ambientais no mesmo local e ao mesmo tempo em que questionários de conforto térmico foram aplicados. Os estudos de campo, realizados nas quatro edificações e em todas as estações do ano, resultaram em mais de 7500 respostas aos questionários, associadas a variáveis ambientais e humanas. Os dados coletados foram analisados estatisticamente. Foram realizadas comparações entre as respostas subjetivas dos usuários e os modelos analítico e adaptativo da ASHRAE 55. Devido aos diferentes modos de operação das edificações com ventilação híbrida, verificou-se a necessidade de um modelo de conforto térmico específico para este tipo de edificação e modelos de conforto térmico adaptativo foram desenvolvidos para o modo de ventilação natural e durante a operação do sistema de ar-condicionado. Além disso, investigou-se a relação entre diferentes variáveis contextuais, como idade, gênero, peso e altura, e a percepção de conforto térmico dos usuários. As principais conclusões desta tese são: 1) o modo de operação atuante em edificações de escritórios com ventilação híbrida e com sistema central de ar-condicionado influencia na percepção de conforto térmico dos ocupantes, 2) não se encontrou evidências para justificar o desenvolvimento de um modelo adaptativo de conforto térmico específico para as edificações com ventilação híbrida. Os usuários das edificações com ventilação híbrida, operando no modo de ventilação natural, adaptaram-se às variações de temperatura interna, de acordo com a teoria de conforto térmico adaptativo; durante a operação do sistema de ar-condicionado os ocupantes estiveram desconectados do clima exterior, 3) diferentes grupos de pessoas requerem diferentes condições térmicas para sentirem-se em conforto térmico.

Palavras-chave: conforto térmico, ventilação híbrida, estudos de campo, modelo adaptativo.

ABSTRACT

The objective of this work is to study occupant's thermal perception in the different modes of operation of mixed-mode and centralized air-conditioned office buildings located in the humid subtropical climate of Florianópolis/SC. Field studies on thermal comfort were conducted during two years in four office buildings located in Florianópolis. Three buildings operated with a mixed-mode strategy and were equipped with air-conditioning systems for cooling and operable windows, both controlled by users according to their preferences. The other building operated with a centralized air-conditioning system. Environmental variables were measured using microclimate instruments at the same location and time that thermal comfort questionnaires were collected. The field studies performed in the four buildings over the four seasons resulted in more than 7,500 questionnaire responses associated to environmental and human variables. The data collected were statistically analysed. Comparisons between user's subjective responses and analytical and adaptive models of ASHRAE 55 were carried out. Due to the different operation modes of the mixed-mode buildings, it was verified the need for a specific thermal comfort model for this type of building and adaptive thermal comfort models were developed for the natural ventilation mode and during the operation of the air-conditioning system. Furthermore, the relationship between different contextual variables, such as age, gender, weight and height, and occupant's thermal comfort perception was also investigated. The main conclusions obtained from this thesis are: 1) the operating mode in mixed-mode and in centralized air-conditioned office buildings influences occupant's thermal comfort perception, 2) no evidence was found to justify the development of an adaptive model of thermal comfort specific for mixed-mode buildings. The users of the mixed-mode buildings operating in the natural ventilation mode adapted to the indoor temperature variations, according to the adaptive thermal comfort theory; during the operation of the air-conditioning system the occupants were disconnected from the outdoor climate, 3) different groups of people require different thermal conditions to be in thermal comfort.

Keywords: thermal comfort, hybrid (mixed-mode) ventilation, field study, adaptive model.

SUMÁRIO

1. INTRODUÇÃO

As edificações (setores residencial, comercial e público) consomem entre 20 e 40% do dispêndio final total de energia nos países desenvolvidos, sendo que metade desta energia é consumida pelos sistemas de ar-condicionado (PÉREZ-LOMBARD; ORTIZ; POUT, 2008). De modo global, como a maior parte da energia utilizada nas edificações é gerada através de fontes não renováveis, o consumo tende a aumentar a poluição atmosférica e contribui para as mudanças climáticas (GAN, 2000).

No Brasil, a parcela do consumo final de energia das edificações é um pouco menor (14,6%) (BEN, 2017). As edificações brasileiras consomem 42,8% do dispêndio total de eletricidade[1] do país (BEN, 2017) e nos setores comerciais e públicos, aproximadamente 50% desta energia é destinada aos sistemas de ar-condicionado (PROCEL, 2007), o que é semelhante aos dados apresentados em escala mundial.

O elevado consumo de energia com sistemas de ar-condicionado é, em grande parte, devido ao controle uniforme e constante da temperatura interna nos espaços, independentemente da localização geográfica do edifício, o que, conforme está sendo demonstrado na literatura, não é realmente necessário para garantir condições de conforto térmico (HOYT et al., 2009; ARENS et al., 2010). A mudança de paradigma

[1] A oferta interna de energia elétrica brasileira é predominantemente renovável, representando 81,7% da total (a energia hidráulica responde por 68,1%) (BEN, 2017). Porém, conforme observado durante a crise hídrica de 2014/2015, principalmente na região Sudeste, quando há limitação do potencial de geração hidroelétrica, as usinas termoelétricas, movidas a derivados de petróleo, entram em operação, elevando os custos de geração de energia e aumentando a poluição atmosférica (CERQUEIRA et al., 2015).

causada pela abordagem adaptativa[2], com relação ao modelo analítico de conforto térmico, trouxe à tona os aspectos sociais, culturais e comportamentais humanos, características interdependentes ao lugar (além do clima). As pessoas começaram a ser vistas como ativas (e não passivas, conforme o modelo analítico de conforto térmico[3]) atuando de modo a buscar o conforto térmico em seus ambientes térmicos, por exemplo, por meio da adaptação de vestimenta ou uso de controles (operação de janelas, uso de condicionamento artificial ou ventilação mecânica) (NICOL; HUMPHREYS, 1973; 2002; 2010; AULICIEMS, 1981; HUMPHREYS; NICOL, 1998; DE DEAR; BRAGER, 1998; HUMPHREYS; RIJAL; NICOL, 2013). Os ambientes homogêneos e estáticos, antes preferidos, levando à monotonia térmica (HEALY, 2008) e a um custo energético

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[2] O modelo adaptativo é baseado em estudos de campo em edificações ventiladas naturalmente conduzidas por Nicol e Humphreys (1973, 2002, 2010), Auliciems (1981), Humphreys e Nicol (1998), de Dear e Brager (1998) e Humphreys, Rijal e Nicol (2013). De acordo com o modelo adaptativo, as temperaturas de conforto variam conforme o clima externo (temperaturas externas mais elevadas permitem maiores temperaturas internas e vice-versa) (NICOL; HUMPHREYS; ROAF, 2002) A relação adaptativa pode ser considerada como um modelo de caixa preta: o sinal de entrada é o clima e a saída é a temperatura interna de conforto. Os processos internos da caixa preta dependem dos aspectos construtivos da edificação, das variáveis ambientais e humanas (incluindo o balanço de calor do corpo), dentre outros. Porém, nenhum desses processos internos precisam ser conhecidos para estimar-se a temperatura de conforto (HUMPHREYS; NICOL; ROAF, 2016).

[3] O modelo analítico de conforto térmico foi proposto por Fanger em 1970 utilizando-se de estudos em câmaras climáticas e baseado no balanço de calor do corpo humano (FANGER, 1970). O modelo de Fanger tem como objetivo predizer a sensação térmica média de um grupo de pessoas e a respectiva porcentagem predita de insatisfeitos com o ambiente térmico, expressos pelos índices PMV e PPD - *Predicted Mean Vote e Predicted Percentage Dissatisfied* (Voto Médio Predito e Porcentagem Predita de Insatisfeitos). O PMV é calculado através de seis variáveis: metabolismo (met), isolamento de vestimenta (clo), temperatura do ar interna (ºC), temperatura média radiante interna (ºC), velocidade do ar interna (m/s) e umidade relativa do ar interna (%). O PPD é dependente do PMV (FANGER, 1970).

elevado, estão cedendo espaço para ambientes mais dinâmicos, nos quais faixas mais amplas de temperaturas internas são preferidas pelas pessoas e a ventilação natural é desejada. O ar-condicionado para resfriamento ambiental somente seria usado quando necessário (HOYT et al., 2009) e poderia ser combinado com estratégias de condicionamento personalizado (VESELÝ; ZEILER, 2014; ZHANG; ARENS; ZHAI, 2015), com o intuito de proporcionar aos ocupantes maior grau de controle sobre seu microclima, adequando-se as suas preferências individuais (JACQUOT et al., 2014).

Em condições térmicas favoráveis, a ventilação natural poderia ser empregada para remover a carga térmica dos edifícios (WOODS; FITZGERALD; LIVERMORE, 2009), principalmente em clima subtropical caracterizado por invernos amenos e temperaturas exteriores mais baixas que as interiores na maior parte do ano (LIN; CHUAH, 2011). Através do movimento do ar em climas ou estações quentes, pode haver melhora das sensações de conforto térmico e maiores temperaturas internas podem ser aceitáveis pelos ocupantes de edifícios ventilados naturalmente (CÂNDIDO; DE DEAR; LAMBERTS, 2011; HUANG et al., 2013). Desta maneira, o uso de sistemas mecânicos de climatização somente seria necessário durante os períodos do dia ou do ano em que a ventilação natural não fosse suficiente para garantir conforto térmico aos ocupantes dos edifícios, devido às condições externas ou internas (alta temperatura do ar exterior, baixa velocidade do ar no interior, alta carga térmica interna, insuficiente ventilação – aberturas fechadas – causada por alto ruído exterior ou poluição) (BARCLAY; KANG; SHARPLES, 2012). Os sistemas mecânicos seriam utilizados para melhorar a distribuição do ar interior e aquecer e/ou resfriar o ar (BRAGER; BORGESON; LEE, 2007; LOMAS; COOK; FIALA, 2007). Esta estratégia que utiliza a integração entre a ventilação natural e o sistema mecânico de climatização é denominada ventilação híbrida ou modo misto (*hybrid ventilation* ou *mixed-mode*, em inglês). É provável que, em um futuro próximo, mais edifícios com ventilação híbrida existirão devido às mudanças climáticas - no Reino Unido há uma crescente preocupação com relação a isso porque muitos edifícios que operam com ventilação natural durante o verão poderão vir a necessitar de resfriamento no futuro (ROETZEL; TSANGRASSOULIS, 2012). Alguns consideram este tipo de edifício como o modelo de sustentabilidade do futuro (HOLMES; HACKER, 2007).

Muitas pesquisas estudaram edifícios com ventilação híbrida tendo como objetivo: (i) analisar o potencial de economia de energia em diferentes climas (apresentando economias de energia de 30-35% com relação a edifícios com ar-condicionado) (BRANDÃO et al., 2008; JI; LOMAS; COOK, 2009; KARAVA et al., 2012; RUPP; GHISI, 2013); (ii) utilizar previsões climáticas e/ou diferentes cenários para avaliar o impacto no consumo de energia (HANBY; SMITH, 2012; ROETZEL; TSANGRASSOULIS, 2012); (iii) estudar o comportamento do usuário e estratégias de controle (alguns trabalhos trataram de algoritmos de controle para as aberturas, em função das temperaturas do ar exterior e interior – ventilação noturna – de modo a proporcionar conforto térmico e minimizando o consumo de energia) (BORGESON; BRAGER, 2008; BRAGER; BORGESON; LEE, 2007; MAY-OSTENDORP et al., 2011; RIJAL; HUMPHREYS; NICOL, 2009; SPINDLER; NORFORD, 2009); (iv) avaliar a expectativa e satisfação do usuário (BRAGER; BAKER, 2009; DEUBLE; DE DEAR, 2012; KIM; DE DEAR, 2012; KORANTENG; MAHDAVI, 2011), demonstrando que, de modo geral, os edifícios com ventilação híbrida têm desempenho superior a edifícios com ar-condicionado, principalmente com relação a conforto térmico e qualidade do ar interior (BRAGER; BAKER, 2009); (v) analisar o desempenho térmico da estratégia híbrida de ventilação por meio de simulação computacional (EL MANKIBI et al., 2006; TOVAR; LINDEN; THOMAS, 2007; ZHAI; JOHNSON; KRARTI, 2011; RUPP; GHISI, 2014; 2017).

Comparativamente a pesquisas realizadas em edificações com sistema de ar-condicionado ou ventiladas naturalmente, estudos de campo referentes a conforto térmico em edifícios com ventilação híbrida, envolvendo aplicação de questionários concomitantemente à medição das condições térmicas internas, ainda são escassos, apesar do recente interesse pelo assunto (ROWE, 2004; BRAGER; BAKER, 2009; DRAKE et al., 2010; DEUBLE; DE DEAR, 2012; KIM; DE DEAR, 2012; INDRAGANTI; OOKA; RIJAL, 2013; INDRAGANTI et al., 2014; LUO et al., 2015; MANU et al., 2016; BARBADILLA-MARTÍN et al., 2017; OROPEZA-PEREZ; PETZOLD-RODRIGUEZ; BONILLA-LOPEZ, 2017; DE VECCHI et al., 2017; TAKASU et al., 2017). A maioria dos pesquisadores que estudaram o conforto térmico em ambientes com ventilação híbrida conduziu suas análises divididas por modo de operação (ar-condicionado e ventilação natural). A maioria dos trabalhos apontou para o uso do modelo adaptativo durante os períodos de ventilação natural e para o uso do modelo analítico (com e sem ajustes) durante a operação do ar-condicionado. Porém, em outros trabalhos foram desenvolvidos modelos específicos de conforto térmico adaptativo para aplicação em edificações com ventilação híbrida, independentemente do modo de operação atuante (MANU et al., 2016; BARBADILLA-MARTÍN et al., 2017). Alguns autores concluem que mais pesquisas são necessárias para entender como as pessoas percebem este tipo de edifício e se um método de conforto térmico específico é (ou não) necessário (ROWE, 2004; BRAGER; BAKER, 2009; DEUBLE; DE DEAR, 2012; DRAKE et al., 2010; KIM; DE DEAR, 2012; LUO et al., 2015). Como de Dear et al. (2013, p.12, tradução nossa) observam: “Do ponto de vista do conforto térmico, edifícios com ventilação híbrida levantam questões teóricas e regulamentares interessantes devido à ‘dualidade de expectativas de conforto’ que estes induzem em seus ocupantes.”. Apesar disso, a norma ASHRAE 55 (2013; 2017) avalia os edifícios com ventilação híbrida por meio do modelo analítico, independentemente do modo de operação atuante (ventilação natural ou ar-condicionado), o que é uma abordagem bem conservadora e que necessita ser revista.

Em edifícios com ventilação híbrida os ocupantes estão em contato com dois modos de operação (ar-condicionado e ventilação natural) e assim podem perceber diferentes sensações durante cada modo de operação e suas preferências térmicas também podem ser distintas. Edifícios com ventilação híbrida podem ser agrupados em três categorias dependendo da estratégia de operação utilizada (BRAGER; BORGESON; LEE, 2007):

• alternante (*change-over*): a ventilação natural e o sistema mecânico de climatização operam no mesmo espaço e são alternados durante o dia ou durante as diferentes estações;

• concorrente: a ventilação natural e o sistema de ar-condicionado são utilizados ao mesmo tempo e no mesmo espaço;

• zonal: a ventilação natural é utilizada em alguns espaços de um edifício ao mesmo tempo em que o sistema mecânico é utilizado em outros).

Em cada um destes tipos de edifícios com ventilação híbrida, uma infinidade de estratégias de controle manual e/ou automatizado (quando é permitido abrir as janelas, qual a temperatura de *setpoint* do sistema de ar-condicionado, quanto a temperatura e a umidade interior podem variar, como é a distribuição do ar interior) podem ser implementadas. Desse modo, a percepção dos ocupantes pode variar amplamente. A maior parte dos trabalhos sobre edifícios com ventilação híbrida foram realizados em edificações com automação da alternância entre a ventilação natural e o ar-condicionado, o que impôs uma série de restrições aos usuários (impossibilidade de acionar o ar-condicionado, por exemplo). Essas restrições podem ter afetado as respostas subjetivas das pessoas. Poucos estudos de campo em edificações com ventilação híbrida, principalmente onde múltiplos usuários compartilham o mesmo espaço e estes possuem a opção de controle manual da alternância entre o ar-condicionado e a ventilação natural, foram realizados até o momento. Nestas condições, o uso do sistema de ar-condicionado é visto pelos ocupantes como mais uma oportunidade adaptativa à disposição na busca por conforto térmico. Mais estudos de campo sobre conforto térmico em edifícios com ventilação híbrida, onde a alternância entre a ventilação natural e o uso de ar-condicionado é feita manualmente pelos usuários, são requeridos para uma melhor compreensão da complexa relação pessoa-ambiente.

No Brasil, devido ao limitado número de estudos de campo realizados em edificações, não existe uma norma ou guia de conforto térmico[4] utilizando-se de dados nacionais, a exemplo de outros países que possuem maiores informações provenientes de estudos de campo, por exemplo: ASHRAE 55 (2013; 2017) nos EUA, EN 15251 (2007) na Europa, van Der Linden et al. (2006) na Holanda, Li et al. (2014) na China, Indraganti et al. (2014) e Manu et al. (2016) na Índia. O modelo de conforto térmico adaptativo da norma americana ASHRAE 55 (2013; 2017) considera uma série de climas e tem sido utilizado como referência internacional quando da não existência de uma norma nacional. O modelo adaptativo utilizado na ASHRAE 55 foi derivado do banco de dados da ASHRAE RP-884 (DE DEAR; BRAGER; COOPER, 1997), o qual contém em torno de 21 mil respostas subjetivas de conforto térmico, oriundas de estudos de campo em 160 edifícios de escritórios localizados no Reino Unido, EUA, Canadá, Tailândia, Austrália, Paquistão, Grécia e Singapura. A maioria dos dados em edificações ventiladas naturalmente foi obtida durante o verão ou em climas quentes (DE DEAR; BRAGER; COOPER, 1997; DE DEAR; BRAGER, 1998), ou seja, condições térmicas diferentes das encontradas nas edificações de escritórios do clima subtropical do Brasil. No clima subtropical brasileiro, as edificações de escritórios normalmente operam com sistema de ar-condicionado no verão ou em períodos mais aquecidos e utilizam a ventilação natural nos demais períodos do ano – não é comum o uso de aquecimento artificial. Devido a este contexto único, modelos adaptativos de conforto térmico deveriam ser desenvolvidos para este clima no Brasil.

Outra limitação dos modelos de conforto térmico existentes na ASHRAE 55, é que estes são considerados válidos para qualquer pessoa (apesar dos modelos indicarem zonas de conforto térmico para 80% ou 90% de conforto/aceitabilidade

[4] Existe uma proposta de norma brasileira de conforto térmico (CÂNDIDO et al., 2011; LAMBERTS et al., 2013) baseada na ASHRAE 55 de 2010. Apesar de ser importante existir um documento em português que estabeleça condições térmicas aceitáveis para edificações brasileiras com caráter normativo, é importante que mais estudos de campo sobre conforto térmico sejam realizados no Brasil. Assim, modelos de conforto térmico específicos para a realidade climática nacional poderiam ser desenvolvidos e aplicados.

térmica, estes não discriminam quais grupos de usuários não estariam em conforto ou não estariam aceitando as condições térmicas). Porém, diferentes grupos de pessoas podem ter diferentes percepções térmicas. Pesquisas têm estudado a influência de diferentes variáveis contextuais, tais como o gênero, idade, composição corporal e histórico térmico[5], no conforto térmico. De modo geral, os estudos concluem que:

1) Gênero: as mulheres são mais sensíveis a variações de temperatura do que os homens, preferem condições mais aquecidas e reportam com maior frequência estarem em desconforto térmico (CHOW et al., 2010; LAN et al., 2008; CHOI; AZIZ; LOFTNESS, 2010; CHOI; LOFTNESS; AZIZ, 2012; SCHELLEN et al., 2012; 2013; KARJALAINEN, 2012; KINGMA; FRIJNS; VAN MARKEN LICHTENBELT, 2012; KIM et al., 2013; DE VECCHI, 2015; MAYKOT; RUPP; GHISI; 2018);

2) Idade: os idosos são mais sensíveis a variações de temperatura em comparação a adultos jovens (SCHELLEN et al., 2010; KINGMA; FRIJNS; VAN MARKEN LICHTENBELT, 2012);

3) Composição corporal: pessoas acima do peso preferem condições térmicas mais resfriadas que pessoas com peso normal (KINGMA; FRIJNS; VAN MARKEN LICHTENBELT, 2012; LEITES et al., 2013; FADEYI, 2014; DE VECCHI, 2015). Em estudos de campo esta variável é usualmente investigada por meio do índice de massa corpórea (IMC) que relaciona o peso e a altura;

4) Histórico térmico: pessoas previamente (aos estudos de campo ou em câmara climática) expostas a: a) condições de temperaturas mais elevadas expressaram sensações térmicas tendendo mais ao lado negativo (frio) da escala sétima de sensação térmica, do que pessoas expostas previamente a temperaturas mais baixas (CHUN et al., 2008; YU et al., 2013), b) ambientes com ar-condicionado (resfriamento) sentiram-se mais aquecidas (CHUN et al., 2008) e preferiram estar mais resfriadas

[5] De acordo com a teoria de conforto adaptativo (HUMPHREYS; NICOL, 1998; DE DEAR; BRAGER, 1998), o conforto térmico também pode ser influenciado pelo histórico térmico das pessoas (as condições térmicas nas quais as pessoas foram recentemente submetidas, além das condições no momento de aplicação de questionários de conforto térmico).

(CÂNDIDO et al., 2010) que pessoas não expostas ao ar-condicionado.

Entretanto, apesar dos estudos indicarem diferenças na percepção de conforto térmico entre diferentes grupos de pessoas, o impacto das diferentes variáveis contextuais nos limites de temperatura da zona de conforto térmico ainda necessita ser investigado levando em consideração estudos em campo.

1.1 OBJETIVOS

1.1.1 Objetivo geral

O objetivo deste trabalho é estudar a percepção térmica de ocupantes nos diferentes modos de operação de edificações de escritórios com ventilação híbrida e com sistema central de condicionamento artificial, localizados no clima subtropical úmido de Florianópolis/SC.

1.1.2 Objetivos específicos

No decorrer deste trabalho pretende-se alcançar alguns objetivos específicos:

- Examinar a adequabilidade de modelos existentes de conforto térmico (tanto analítico quanto adaptativo) para aplicação em edificações de escritórios localizadas no clima subtropical úmido;

- Identificar relações entre a temperatura predominante externa e as temperaturas operativas internas de neutralidade térmica (modelo adaptativo de conforto térmico) para cada modo de operação em edificações com ventilação híbrida;

- Verificar a necessidade de um modelo de conforto térmico específico para descrever a percepção térmica dos usuários de edificações operando com ventilação híbrida;

- Investigar a relação entre variáveis contextuais (gênero, idade, peso e altura, histórico térmico e estratégia de ventilação – ventilação híbrida ou ar-condicionado central) e a percepção de conforto térmico de usuários em edificações de escritórios.

1.2 ESTRUTURA DO TRABALHO

A estrutura deste trabalho é diferente do formato convencional. A estrutura desta tese consiste em cinco capítulos: o **primeiro capítulo** tem caráter introdutório, apresentando as justificativas do trabalho, o objetivo geral e os objetivos específicos e a estrutura da tese. O **segundo capítulo** apresenta a revisão da literatura sobre conforto térmico humano no ambiente construído em formato de artigo, publicado na revista *Energy and Buildings* (portanto, o artigo é apresentado em inglês). As teorias de Fanger (modelo analítico) e de conforto adaptativo são discutidas, considerando sua inserção nas normas de conforto térmico. Experimentos em câmaras climáticas e estudos de campo em edificações reais operando com ventilação natural, sistema de ar-condicionado e ventilação híbrida foram considerados, os quais abordaram uma série de tópicos de pesquisa, por exemplo: 1) modelos de conforto térmico para edificações com ventilação híbrida e 2) a influência da idade, peso e altura, gênero, histórico térmico, dentre outros, no conforto térmico. Este artigo serviu como base teórica para o desenvolvimento desta tese.

O **terceiro capítulo** trata do método da pesquisa. O **quarto capítulo** apresenta dois artigos publicados na revista *Energy and Buildings* e um publicado na revista *Building and Environment* - cada artigo está relacionado a um ou mais de um dos objetivos da tese.

No quarto capítulo os três artigos são apresentados em inglês conforme os requisitos para a publicação nos periódicos. O **primeiro artigo** examina a adequabilidade dos modelos analítico e adaptativo presentes na ASHRAE 55 para aplicação em edificações de escritório com sistema de ar-condicionado central e com ventilação híbrida, localizadas no clima subtropical úmido de Florianópolis. As respostas subjetivas foram coletadas, por meio de estudos de campo de conforto térmico durante o ano de 2014, em três edificações: uma equipada com sistema de ar-condicionado central e as outras duas operando com ventilação híbrida. Os 2589 votos de sensação térmica e de aceitabilidade térmica dos usuários foram comparados com os modelos preditivos.

O **segundo artigo** investiga a influência do modo de operação de edificações com ventilação híbrida nas respostas subjetivas das pessoas, avalia se a teoria de conforto adaptativo se aplica aos diferentes modos de operação e define modelos adaptativos para edificações com ventilação híbrida. O trabalho também apresenta a operação, por parte dos usuários, das edificações com ventilação híbrida ao longo das diferentes estações climáticas e investiga a relação entre os votos de sensação térmica e o desconforto térmico. Estudos de campo sobre conforto térmico em três edificações de escritórios com ventilação híbrida foram realizados durantes os anos de 2014 a 2016 e as 5470 respostas subjetivas associadas às variáveis ambientais e humanas foram analisadas de modo a atingir os objetivos deste trabalho.

O **terceiro artigo** estuda a associação entre variáveis contextuais (idade, gênero, peso e altura, histórico térmico e estratégia de ventilação) e a percepção de conforto térmico. O trabalho também determina faixas de aceitabilidade em função do gênero, idade e índice de massa corpórea. As análises foram realizadas considerando um banco de dados com 7564 respostas subjetivas associadas às variáveis ambientais e humanas. O banco de dados consiste nos resultados provenientes de estudos de campo de conforto térmico em quatro edificações (três operando com ventilação híbrida e uma com sistema de ar-condicionado central) entre os anos de 2014 e 2016.

O **quinto capítulo** é referente às conclusões gerais da tese. O primeiro, terceiro e quinto capítulos apresentam uma seção com as respectivas referências dos trabalhos citados naqueles capítulos.

1.3 REFERÊNCIAS DO CAPÍTULO 1

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2. REVISÃO DA LITERATURA

A revisão da literatura deste trabalho é apresentada na forma de um artigo de revisão, publicado na revista *Energy and Buildings* em 2015. Artigos mais recentes foram considerados quando da apresentação dos resultados deste trabalho no capítulo 4.

Neste artigo, foram abordados assuntos relacionados ao conforto térmico envolvendo estudos com seres humanos. Este artigo contribuiu para um melhor entendimento da área de conforto térmico e por meio da revisão foi possível identificar lacunas no conhecimento, incluindo a necessidade da realização de mais estudos de campo em edificações operando com ventilação híbrida.

Devido às exigências da Universidade Federal de Santa Catarina quanto à formatação da versão final da tese em formato A5, o artigo é apresentado em sua versão final, porém, sem a diagramação do próprio periódico internacional.

RUPP, R. F.; VÁSQUEZ, N. G.; LAMBERTS, R. A review of human thermal comfort in the built environment. **Energy and Buildings**, v. 105, p. 178–205, 2015. doi: 10.1016/j.enbuild.2015.07.047

Declaração de contribuição de coautores

Ricardo Forgiarini Rupp: como primeiro autor, Ricardo participou de todo o processo de revisão dos artigos e redação deste artigo de revisão.

Natalia Giraldo Vásquez: como coautora, Natalia participou no processo de revisão dos artigos e redação deste artigo de revisão.

Roberto Lamberts: como coautor, Roberto supervisionou todo o processo de produção do artigo e contribuiu para a organização dos artigos revisados em tópicos. O artigo também foi revisado e editado por Roberto.

A review of human thermal comfort in the built environment

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Abstract
The aim of this paper is to review the literature on human thermal comfort in the built environment. First an overview about the subject area is presented. This is followed by a review of papers published in the last 10 years that examine the various sub-areas of research related to human thermal comfort. Some remarkable works about both the Fanger’s and adaptive thermal comfort models are also discussed. This review does not contain simulation works and/or experimental studies without subjective results of people. As a result of the literature review, 466 articles were classified and grouped to form the body of this article. The article examines standards, indoor experiments in controlled environments (climate chamber) and semi-controlled environments, indoor field studies in educational, office, residential and other building types, productivity, human physiological models, outdoor and semi-outdoor field studies. Several research topics are also addressed involving naturally ventilated, air-conditioned and mixed-mode buildings, personalized conditioning systems and the influence of personal (age, weight, gender, thermal history) and environmental (controls, layout, air movement, humidity, among others) variables on thermal comfort.

Keywords: review; human thermal comfort; built environment.

INTRODUCTION

Urbanized areas worldwide have increased and according to the United Nations [1] it is expected that more than 70% of the world population will be located in urban centers by 2050. According to the world development indicators, 85% of the population will be located in developing countries in 2030 [2]. This growth is leading to an increase in the urban density of buildings, especially in the city center, thereby influencing the characteristics of indoor environments that increasingly rely on artificial systems to operate satisfactorily. The increased amount of time people spend inside buildings is significant. As architects and engineers think of ways to improve the user's environmental comfort while improving the performance of buildings, it is imperative they consider that people spend between 80% and 90% of their days indoors [3].

In developed countries, the building sector (residential, commercial and public) uses between 20% and 40% of final energy consumption [4]. Worldwide, buildings consume about 70% of final energy consumption through air-conditioning systems and artificial lighting [5]. The high energy consumption of air-conditioning is largely due to the uniform control of indoor temperature regardless of the building's location, yet as demonstrated in the literature, it is not really necessary to ensure thermal comfort [6]. Great energy savings could be achieved by allowing air-conditioning systems a wider range of indoor temperature fluctuation [6].

Specifically, thermal comfort and energy efficiency were the focus of multiple studies [7–16]. In recent years, the field of research in thermal comfort has attracted the attention of many researchers around the world, perhaps partially due to the increased public discussion about climate change. Overall thermal comfort and the assessment of indoor environmental quality do not depend solely on physical parameters. The human body's physiological and psychological responses to the environment are dynamic and integrate various physical phenomena that interact with the space (light, noise, vibration, temperature, humidity, etc.) [17]. The specialization of existing standards to study and improve each of these environments (thermal, lighting and acoustics, etc.) is an example of the difficulty in the whole evaluation of environments. In the area of thermal comfort, the international standards commonly used to evaluate the thermal environments are ISO 7730-2005 [18], ASHRAE 55-2013 [19] and EN 15251-2007 [20].

Despite the difficulty of conducting a whole evaluation of environments (thermal, visual and acoustic), there are several studies that deal with the topic. The literature review performed by Frontczak and Wargocki [21] presents an analysis of the main conditions of the indoor environment, characteristics of users, design of buildings and outdoor climatic conditions that have a greater impact on the comfort and satisfaction of the indoor environment. The nine studies investigated by the authors included work carried out in various cities and with adults both in controlled environments and in the field [21]. In seven of the studies, users rated the thermal comfort as the most important condition for improving satisfaction with the indoor environment [21]. The authors of the studies [21] highlighted the importance of providing users with controls over indoor conditions to improve thermal comfort. It is important to note that there are differences in thermal acceptability for users of naturally ventilated buildings compared to users of buildings with air-conditioning [21]. In the former, users are more tolerant of indoor thermal conditions [21].

Thermal comfort is defined by ASHRAE 55 [19] as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. Thus, the vast majority of works in the area are carried out while people are awake, performing some activity and able to answer a questionnaire. However, there is also research dealing with thermal comfort during sleep [22–24] and brief reviews about thermal comfort for sleeping environments are found in the literature [25,26]. Other studies have shown the relationship between indoor climate and the quality of sleep [27–33], stating that the optimal thermal conditions for a good night's sleep are different from ASHRAE 55 [27,28]. For example, research indicates that in the summer indoor temperatures during sleep could be higher than those prescribed by ASHRAE 55. This is significant because it would result in a decrease of energy consumption [28].

In this work, we aim to conduct a review of thermal comfort in the built environment. In order to know the breadth of this research area, we searched for the term “thermal comfort” in four electronic databases: Google Scholar, Web of Science, Scopus and ScienceDirect.

RESULTS OF LITERATURE SEARCH

The results of the literature search carried out on 11/25/2014 with the term "thermal comfort" in Google Scholar, Web of Science, Scopus and ScienceDirect are presented in Table 1. Table 1 also shows the search mode, the chosen sort type and the meaning of classification for the four search engines.

Among the four databases used, ScienceDirect is the only one that does not provide the option to sort the search results by articles with greater impact; it is possible only to sort by year or relevance. When sorted by relevance in ScienceDirect, articles are ranked in order of occurrence of the search term in each article, i.e., the first article listed is the one in which the search term appears most frequently in the document. Google Scholar sorts articles by means of an algorithm considering factors such as number of citations, authors and publisher. Meanwhile Web of Science and Scopus sort the results by number of citations. Thus, Tables 2-4 show the top 10 documents in Google Scholar, Web of Science and Scopus databases, disregarding work on phase-change materials, heat stress and cold stress.

Table 1: Results for general literature search on thermal comfort in different databases.

Parameter/ database	Google Scholar	Web of Science	Scopus	Science Direct
Number of results	59,800	5,979	8,302	2,285
Search in	All (not optional)	Title, abstract and keywords	Title, abstract and keywords	Title, abstract and keywords
Sort type	Relevance (not optional)	Number of citations	Number of citations	Relevance
Meaning of classification	Considers publisher, authors, number of citations, recent citations	Highest number of citations	Highest number of citations	Highest occurrence of search term

Table 2: Top 10 documents (out of 59,800) of thermal comfort in Google Scholar.

Google Scholar					
Top 10	**Article title**	**Authors**	**Year**	**Published in**	**Nº of citations**
1	Thermal comfort. Analysis and applications in environmental engineering	PO Fanger	1970	Danish Technical Press	4690
2	Comfort and thermal sensations and associated physiological responses at various ambient temperatures	AP Gagge, JAJ Stolwijk, JD Hardy	1967	Environmental research	474
3	Developing an adaptive model of thermal comfort and preference	R de Dear, GS Brager	1998	ASHRAE Transactions	828
4	Adaptive thermal comfort and sustainable thermal standards for buildings	JF Nicol, MA Humphreys	2002	Energy and Buildings	541
5	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	R de Dear, GS Brager	2002	Energy and Buildings	493
6	Thermal comfort of man in different urban environments	H Mayer, P Höppe	1987	Theoretical and Applied Climatology	309
7	Thermal comfort for free-running buildings	N Baker, M Standeven	1996	Energy and Buildings	160
8	Different aspects of assessing indoor and outdoor thermal comfort	P Höppe	2002	Energy and Buildings	233
9	Thermal comfort in outdoor urban spaces: understanding the human parameter	M Nikolopoulou, N Baker, K Steemers	2001	Solar Energy	245
10	Thermal comfort and psychological adaptation as a guide for designing urban spaces	M Nikolopoulou, K Steemers	2003	Energy and Buildings	236

Table 3: Top 10 documents (out of 5,979) of thermal comfort in Web of Science.

Web of Science					
Top 10	**Article title**	**Authors**	**Year**	**Published in**	**Nº of citations**
1	The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment	P Höppe	1999	International Journal of Biometeorology	269
2	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	R de Dear, GS Brager	2002	Energy and Buildings	220
3	Adaptive thermal comfort and sustainable thermal standards for buildings	JF Nicol, MA Humphreys	2002	Energy and Buildings	218
4	Thermal adaptation in the built environment: a literature review	GS Brager, R de Dear	1998	Energy and Buildings	215
5	Thermal comfort of man in different urban environments	H Mayer, P Höppe	1987	Theoretical and Applied Climatology	158
6	A model of human physiology and comfort for assessing complex thermal environments	C Huizenga, Z Hui, E Arens	2001	Building and Environment	129
7	A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia	J Spagnolo, R de Dear	2003	Building and Environment	128
8	Extension of the PMV model to non-air-conditioned buildings in warm climates	PO Fanger, J Toftum	2002	Energy and Buildings	118
9	Relative contribution of core and cutaneous temperatures to thermal comfort and autonomic responses in humans	SM Frank, SN Raja, CF Bulcao, DS Goldstein	1999	Journal of Applied Physiology	118
10	Thermal comfort in outdoor urban spaces: understanding the human parameter	M Nikolopoulou, N Baker, K Steemers	2001	Solar Energy	97

Table 4: Top 10 documents (out of 8,302) of thermal comfort in Scopus.

Scopus					
Top 10	**Article title**	**Authors**	**Year**	**Published in**	**Nº of citations**
1	Developing an adaptive model of thermal comfort and preference	R de Dear, GS Brager	1998	ASHRAE Transactions	341
2	The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment	P Höppe	1999	International Journal of Biometeorology	323
3	Adaptive thermal comfort and sustainable thermal standards for buildings	JF Nicol, MA Humphreys	2002	Energy and Buildings	322
4	Thermal adaptation in the built environment: a literature review	GS Brager, R de Dear	1998	Energy and Buildings	317
5	Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55	R de Dear, GS Brager	2002	Energy and Buildings	301
6	Comfort and thermal sensations and associated physiological responses at various ambient temperatures	AP Gagge, JAJ Stolwijk, JD Hardy	1967	Environmental research	235
7	The assessment of sultriness. Part I. A temperature-humidity index based on human physiology and clothing science	RG Steadman	1979	Journal of Applied Meteorology	228
8	Thermal comfort of man in different urban environments	H Mayer, P Höppe	1987	Theoretical and Applied Climatology	176
9	A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia	J Spagnolo, R de Dear	2003	Building and Environment	173
10	A model of human physiology and comfort for assessing complex thermal environments	C Huizenga, Z Hu, E Arens	2001	Building and Environment	150

Due to the possibility of classification by number of citations and the amount of resulting articles, we chose Scopus to continue with this review. The recent interest in the field of thermal comfort follows an exponential trend (Figure 1), with a considerable increase in publications in the last 10 years. As a result we honed our focus to articles on thermal comfort published in the last 10 years. We refined our search to only articles published in journals and written in English; other types of publications[6] such as conference papers, books, theses, etc. were excluded from the search. A general search in Scopus produced 8,302 articles, while just 3,235 papers remained after refining the search to only include those written in English and published in journals from 2005-2015. Tables 5 and 6 present the international journals while Table 7 presents the authors with the highest number of works from the general and refined searches.

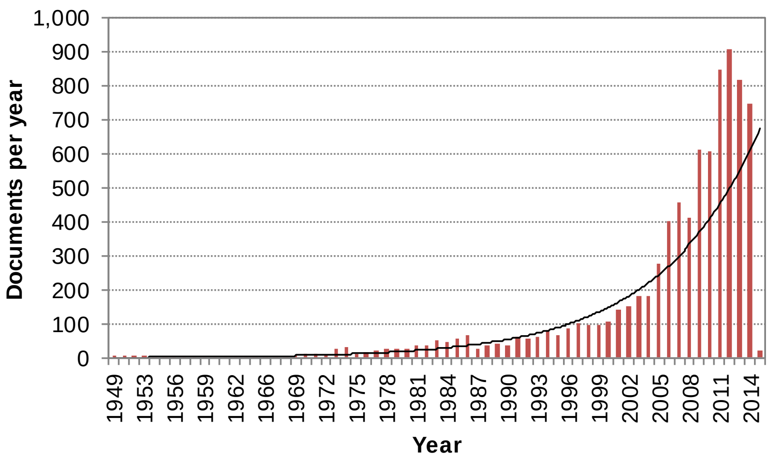

Figure 1: Number of articles published per year - Scopus.

[6] Nevertheless, it is noteworthy that a significant number of other types of publications dealing with thermal comfort are available in the literature, as the Chartered Institution of Building Services Engineers (CIBSE - UK) guides and technical memoranda, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE - US) guidelines, handbooks and reports and the Center for the Built Environment (CBE - University of California - US), publications and reports.

Table 5: International journals with the highest number of papers in Scopus. General search. Number of articles: 8,302.

Scopus (in parenthesis the number of articles per source)				
Top 10	**Source**	**Source IF[1]**	**Source SNIP[2]**	**Source SJR[3]**
1	Energy and Buildings (582)	2.465	2.381	1.978
2	Building and Environment (560)	2.700	2.544	1.634
3	ASHRAE Transactions (269)	-	0.436	0.436
4	SAE Technical Papers (150)	-	0.638	0.347
5	Advanced Materials Research (118)	-	0.198	0.144
6	International Journal of Biometereology (109)	2.104	1.308	0.762
7	Applied Mechanics and Material (102)	-	0.196	0.134
8	Renewable Energy (88)	3.361	2.681	2.256
9	Applied Energy (83)	5.261	3.262	3.385
10	HVAC and R Research (75)	0.745	0.862	0.621

[1] Impact Factor 2013
[2] Source Normalized Impact per Paper 2013
[3] SCImago Journal Rank 2013

Table 6: International journals with the highest number of papers in Scopus. Refined search (first refinement). Number of articles: 3,235.

Scopus (in parenthesis the number of articles per source)				
Top 10	**Source**	**Source IF[1]**	**Source SNIP[2]**	**Source SJR[3]**
1	Building and Environment (444)	2.700	2.544	1.634
2	Energy and Buildings (423)	2.465	2.381	1.978
3	International Journal of Biometereology (77)	2.104	1.308	0.762
4	HVAC and R Research (70)	0.745	0.862	0.621
5	Applied Energy (65)	5.261	3.262	3.385
6	International Journal of Ventilation (64)	0.303	0.212	0.225
7	Indoor and Built Environment (63)	1.716	1.099	0.715
8	Applied Thermal Engineering (57)	2.624	2.440	1.598
9	Renewable Energy (53)	3.361	2.681	2.256
10	SAE Technical Papers (50)	-	0.638	0.347

[1] Impact Factor 2013
[2] Source Normalized Impact per Paper 2013
[3] SCImago Journal Rank 2013

Table 7: Authors with the highest number of articles in Scopus. General and refined search (first refinement).

Scopus (in parenthesis the number of articles per author)		
Top 10 Authors	**General search (8,302 papers)**	**Refined search (3,235 papers)**
1	Olesen, B.W. (52)	Matzarakis, A. (46)
2	Matzarakis, A. (48)	Orosa, J.A. (25)
3	Zhu, Y. (47)	Santamouris, M. (24)
4	Arens, E. (42)	Lin, Z. (24)
5	De Dear, R. (38)	Ghali, K. (23)
6	Khalil, E.E. (35)	Ghaddar, N. (22)
7	Santamouris, M. (34)	Lian, Z. (21)
8	Tanabe, S.I. (33)	Lin, T.P. (21)
9	Li, B. (33)	Chow, T.T. (21)
10	Fanger, P.O. (32)	Hwang, R.L. (20)

The 3,235 articles resulting from the refined search were cataloged in CSV (comma-separated values) and the Mendeley[7] program to facilitate their reading and classification. Mendeley was also used to carry out the citations in this document and generate the list of references. The authors of this review read the titles, abstracts and keywords of the 3,235 articles. A second refinement was then performed to exclude simulation works and/or experimental studies without subjective results. Duplicate articles and other works that did not deal with human beings or thermal comfort were also disregarded. Thus, from the 3,235 articles, 2,769 were excluded. The remaining 466 articles, including 39 review papers, are the basis for the definition of

[7] Mendeley is a reference management software, that allows the user to import research papers and bibliographic information from Scopus to its online server (user's account). The citations can be integrated with word processors and then a reference list can be produced automatically during the writing process. For this paper the free version of the program was used.

topics (items) that compose the remainder of this review article. Thirty-three other important works in the area of thermal comfort that were not classified in these refinements were also included in this review because of their historical importance: classic works about Fanger's [34,35] and adaptive [36–42] models of thermal comfort, physiological models [43–51], a review about semi-outdoor thermal comfort [52] and a number of papers dealing with specific subjects were included [53,54]. Additional works are included in the introduction [1–6,17], as are works related to standards [18–20,55] and a recent review on personal comfort systems [56].

STANDARDS FOR THERMAL COMFORT

In general, thermal comfort is classified in relation to the type of environment: outdoor, semi-outdoor or indoor. In terms of indoor thermal comfort, the current discussion centers mainly on two distinct approaches. The first approach is the classic steady-state model developed by Fanger in the 1970s [34] for air-conditioned spaces, which is based on a heat balance model of the human body. Fanger's model [34] aims to predict the mean thermal sensation of a group of people and their respective percentage of dissatisfaction with the thermal environment, expressed through the indices Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD). PMV is calculated through six variables: metabolism, clothing, indoor air temperature, indoor mean radiant temperature, indoor air velocity and indoor air humidity. PMV method was the basis of the ISO 7730 [18] and ASHRAE 55 [19] standards and still is used in practice. More recently the model was extended to non-air-conditioned buildings in warm climates [35].

The second approach typically used to determine thermal comfort is the adaptive model[8], which is based on the adaptive

[8] In 2012 a book entitled "Adaptive thermal comfort: principles and practice" was published by Nicol, Humphreys and Roaf aiming to be an introductory book on adaptive thermal comfort [42]. More information about the theory behind adaptive thermal comfort may be found in this book [42].

principle [42] “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.”, i.e., user’s are active and not passive (as in PMV method) relating to their thermal environment. The adaptive model is based on field studies in naturally ventilated buildings by Nicol and Humphreys [36,40,57,58], Auliciems [37], de Dear, Brager and Cooper [38] and de Dear and Brager [39]. From the field studies, linear regressions relating indoor operative temperatures (acceptable ranges) to prevailing outdoor air temperatures were established, i.e., comfort temperatures varies according to outdoor climate, higher outdoor temperatures allowed for higher indoor temperatures. This was a paradigm shift compared to Fanger’s theory. The adaptive model was first included in the ASHRAE standard 55[9] [19] in 2004 as an optional method for evaluating naturally ventilated buildings. In 2007 the adaptive model was also included in EN 15251[10] [20]. The adaptive model was included in the Dutch ATG guideline [59] and in the proposal of the Brazilian standard of thermal comfort [55,60]. The adaptive model is based on three inter-related aspects (which are not fully taken into consideration in the PMV-PPD method, mainly in climate chamber studies): psychological (comfort expectation and habituation in relation to indoor and outdoor climate), behavioral (including opening windows – which was the most common, and the use of blinds, fans and doors) and physiological (acclimatization) [38]. The concept of alliesthesia proposed by Cabanac [53] and revisited by de Dear [61,62] was used to defend the physiological and the behavioral aspects of the adaptive method (thermal pleasure). The term “alliesthesia” was defined by Cabanac [53] to describe that “a given external stimulus can be perceived either as pleasant or unpleasant

[9] The model of adaptive thermal comfort used in ASHRAE 55 was derived from the ASHRAE RP-884 database [38]. Such database contains around 21,000 actual votes from field studies in 160 office buildings from 9 countries located on four continents.

[10] The adaptive thermal comfort model used in EN 15251 was developed from the European project Smart Controls and Thermal Comfort (SCATs) [41]. The SCATs database is composed by approximately 5,000 subjective thermal responses from field studies in 26 office buildings located in 5 countries in Europe.

depending upon signals coming from inside the body”. People naturally attempt to avoid unpleasant stimuli and search for pleasant ones [53]. De Dear [61] differentiates thermal pleasure from thermal neutrality using as example the PMV method: a PMV=0 is supposed to provide thermal neutrality, but not necessarily thermal pleasure (people may like or dislike it). For example, Humphreys and Hancock [63] analyzed the results of field studies in university lecture halls and in dwellings and found that by asking people how they would like to feel, 57% of the time the answer was different from “neutral”, varying according to the thermal sensation experienced at that moment. However, the concept of alliesthesia is not yet established in any standard or regulation and therefore more studies are needed in order to consider this concept when thinking about thermal comfort in the built environment.

Recently the Chinese Evaluation Standard for the indoor thermal environment was proposed [64]. It is based on Fanger’s and adaptive theories as well as field and laboratory studies from different climate zones in China. The proposal included different evaluation methods for heated/cooled environments (PMV model with different assessment criteria than ISO 7730) and free-running buildings (an adaptive graphic method or an adaptive predicted mean vote may be used) [64].

Review papers discussing the main thermal comfort approaches were also found [25,65–70], including an analysis of existing standards (ISO 7730, EN 15251). A review of several indices (among them, some from ISO 7730 and EN 15251) for the long-term evaluation of thermal comfort conditions in a building was conducted by [71]. A briefly overview of the adaptive approach was conducted by Nicol and Humphreys [72] and a discussion about actual comfort in buildings and expectations was carried out by Moezzi [73]. A critique of European Standard EN 15251 was performed by Nicol and Wilson [74] and a discussion about this standard is found at [75]. Another critique of EN 15251 and ASHRAE 55 relating to the effects of the mean radiant temperature on thermal comfort was conducted by [76]. The measurement/estimation methodologies of the mean radiant temperature was reviewed in [76,77].

ISO 7730 [18] classifies the environments in three classes: I (PMV±0.2), II (PMV±0.5) and III (PMV±0.7), as a function of variability of indoor conditions. Class I is supposed to offer users a higher percentage of thermal comfort, while consuming more energy. However, in practice, greater control over the variability of indoor conditions (class I environments) does not guarantee greater user acceptability when comparing spaces with greater thermal variation (classes II and III) [78]. Moreover, through a sensitivity analysis, the classification into the three classes of the environments was considered as random, because the widths of the ranges of each class of ISO 7730 are similar to the uncertainties of measurements of the variables for the PMV [79]. Thus, ISO 7730 needs to be updated, taking into account wider ranges of indoor temperature, to help reduce the higher consumption of air-conditioning systems and adapting to the needs of a world in an environmental crisis. Data from field work in offices in Japan during the summer, with campaigns for energy savings, using an air-conditioning set point temperature of 28ºC, show that users accept high temperatures and make use of adaptive opportunities to improve their thermal environment [80,81]. However, these results may be limited to the case of the Japanese population which was experiencing a supply crisis following a tsunami [80].

Further argument for allowing broader ranges of indoor temperature comes from the health perspective [82] because variable temperatures may have positive health effects [82]. Mild (seasonal) cold exposure may cause a reduction in weight, which could be helpful in combatting obesity [83,84]. The impact of the homogenization of the built environment goes beyond, as stated by Healy [85]:

> [T]he widely varied and, often deeply cultural and symbolic, thermal sensibilities of various cultures have become, and are increasingly becoming, subsumed by an innovative and inventive trajectory facilitated by science – thermal monotony. This is not simply a matter of the achievement of 'optimal thermal comfort' but also, particularly via the effect of standards on the form and content of the built environment, a matter of a reduced diversity in thermally influenced practices and behaviours, much of which are highly cultural in character.
>
> (p. 321)

Broader ranges of indoor temperatures were proposed by Zhang et al. [86] for HVAC (mixed-mode) buildings based on the ASHRAE database. Between 19.5-25.5ºC buildings may operate in free-running mode. Above 25.5ºC up to 28.0ºC and even 30.0ºC, the use of ceiling fans and personally controlled fans may guarantee thermal acceptability [86]. In higher temperatures cooling is needed [86]. Below 19.5ºC the use of personal control heaters can be used [86]. These recommendations will not compromise thermal comfort, but will help save energy in buildings [86]. Recently, Zhang et al. [56] reviewed personal comfort systems and proposed an even wider range of indoor temperatures when using personal comfort systems.

EXPERIMENTS IN CONTROLLED ENVIRONMENTS

Studies in controlled environments have been performed around the world, including classic experiments in climate chambers where researchers have full control over environmental and human variables [87–90]. There is a tendency to emulate/simulate real environments in such climate chambers through the inclusion of windows looking to the outside and furnishing the space in a more harmonious way with the activity being studied, for example [91,92]. Another trend observed was an increase in studies in semi-controlled environments [93–95] usually carried out in adapted rooms in real buildings, where researchers set (control) some but not all variables, for example, allowing participants to freely choose their clothes during the experiment.

Experiments in climate chambers

The influence of control, thermal history and individual preferences

In a study performed in a climate chamber in China, the possibility of control over the thermal conditions improved occupants' thermal sensation and thermal comfort [96]. Thermal history was the focus of a work by Chun et al. [97] conducted in climate chambers in Seoul (Korea) and Yokohama (Japan) over the same indoor thermal conditions. Those exposed to higher temperatures prior to their time in the climate chamber responded with cooler thermal sensations than people who were first exposed to cooler temperatures [97]. Another study in climate chambers was conducted with young men in Beijing – where heating is commonly used in winter - and in Shanghai – where heating is not commonly used in winter. The subjects were exposed to the same variations in temperature (12ºC to 20ºC, cold indoor environment) [98]. The research shows that subjects accustomed to higher indoor temperatures (Beijing) feel colder thermal sensations than subjects accustomed to lower indoor temperatures (Shanghai) [98]. Yu et al. [99] used a climatic chamber to study whether the length of time in air-conditioned or naturally ventilated environments influences peoples physiological acclimatization. Results show greater physiological adaptability of people in naturally ventilated environments, especially under warmer conditions [99].

The individually thermoneutral zone is influenced by many factors (clothing, age and gender, among others) and varied between conditions and between individual subjects [100]. Interindividual differences in thermal comfort in young Japanese woman were identified by Yasuoka et al. [101]. Subjects were divided into two groups based on their preferred ambient temperature (H group preferred warmer sensations than M group) and they were subjected to temperature variations (33ºC to 25ºC) in a climate chamber. H group felt colder than M group (no differences in mean skin temperature were observed). In the Netherlands, another study in a climate chamber emphasized the importance of categorizing people based on their thermal preferences (narrow range preference, broad range preference, cool preference and warm preference), thus improving the predictions of thermal sensation [102].

The influence of weight, gender and age

A comparison of 27 lean and obese prepubertal girls (who were physically active) during and after exercise under heat and thermo neutral conditions was performed in South Brazil [103]. No differences in thermal sensation were found between the two groups in both thermal conditions [103].

Studies were also carried out, in a climate chamber, to examine the difference gender played in the thermal comfort of Chinese [104,105] and Dutch [106] participants. Women are more sensitive to temperature (mainly cool) [104,105] and less sensitive to humidity than men [104] and feel more uncomfortable and dissatisfied compared to males [106]. Women have a lower skin temperature than men [104,106]. Men prefer a slightly cooler environment and women prefer slightly warmer condition [104,105], despite presenting similar neutral temperatures and no difference in thermal sensation near neutral conditions [104]. In another study in a climate chamber, the effect of variation of temperature with height in skin temperature and thermal discomfort was more significant in women than in men [107]. Still another study showed that in women the overall thermal comfort sensation is significantly affected by the temperature of the skin and extremities, a fact that should be considered in non-uniform environments [87]. Furthermore, Schellen et al. [87,88] state that the operative temperature is insufficient for the evaluation of thermal comfort in non-uniform thermal environments.

The results obtained by Fanger when validating his model with elderly people indicate that there is no difference in perceptions of comfort with age, although the metabolic activity and the basal metabolism are lower in this type of users [108]. In steady and transient temperature conditions, Schellen et al. [109] found that older people (67-73 years) had more distal vasoconstriction than young adults (20-25 years) [109]. The thermal sensation results also indicate that elderly people prefer a higher temperature than young adults [109].

Steady/dynamic and uniform/non-uniform environments

Thermal comfort studies in steady and uniform environments and non-uniform and dynamic environments were carried out in climatic chambers in USA [89,90] and in China [110,111], where a personalized conditioning system was used to change the thermal conditions. Fanger's model only proved to be applicable to steady and uniform environment [110]. In another study in China in non-uniform and dynamic environments, the effect of temperature on thermal comfort and energy consumption by using local ventilation was assessed [112]. Also in China, but in steady and non-uniform environments, other studies were conducted to assess the effect of local thermal sensation on whole-body thermal sensation [113] and to investigate the temperature ranges for thermal comfort [114]. In transient and uniform environments, studies were performed in China, to investigate the human thermal perception and skin temperature due to step-change temperatures [115] and to research the effects of step changes of temperature and humidity on human responses [116]. They were also conducted in Taiwan [117] to analyze the effects of temperature steps (instantaneous change of air temperature) on thermal sensation, in Kuwait [118], to investigate the step change in environment temperature using a chilled ceiling displacement ventilation system aided with a personalized evaporative cooler on thermal comfort and in Austria [119], to assess the thermal comfort under spatial transition between a cold or warm controlled environment to a mechanically ventilated –unconditioned- during spring and winter. Another study aimed to create a new index to assess the ventilation performance in uniform and non-uniform thermal environments (assessing the indoor thermal comfort) [120].

Personalized conditioning systems

Personalized conditioning is another area of research that has emerged. Such a conditioning system aims to create a microclimate around a person, optimizing energy consumption and improving thermal comfort [121]. According to Veselý and Zeiler [121] in their review paper about personalized conditioning and its impact on thermal comfort and energy performance, the majority of scientific papers in the area were performed in climate chambers with studies involving the increase of the air velocity for cooling of the body [121]. In those situations thermal comfort was reached with indoor temperatures of up to 30ºC and relative humidity of 70% [121]. In heating mode, the use of personalized conditioning strategies can promote comfort at temperatures of 15ºC [121]. Thus, an annual energy savings of approximately 40% may be achieved considering the range of comfort temperatures (15-30ºC) and using personalized conditioning [121].

Different task conditioning systems were studied in a climate chamber involving users in Japan [122]. Other studies in climatic chambers, involving an individually/personally controlled system were performed in Denmark (with mechanisms for facial ventilation and heating [123] and ventilation, heating and cooling [124], radiant and convective cooling [125] and another system using a ductless personalized ventilation in conjunction with displacement ventilation [126]), in Hong Kong (chair-based personalized ventilation -PV- system) [127], in Lebanon (low-mixing ceiling-mounted personalized ventilator system) [128], in Hungary (a novel PV system with air flow coming alternatively from three different directions) [129,130], in the United States (heated/cooled chair [131], ceiling fans [132] and floor fans [133]), in South Korea (floor-standing room air-conditioner) [134], in China (electric fans were placed in front of subjects, directed at their faces) [135] and in Japan (chair equipped with fans) [136]. Results of the personalized conditioning systems with regard to thermal comfort were equal or better than conventional cooling systems [122–126,128–132]. The use of floor fans [133] and the chair equipped with fans [136] were able to maintain acceptable thermal comfort conditions with air temperatures up to 30ºC; the use of electric fans (China) could provide a comfortable environment at 28°C to 32°C [135]. Another type of chair with fans was studied in a chamber operating with displacement ventilation; users were satisfied with the cooling provided by the fans with air temperature of 26ºC [137]. The performance of a seat headrest-incorporated personalized ventilation system was studied showing acceptable air movement and cooling capacity [138].

Other studies

In a study in China, three different altitudes were simulated in a decompression chamber, to verify the impact on thermal sensation [139]. The research shows that with the increase in altitude, thermal sensation decreases (people feel cooler) and people are more sensitive to draught and expect lower air movement [139].

Regarding clothing, a study investigated the influence of cooling vests with phase change materials on thermal comfort [140] and another study determined the relationship between environmental temperature and actual daily clothing insulation during a year with Korean subjects [141].

In Taiwan [142] and in Hong Kong [143], in climate chambers, studies in different thermal conditions were performed comparing the actual sensation vote (ASV) and actual percentage of dissatisfaction (APD) with the PMV-PPD method. In Taiwan, the lowest value of APD (16%) was found for ASV equal to -0.4, contradicting the value predicted by Fanger, who said that the lowest percentage of dissatisfied (PPD=5%) would be met with a PMV=0 [142]. In the study in Hong Kong, the ASV also did not match the PMV when considering the different air velocities studied (air temperatures up to 28.2ºC with air velocity of 0.8 m/s were considered comfortable by users) [143].

Researchers also attempted to determine the thermal neutral temperature of different air distribution systems (mixing ventilation, displacement ventilation and stratum ventilation) [144], to evaluate a rule of thumb to assess the risk of downdraught during design phase [145] and to evaluate the effect of using fans with simulated natural wind [146] and with different airflow fluctuation frequencies [147,148] in thermal comfort.

In a climate chamber in Hungary, a study on the combined effects of two local discomfort parameters (radiant temperature asymmetry – a cold wall and a floor warmed through floor heating) was conducted with subjects in thermal neutral conditions [149,150]. In the testing conditions, the subjects felt comfortable and reported no discomfort by warm feet, which may have been due to the presence of the cold wall [149]. Another study compared the thermal comfort of South Korean subjects by using a forced-convection cooling system with a system combining radiant-floor and convective cooling [151].

Studies of thermal comfort involving subjects in climate chambers have been performed to evaluate the influence of local skin wettedness and overall thermal comfort [152], to study the regional (body parts) differences in temperature sensation and thermal comfort [153,154], to study the effects of skin temperature on the finger, hand and wrist in the assessment of overall comfort [155], to investigate the response of physiological parameters (skin temperature, electrocardiograph and electroencephalogram) to different ambient temperatures and its relationship with the sensation of thermal comfort [156], to study the relationship between floor surface temperature and the overall and local thermal sensation (feet) [157], to assess the effects of solar radiation (direct and indirect) on the thermal comfort [158], to analyze the influence of mean skin temperatures [159–164] and heart rate [165] to predict thermal comfort, to analyze the sensitivity range of the static thermal comfort equation [166], to investigate the effects of climatic characteristics and adaptability of people on the thermal comfort [167] and to investigate the impact of temperature differences between radiant and air temperature on mean skin temperature, thermal sensation and thermal comfort [168].

Experiments in semi-controlled environments

The influence of control and layout

In Germany, experiments in a semi-controlled environment simulating an office with different thermal environments and with diverse adaptive opportunities were performed in order to better understand the processes leading to adaptive comfort (physiological, behavioral and psychological) [91,92]. The experiment shows that the use of controls (fans, sun shading devices and windows) over the thermal environment is important to make people feel more comfortable [92].

In the Netherlands in an office building, researchers controlled indoor temperatures and the presence or absence of plants (quasi-experiment) [169]. Users felt more thermally comfortable when plants were present in the room [169].

Personalized conditioning systems

Studies in semi-controlled environments, simulating an office and operating with a displacement ventilation (DV) system [170,171], with under-floor air distribution + personalized ventilation (UFAD+PV) [172,173], with an individually controlled PV system [174] and with a ceiling-mounted PV system [175], were conducted with users in Singapore. Regarding studies with DV, the overall thermal sensation was mainly affected by local thermal sensations of the arm, calf, foot, back and hand [170]. When people felt a cold sensation or slightly warm sensation, they preferred that all parts of the body were more heated or more cooled, respectively [170] and in these two conditions, the temperature gradient did not affect the overall comfort sensation [171]. In the study with UFAD+PV, the use of the two strategies together led to improved thermal sensation of people with respect to the conventional air-conditioning system [172,173]. In Denmark, a study in a simulated office room equipped with different personalized ventilation systems shows that such systems have improved the perception of air quality and users evaluated the thermal environment as acceptable [176]. In Thailand a study was conducted to evaluate the influence of local air movement (small fans) in a semi-controlled environment operating with air-conditioning [177]. The thermal environment was considered acceptable by users with air temperatures of up to 28ºC, using small fans with air velocities between 0.5-2.0 m/s [177].

Other studies

In China, in a laboratory environment (furnished by the researchers) that was naturally ventilated and with no control over the environmental and personal variables, a study involving university student volunteers was conducted to assess their thermal comfort responses due to environmental changes that varied over the four-year experiment [178].

In India, a study was carried out with young male university students in a semi-controlled environment demonstrating that the PMV model overestimated the actual sensation vote (ASV) of people (subjects are less sensitive -more tolerant- to hot but more sensitive to cold) [179,180]. In South Korea, young adults participated in a study in a semi-controlled environment; PMV presented good correlation with ASV, but not with the votes of thermal comfort (authors stated that PMV may be inappropriate to control the indoor environment in order to establish thermal comfort) [181].

Thermal comfort studies with subjects in semi-controlled environments were conducted in Sweden to examine the effects of intermittent air velocity on thermal and draught perception [93], in China, to investigate the acceptable range of thermal, luminous, and acoustic environment (individually and cumulative effects) [94] and in United States, to study the effect of temperature, metabolic rate and dynamic localized airflow on thermal comfort [95].

FIELD STUDIES IN REAL BUILDINGS

Classic field studies involve the application of questionnaires and measurement of indoor variables (and outdoor in some cases). A review article about field studies grouped by climatic classification was presented by [182] and another review paper of thermal comfort studies in office, residential and educational buildings was written by [183].

Thermal comfort in kindergartens

Regarding thermal comfort in kindergartens or with children who have not yet developed their reading and writing skills, some works began to be developed since 2012. In the literature search performed, we only found three works with these users.

Conceição et al. [184] developed an adaptive model for evaluating the thermal comfort in kindergarten (aPMV). The model was applied during winter and summer in a kindergarten equipped with natural and forced ventilation and located in southern Portugal, a Mediterranean climate. Results showed that the aPMV in summer conditions is lower than PMV (user's thermal comfort sensation could feel less warm than PMV) while in winter conditions the aPMV is greater than PMV (user's thermal comfort sensation could feel less cold than PMV) [184]. In this study, the influence of the outdoor temperature in the thermal evaluation of indoor environment was identified [184].

In northern Italy, Fabbri [185] collected subjective evaluations of children between 4 and 5 years by adjusting the ISO 10551 questionnaire with a psycho-pedagogical approach. The analysis showed that children understand the concept of comfort and have the ability to define and choose their level of thermal comfort. However, the author points out that the PMV of children is slightly higher in relation to adults [185].

In Seoul, South Korea, Yun et al. [186] sought to provide data to propose a new model of PMV for children by studying the effects of metabolism and clothing on the thermal comfort of children. The study was conducted in naturally ventilated classrooms, between April and June 2013, with children from 4 to 6 years old. Results showed that children have a greater sensitivity to changes in their metabolism than adults and prefer lower temperatures than those predicted by the PMV model and the standard EN 15251. Such results may contribute to the development of a new model of PMV for children [186].

Overall, the research carried out with children in preschool, highlights the need for a comfort model that considers both their physical and physiological differences in their cognitive abilities. Additionally, studies of adaptive attitudes of children are needed.

Another issue to consider is the design of questionnaires for children and further studies are needed to help improve them. The questionnaires themselves can influence the reliability of the responses and must be improved the identification of the influence of the type of scale used in the response options according to the variable evaluated [187], the translation of some terms in other languages, the climate context in which the work is carried out and the age of the users, such as very young children [54,188].

Thermal comfort in schools

Research in schools has been widely developed in several countries to evaluate the thermal comfort of pupils from 7 years old.

In the hot humid climate of the southern region of Malaysia, Hussein et al. [189] conducted studies in two schools with fans. Although 80% of respondents found the thermal environment acceptable, the actual sensation vote (ASV) exceeded the one specified by ASHRAE 55, showing that people of this region have a higher tolerance and adaptability to the heat [189]. Hwang et al. [190] studied the applicability of an adaptive model in naturally ventilated schools in Taiwan. The results show that the comfort zone for 80% acceptability has a wider band and the comfort zone for 90% acceptability has a narrower range than ASHRAE 55 adaptive model [190]. Mors et al. [191] studied the parameters of thermal comfort with children between 9 and 11 years of age in unconditioned environments in the Netherlands during winter, spring and summer. Through the PMV model the mean thermal sensation was underestimated at 1.5 points, an inaccurate result. When the thermal sensation was compared to the comfort zone of the adaptive model, authors found that children prefer lower temperatures [191]. Teli et al. [192] studied the applicability of the adaptive model of EN 15251 with children between 7 and 11 years old in naturally ventilated classrooms in England. Results indicated that the temperature of comfort achieved through the PMV was 4°C lower than that obtained by questionnaires and the one obtained by the adaptive model was 2°C lower, indicating that children are more sensitive to high temperatures. In another study, Teli et al. [193] show the adjustments that should be made in the current comfort criteria to evaluate the thermal perception of children in various climates. The current thermal comfort criteria lead to an underestimation of the thermal sensation of children during the summer [194]. The study of De Giuli et al. [195] held in a school in Padova (Italy), found no match between the PMV/PPD and the children's' ASV neither between the adaptive model nor the ASV [196].

Corgnati et al. [197] studied the thermal preferences of students in schools and in a university in the city of Torino, Italy. The mean of subjective votes was compared with the perception of the thermal environment and the results showed that people accept those environments judged as neutral or warm [197]. In the research of Teli et al. [193], held during the end of summer in Southampton (UK), children tended towards warm thermal sensations which was not complemented in the same way by strong preference for cooler spaces [193]. Another study by Corgnati et al. [198] performed during the mid season in schools under free running conditions in Turin (Northwest Italy) compared the subjective responses with those obtained in another study [197] conducted during the heating season. Results show a gradual change in thermal preference starting in the heating period until the mid season. During the mid season the preference was for neutral environments, while during the heating season the preference was for slightly warm or warm environments [198]. A study conducted in naturally ventilated classrooms in Beja (Portugal), in a Mediterranean climate, found that students preferred slightly warm environments in the mid season, with an acceptable temperature range beyond the comfort zone [199]. In Sweden, Wigo et al. [200] presented the evaluations of students who were subjected to intermittent air velocity in a school, during the spring and autumn. Results indicate that variations in air velocity cause people to perceive the air as being cooler and more refreshing than when the air velocity is constant. Pupils in the study also requested slightly more air movement [200].

Based on data from more than 4,000 Italian students during the winter and the summer in about 200 naturally ventilated classrooms, the expectancy factor for the Mediterranean climate was proposed [201]. The expectancy factor when multiplied by PMV could correct the index for use in naturally ventilated environments. By doing that, authors concluded that PMV was effective in predicting thermal comfort in the studied naturally ventilated environments [201].

A study conducted by Montazami and Nicol [202] in 18 naturally ventilated schools in the UK analyzed the new version of overheating guidelines for schools with the old version, both published by the British government. Despite the new guidelines are more stringent, further development are needed [202].

In Taiwan, Liang et al. [203] found that the building envelope energy regulation has great impact on the thermal comfort sensation in naturally ventilated buildings. Katafygiotou and Serghides [204,205] showed that there is a relation between poor indoor quality conditions and the low-energy efficiency of buildings.

Zeiler et al. [206] evaluated the performance of thermo active building systems for heating schools during the winter in the Netherlands. According to the results of the questionnaires, these systems generate a slight improvement in the perception of thermal environment and greater user satisfaction with respect to the indoor temperature, when compared with traditional heating systems [206].

The influence of gender

Regarding the influence of gender in the evaluation of thermal comfort, the study by Katafygiotou and Serghides [204] in a typical classroom and a laboratory of a secondary school building in Cyprus, during different seasons, found differences in thermal sensation between girls and boys. During the winter, girls were more sensitive to low temperatures, which led to greater use of the heating system and affected the comfort sensation of the boys. During the summer, boys were more sensitive to high temperatures, feeling warmer than girls. The researchers attributed these differences in thermal sensation to the characteristics of the metabolism and the skin surface of each gender [204].

Adaptive behavior

A study by Chen et al. [207] analyzed the adaptive behaviors regarding the use of fans and air-conditioning in a mixed-mode school in Taiwan (under the control model fee-for-service) and the impact on energy savings. Results show that the least used mechanism (11%) was air-conditioning + fans while the most frequently used mechanism was to jointly opening the windows and running the fans (64%). The mechanism of fee-for-service restricted the use of air-conditioning by students and increased the temperature threshold at which the air-conditioning was activated [207]. Kurabuchi et al. [208] studied the behavioral differences in the indoor environment control and the thermal sensation of children before and after the installation of cooling systems at a school in Tokyo. Results of this research were used to produce guidelines for the use of equipment based on thermal sensations [208].

Thermal comfort in universities

Several studies have been conducted in university buildings in a hot and humid climate in China [209–215], India [216,217], Indonesia [218], Malaysia [8] and Brazil [219,220].

Hwang et al. [209] conducted field studies in 10 naturally ventilated and 26 air-conditioned classrooms in seven universities in Taiwan. The analysis found that relative humidity had no significant influence on the assessment of students' thermal sensation. Student responses point to wider ranges of thermal acceptability in Taiwan [209]. In a later study carried out in university dormitories in Taiwan [210], the neutral and preferred temperatures of students were similar in both classrooms and dormitories.

Zhang et al. [211] conducted a study in naturally ventilated classrooms with ceiling fans in Hunan University in China. Results showed that most students were satisfied with the thermal environment during the experiments (March-April). Authors analyzed a modified model of PMV, but the discrepancy between predicted and actual thermal sensations did not reduce noticeably [211]. In another study, Zhang et al. [212] evaluated the adaptive behaviors of students during a year in free-running buildings in a hot-humid area of China. A close match between the physical variables of the indoor environment and the clothing with outdoor climate was found. People in the analyzed climate are more tolerant of heat and humidity and less tolerant of cold environments when compared to studies conducted in temperate climates [212]. In a study performed in buildings with split air-conditioners in a hot-humid area of China, Zhang et al. [214] conclude that occupants of buildings with split air-conditioners keep their environment cooler, use adaptive opportunities early on and perceive their environment more sensitively and rigidly than users of naturally ventilated environments.

In the study by Yao et al. [213] carried out for a year in university classrooms in China, the comfort range found was broader than that recommended by the ASHRAE 55, with the exception of the hottest and coldest months, in which the range was narrower. In the oceanic temperate climate of Korea, a field study conducted in university classrooms during the spring and fall showed that the thermal acceptability range diverged from that recommended by ASHRAE 55 [221].

Wang et al. [215] conducted a study during the winter in Harbin (China) in university classrooms and offices, and concluded that the neutral temperatures were different in winter and spring (the neutral temperature was higher in spring than in winter), demonstrating the influence of the prevailing weather conditions in adaptation.

De Carvalho et al. [222] studied classrooms in an academic campus (university students) in Portugal and found that the level of insulation of clothing has the most significant relationship to the previous day's mean outdoor temperature.

A study conducted in the laboratories of a university in India showed high acceptance of the indoor thermal environment and adaptability by the students to high levels of humidity [217]. The answers from the questionnaires showed a strong correlation between indoor comfort conditions and the outdoor temperature [216].

Based on the results of two field studies conducted in two cities, Karyono [218] evaluated the applicability of the adaptive model in Indonesia. Results showed that user's comfort temperatures were in line with mean outdoor temperatures, as stated by the adaptive model [218].

A post-occupancy evaluation assessed the perception of students and staff of a zero-energy building, located in a French island in the Indian Ocean (tropical climate) [223]. The building was designed to be mixed-mode in some areas and uses passive strategies. Results indicate that during most of the year, users are in thermal comfort without using air-conditioning [223]. Serghides et al. [224] identified the inappropriate use of cooling and heating systems (very low temperatures in summer and very high temperatures in winter) in a university building in Cyprus. In the field study carried out in buildings of a university in Malaysia, the results of measurements and questionnaires showed that most of the buildings failed to provide a thermally comfortable environment and that the HVAC system should be changed [8].

During the fall, winter and spring, Buratti and Ricciardi [225] performed a field study in classrooms of three universities located in three cities in Italy. The correlation of the responses from questionnaires and PMV showed significant differences between them [225]. The results of the study by Memon et al. [226], at a university in the subtropical region of Pakistan, indicated that people in this area felt in thermal comfort with effective temperatures of 29.85°C (operative temperature of 29.3°C). Such a result was compared with the neutral effective temperature determined by the adaptive model, demonstrating that this model predicted it very well. PMV was compared with the actual sensation vote (ASV) and significant discrepancies were found, for example, an ASV=0 was predicted by PMV as +1.34 [226].

The effect of ventilation was studied by Norback and Nordström [227] in computer classrooms (university students) with different air exchange rates. Higher air exchange was associated with a perception of lower temperature, higher air movement and better air quality [227].

The results of the study by Cândido et al. [219,220], performed in the hot and humid climate of the city of Maceió, Brazil, demonstrate the importance of the occupants' thermal history and their preference for higher air movement. According to the authors, people who are under steady conditions in their thermal environment (air-conditioned -AC- environments) have less tolerance and are less able to adapt to the dynamic conditions of naturally ventilated spaces. People who were constantly exposed to AC preferred this type of conditioning while people accustomed to free-running buildings preferred not to have AC [219]. The minimum air velocities required to achieve 80% and 90% of acceptability were closer or above the maximum velocity (0.8m/s) recommended by ASHRAE 55 [220].

Thermal comfort in offices

Two office buildings of a university in Sydney (Australia), one operating with natural ventilation and the other with hybrid ventilation, were studied by Deuble and de Dear [228]. The authors compared the post-occupational evaluation (POE) of buildings with data from a classic field study of thermal comfort and concluded that the POE does not accurately assesses the performance of buildings [228]. Furthermore, the results of satisfaction and thermal acceptability indicate that the users of the naturally ventilated building are more tolerant with respect to their thermal environment, despite experiencing higher temperatures [228]. That conclusion was also carried out by other researchers: i) Daghigh et al. [229], in a study in an office room with hybrid ventilation in Malaysia (users were more tolerant during the use of natural ventilation); ii) Yang and Zang [230], in another study in different cities in the humid subtropical zone of China, during the summer, but comparing buildings with natural ventilation and others operating with air-conditioning (users were more tolerant in the naturally ventilated building).

In another study conducted in two cities in India (Chennai and Hyderabad, warm humid and composite climates, respectively) with air-conditioned and mixed-mode buildings, Indraganti et al. [231,232] determined thermal comfort temperatures and proposed an adaptive model of thermal comfort, respectively. Authors highlighted the increased air velocity by fans as one of the measures participants used to improve their comfort conditions [232]. Thermal comfort temperatures were also determined for an office building with hybrid ventilation in Seoul, South Korea and a new adaptive comfort model to that climate was proposed [233]. Nicol and Humphreys [234] determined adaptive comfort models (thermal acceptability ranges relating the outdoor running mean temperature and the indoor comfort temperature) for European office buildings operating with natural ventilation or during the heating or cooling operation, based on SCATs database.

In order to verify the applicability of the adaptive model of thermal comfort in mixed-mode buildings, studies were carried out in offices in Shenzhen (hot and humid subtropical climate) [235], China and Melbourne [236] and Sydney, Australia [236,237]. The different conditioning modes were perceived differently by users [235,237]. PMV-PPD model is inadequate to describe the thermal comfort in mixed-mode buildings [236]. The adaptive model is more applicable to this type of building, during the use of natural ventilation [235,237].

Classic thermal comfort field studies were carried out in naturally ventilated buildings in the cities of Douala and Yaounde (offices and schools), humid tropical climate of Cameroon [238], in the Southeast of France (offices) [239], in Karlsruhe (Germany) during the summer (offices) [240] and in Libya (offices and homes) [241]. When considering local discomfort, more than 40% of users were dissatisfied with their thermal environments in both cities in Cameroon [238] and over 50% in France during the warmer period (users preferred higher air movement) [239]. In the French and German studies, authors calculated PMV, which did not correlate well with the actual mean vote (the adaptive model described better the subjective responses) [239,240]. In the work in Libya, authors developed an adaptive model of thermal comfort and stated that Libya's population has a greater degree of adaptation than the European population (SCATs project) [241].

In the hot and humid climate of Taiwan, a classic study of thermal comfort in an air-conditioned office building retrofitted with a total heat exchanger resulted in improvements in thermal comfort and air quality after the air-conditioning retrofit [242]. Other studies of thermal comfort in office buildings with air-conditioning were carried out in Thailand (neutral temperatures and thermal acceptability were determined) [243], in Malaysia (the main problem was overcooling and the neutral temperatures proved to be higher than those predicted by PMV) [244], in China (low relative humidity was the main cause of thermal discomfort) [245], in Hong Kong (neutral temperatures were determined and in the summer these were lower than those predicted by PMV) [246] and in Saudi Arabia (63% of users felt dissatisfied during the summer) [247]. In this last study, a multi-phase approach proposed by Budaiwi [248] was applied for assessing and suggesting appropriate remedial measures for the thermal comfort problem [247].

Based on the available information in CBE's post-occupancy evaluation database (mainly offices), Kim and de Dear [249] identified that the type of conditioning (air-conditioning-AC-, mixed-mode-MM- and natural ventilation-NV) influences the expectation of users with respect to indoor environment quality satisfaction. In NV buildings, good thermal conditions improved overall satisfaction with the working environment (positive effects), while in AC buildings the thermal conditions were associated with negative evaluations in relation to the overall environment [249]. In MM buildings, thermal conditions provided both positive and negative impacts [249].

A comparison between the actual sensation vote and PMV conducted in air-conditioned office buildings in northern Italy, Singapore, Beijing (China), Belgium and Taiwan shows a weak correlation between these two parameters [250–253]. In Italy, the reason for the differences was the lack of thermal control by users, low air movement and the dissatisfaction generated due to the vertical temperature gradient [250]. In Singapore, overcooling was the main problem (users preferred higher operative temperatures) [251]. However, in another study during the winter in different office buildings in Germany, the authors concluded that the calculated PMV showed results close to the actual sensation vote [254].

In an air-conditioned office building in London (UK), a study was conducted during the summer comparing two groups of users in different thermal environments: i) set point temperature of 22ºC and ii) set point temperature of 24ºC (British Council for Offices - energy savings recommendation) [255]. While users felt the environment slightly warmer in the second case than the first, there was no significant difference with respect to thermal comfort [255].

Twenty federal office buildings in the United States were studied over periods of three [256] and seven years [257] through post-occupational evaluation. The thermal conditions of the spaces were kept within the thermal comfort ranges of the ASHRAE 55 (PMV) through air-conditioning use. However, 50% of users (especially women) expressed dissatisfaction with their thermal environments [257]. The authors recommended raising the summer set-point temperature by 2ºC to improve the thermal satisfaction of women and at the same time adjust the clothes of men in 0.57 clo (light trousers and short-sleeve shirts) to compensate for the increase in temperature [257].

Studies about environmental control and clothing

Healey [258] studied an office building with hybrid ventilation at a university in the Australian city of Gold Coast (hot and humid climate), where most users had a private room or at most shared with 3 people, thus having a considerable environmental control. The building was designed to work with natural ventilation and due to this, users tended to choose and prefer this mode of ventilation, although they could turn on the air-conditioning [258]. Other office buildings with hybrid ventilation located at a university in Changsha [259] and Chongqing [260], both Chinese climates with hot summers and cold winters, were studied for a whole year. The use of controls (windows, fans, heaters, air-conditioners, others) was observed and indicated that the main parameter for the adaptive thermal behavior of users was the outdoor air temperature (different seasons) [259,260]. On the other hand, in another study conducted during the summer in naturally ventilated office buildings in Switzerland, the authors concluded that the probability of users interacting with personal/environmental controls was best described by the indoor temperature [261]. Another analysis on the use of controls by users was carried out using data from classic studies of thermal comfort in Europe and Pakistan [262]. The authors concluded that the outdoor temperature was a better indicator for heating use, but the use of windows, fans and cooling was better described by the indoor temperature [262]. In the field of personalized conditioning, Karjalainen and Koistinen [263] identified users' problems controlling the personalized temperature through field study in Finnish office buildings. The main one is related to the interface of these systems and the assumption that users have knowledge of them [263]. Often people do not use the system or even know about it. Langevin et al. [264] studied the relationship between the perceived control of the thermal environment and the comfort sensation based on ASHRAE RP-884 database. Satisfaction with perceived control is more important to thermal comfort than just having personal control options [264]. Another study based on ASHRAE RP-884 database was performed in

Hong Kong [265], where a comfort temperature chart for naturally ventilated buildings was developed.

Through observation data from ASHRAE RP-884 and RP-921, Schiavon and Lee [266] developed two dynamic models to predict the insulation of clothing in offices and found that climate variables explain only a small part of human behavior in relation to clothing. De Carli et al. [267] studied the clothing behavior in naturally ventilated and air-conditioned buildings based in others databases. The selection and change of clothes are affected by the parameters of the indoor and outdoor environment [267]. Huang et al. [268] performed a review about four standards (ISO 15831, ASTM F 1291, ASTM F 1720 and EN 342) for measuring the thermal resistance of the clothes and pointed out several suggestions to be considered in future revisions of these standards.

Green buildings studies

Baird and Field [269] studied various commercial and institutional buildings with sustainability labels in 11 countries. Overall, results indicated a good level of satisfaction with the indoor conditions of thermal comfort, which is better on average than the corresponding benchmarks [269]. However, in most of the analyzed buildings, users perceived the environment too cold in winter and too hot in summer [269].

A comparison of thermal comfort between conventional office buildings and green ones, operating with air-conditioning system was held in Taiwan [270], in Canada and the United States [271] and in Australia [272]. Another US study compared buildings with hybrid ventilation (most of them with green building certification) with a benchmarking database of 370 buildings (Center for the Built Environment-CBE) [273]. Users of green buildings were more satisfied with their thermal environments [270–273]. However, in another study in the US using the CBE database (144 buildings, 65 of them with a sustainability label), no significant difference between the two types of buildings was observed [274].

Green certified office buildings operating with an under floor air distribution system and with radiant slab cooling located in Calgary, Canada were studied by Bos and Love [275] and by Tian and Love [276], respectively. Bos and Love [275] concluded that, in general, the thermal environment was evaluated as satisfactory (actual mean vote = -0,5), although about 1/3 of users prefer higher air movement and higher temperatures.

Air movement studies

Zhang et al. [277] analyzed the air movement preference using the CBE database (data from office buildings in North America and Finland) and found higher dissatisfaction among users in lower air velocities, questioning the low air velocity limits set by ASHRAE 55 and ISO 7730. Yang et al. [278] investigated the air movement preference during the different seasons in naturally ventilated buildings in humid subtropical China, including offices, residences and classrooms and also found user's preference for higher air movement, mainly in warm conditions [278]. In ASHRAE 55-2009, SET model was implemented to assess thermal comfort in high air velocities, by compensating with air temperature [279]. Arens et al. [279] point out that this model is based on field studies with neutral and warm thermal environment, where people preferred higher air velocities.

Thermal comfort in residential buildings

Several research groups have found that there are differences between the PMV and the responses of the questionnaires (actual sensation vote-ASV) in residential buildings [280–284]. Becker and Paciuk [280] studied homes in Israel with and without HVAC systems during the summer and winter and found that the ASV was higher than PMV. Based on field study in 25 air-conditioned domestic buildings in Kuwait, Al-ajmi et al. [283] found that through the PMV neutral temperature was underestimated. The studies of Indraganti [285–288] in apartments in India found that the PMV overestimated the ASV of the residents. Another study in naturally ventilated apartment buildings in India determined neutral temperatures and a wider comfort band than Indian standards [289]. Based on studies conducted in 26 homes located in Central Southern China it was identified that the neutral operative temperature calculated by the Fanger model was lower than that obtained from questionnaires [9]. In another study performed in multi-story residential buildings in India, ASV had lower values than PMV, but when applied a expectancy factor of 0.6, the extended PMV model fit well with the ASV values [290].

According to the research results performed by Alexis et al. [291] in air-conditioned buildings in Cameroon, the comfort ranges of the ASHRAE 55 and ISO 7730 should be reviewed, as in the tropical climate users are acclimatized to higher temperatures, which could reduce energy consumption in air-conditioning [291].

In the hot humid climate of Venezuela, Bravo and González [292] investigated indirect evaporative passive cooling systems in a bioclimatic prototype dwelling and concluded that the house was thermally comfortable for most of the subjects. In Sweden, people who completed post-occupancy evaluations for nine passive houses complained about cold floors and high summer temperatures [293].

Yang et al. [294] studied residential buildings in high-latitude regions in China and determined an adaptive comfort model for that climate. Tablada et al. [295] proposed a comfort zone for the summer in residential buildings located in Old Havana, Cuba. In the questionnaires residents identified a preference for higher air velocities [295].

A study conducted in Leicester, UK, in 230 free running homes found that the indoor temperatures were much lower than anticipated by the EN 15251 model [296]. In low-income dwellings in England, Hong et al. [12] studied the impact of the Warm Front energy efficiency refurbishment scheme on the thermal comfort of residents. Results indicate that the energy efficiency refurbishment scheme was effective in improving user’s thermal comfort [12]. In eastern Ukraine, Petrova et al. [297] identified that public policy on housing and energy regulation affect the performance of buildings, resulting in very cold thermal environments due to inadequate heating. In Sweden, Engvall et al. [298] reached a similar conclusion.

Based on the studies of Han et al. [282] in homes located in urban and rural areas of Hunan (South China) and Huang et al. [299] in suburban Beijing, it is clear that rural residents have greater cold tolerance.

Li et al. [300] compared the results of an artificial neural network model with an actual sensation vote obtained through evaluations that were carried out in residential buildings in China, where a maximum deviation of 3.5% was achieved [300].

Adaptive behavior and environmental control

A pilot experiment researched the adaptive behaviors (to heat) of people who have recently migrated to Spain [301]. The authors noted that people used various mechanisms of adaptation in their homes (change of clothes, food and drink intakes also changed in summer, as did the use of blinds) and that not all respondents possessed or were using air-conditioning because it was not necessary in the opinion of the users (some users also complained of overcooling in public spaces) [301].

By searching the adaptive behaviors of elderly people in homes in Taiwan, Hwang and Chen [302] found that their main strategy during summer was operating apertures, while during winter they wore more clothes to provide insulation [302].

Majid et al. [303] conducted a study in houses about the use of air-conditioning in the hot and dry weather of Oman. The survey revealed extended periods of air-conditioning operation and the preference of users for cooler environments, despite users reporting neutral to cold thermal sensations [303]. In naturally ventilated residential buildings in Harbin, China, users preferred lower air velocities even at higher indoor temperatures during the summer (cool conditions) [304]. During the winter in residential buildings in China, Luo et al. [305] and Cao et al. [306] found that residents with the possibility of personal control on the environment presented lower neutral operative temperature compared to those residents without control. In a study in passive houses in Denmark, users evaluated the thermal environment as hot in summer and cold in winter and reported feeling frustrated by not having control over the heating system, which was centrally controlled [307].

In Seoul, the behavior of users with respect to the control of cooling and heating systems was studied in houses [308]. Results indicated that the HVAC systems generated a comfort expectation for users, adjusting the comfort zone to warmer in winter and cooler in summer [308]. A research project conducted in naturally ventilated university dormitories in China demonstrated that user have a higher tolerance of temperature and that the effect of humidity on thermal comfort at high and low temperatures should not be ignored [309]. Sekhar and Goh [310] found that, although thermal acceptability was good in dormitories with naturally/mechanically ventilated (NMV) and others with air-conditioning, the thermal environment was better in the NMV rooms [310]. Regarding adaptive opportunities in naturally ventilated houses, a study in Japan showed that the opening of windows depends on the outdoor and indoor temperatures [311]. In Nigeria, the study by Adunola [312] identified the impact of urban microclimate in the comfort inside the residences. Another study performed in low to middle income housing in South Australia demonstrated that, due to the cost of using air-conditioning, people primarily tried to cool themselves through less expensive methods: by turning on fans, operating openings and curtains and by changing their clothes [313].

In Finland, Karjalainen [314,315] performed field studies in offices, and in homes – where a greater amount of data was collected. The results show better thermal comfort levels in homes; additionally, in the offices, people realized they had less control over the thermal environment and fewer adaptive opportunities [315]. Karjalainen also concluded that there are differences in the thermal comfort sensation, preferences and use of the thermostat according to gender.

The influence of age and gender

In his review paper, Karjalainen [316] concluded that women are less satisfied with the thermal environment than men in the same thermal environments, and that women prefer higher temperatures and are more sensitive to heat and mainly cold discomfort [314]. In a study conducted in homes in Harbin (China), results show lower sensitivity of men to temperature changes, as well as differences of 1°C in the neutral operative temperature between men and women [317]. Indraganti [318] performed a field study in naturally ventilated apartments in India and found no significant correlation between age and thermal comfort. Another study conducted in naturally ventilated residential buildings demonstrates that the effects of gender and age, when compared with the effects of environment variables, are of little significance in the evaluation of thermal comfort [319].

Studies about traditional and modern buildings

Other studies compared the thermal comfort in traditional and modern houses located in Mardin (Turkey) [320], in Kerala

(India) [321], in Indonesia [322] and in Cameroon [284,323]. Results show that the traditional houses provided a more comfortable indoor environment than the modern ones [284,320–323]. A study performed in traditional vernacular houses in different climates of Nepal indicates that indoor neutral temperature is highest in subtropical climates, medium in temperate climates, and lowest in cool climates [324]. The study by Singh et al. [325] evaluated the thermal comfort of vernacular buildings located in North-Eastern India and found that these buildings provided satisfactory comfort conditions, with the exception of winter months. In Japan, the temporary log houses built after the Great East Japan Earthquake, showed better thermal conditions during the summer than pre-fabricated houses, however during the winter, the indoor temperature in both houses was uncomfortable, especially in the temporary log houses [326]. The study conducted in homes (traditional and modern) during the period of the Harmattan (a cold-dry wind) in two cities in Cameroon (Ngaoundere and Kousseri, the last one located in a more severe climate), indicates that just 58% and 47% of occupants consider their thermal environments acceptable, respectively [327].

A study carried out in terraced houses in Malaysia identified the relationship between the perceived comfort and the health of residents (occupants with a higher level of comfort were healthier) [328].

Thermal comfort in other indoor environments

Studies in buildings with the most varied uses have been developed in several cities. The post-occupational study of Kavgic et al. [329] held in a theater in Belgrade, Serbia shows that the space was over-ventilated and the ventilation system was generating cold discomfort beyond the predicted point. Another post-occupational evaluation was carried out in the United States in a LEED platinum campus building (a multi-function structure that includes classrooms, seminar rooms, high-tech research laboratories, offices and studios). Despite the fact that users were overall satisfied with the indoor environment, there were complaints about overcooling and low air movement and thermal comfort was comparatively low [330]. In mosque buildings in Kuwait, the neutral temperature found through occupants' questionnaires was higher than the temperature obtained from PMV [16]. In a coalmine emergency refuge facility, Li et al. [331] proposed a simplified PMV equation that evaluated this type of environment [331].

Study by Yau et al. [332] evaluated the thermal conditions in the National Museum of Malaysia. Revel and Arnesano [333] studied the perception of the thermal environment in a gym and swimming pool in Italy and concluded that PMV could be used to evaluate sports buildings. A lobby working with air-conditioning in Malaysia was studied through field study with subjects and the results were analyzed by the extension of PMV (with an expectation factor) [334,335]. A guest service center with air-conditioning in Taichung, Taiwan was the subject of a field study investigating the influence of step changes in environmental variables (from outdoor to indoor) on comfort sensation and comfort expectations [336]. A field study of thermal comfort was conducted in naturally ventilated waiting areas of a railway station in Chennai, India [337].

Based on field study in workplaces and in residences in Taiwan, Hwang et al. [338] proposed a new equation to calculate the PPD in hot humid climates, increasing the value of the percentage of dissatisfied to 9% in the cold side of the scale [338]. Wijewardane et al. [339] studied the thermal adaptability of workers in naturally ventilated factories in Sri Lanka (a hot and humid climate), demonstrating the influence of air velocity in tolerance to higher temperatures (above 34°C) [339]. At workstations in the automotive industry in Malaysia, Ismail et al. [340] identified the poor condition of the thermal environment. By using a metabolic analyzer in workplaces in a industrial company Broday et al. [341] set new values for the metabolic rate through calculations and measurements. The findings differ from the values provided in ISO 8996 (2004). By using the new metabolic rates the actual thermal sensation correlated better with PMV [341].

In four cities in three countries (Korea, the United States and Japan), Kim et al. [342] studied peoples' adaptation to air-conditioned environments in several building types (hotel, market, café, amongst others). Results demonstrated how cultural aspects (as in the Japanese case) influence user's adaptation to thermal environments and showed variations in the insulation of the clothes by the type of environment [342]. One specific finding indicates that people who are exposed to narrow range of temperatures (AC cooling) cannot stand hot indoor climates [342].

Simone et al. [343] studied a hypermarket, a large retail facility, in Italy and found discrepancies between subjective responses and PMV. This suggests that PMV could be unable to estimate thermal comfort when clothing insulation is unevenly distributed on the human body. This is more commonly a problem for women than men [343]. Della Crociata et al. [344] proposed a measurement protocol and questionnaires to assess the thermal comfort of the hypermarkets' employees. In commercial kitchens, the study by Simone et al. [345] also found that the use of PMV is not suitable for thermal evaluations in such environments.

Through interviews, Lai et al. [346] found that users of air-conditioned commercial buildings in Hong Kong were dissatisfied with the thermal environment and among the IEQ attributes evaluated, thermal comfort was perceived as the worst.

Lee et al. [347] studied the descriptors "warm" and "slightly hot", when translated from English to Korean and used in scales to assess the thermal comfort sensation. Results indicate that for Koreans, the term "warm" indicates thermal comfort, while "slightly hot" refers to some sort of discomfort [347]. The authors concluded that it is necessary for a Korean scale to consider such descriptors, when mild hot environments are evaluated [347]. A similar study was conducted by Tochihara et al. [348], but with Japanese, English and Indonesian people. The descriptor "cool" was associated with the thermal comfort sensation for Indonesians [348]. Both studies were conducted indoors [347,348], however authors did not specify the type of building.

Hospitals, healthcare facilities and elderly centers

In the tropical climate, Yau and Chew [349] assessed four hospitals and found that 49% of the occupants were satisfied with the thermal environments in the hospitals. Higher comfort temperature than that prescribed by ASHRAE 55 was required for Malaysians in hospitals [349], which was also corroborated by Azizpour et al. [350,351] in the study of a hospital in Malaysia. Based on staff evaluations from nine hospitals, Yau and Chew [352] developed an adaptive thermal comfort model for hospital environments with air-conditioning in a tropical climate. Verheyen et al. [353] found that in patients rooms at a Belgian healthcare facility, 29% of the thermal environments evaluated did not reach the conditions recommended by ASHRAE 55. Still, the patients' thermal acceptability was 95%. This indicates that the comfort bands of the standard could be wider for this type of users. Other studies in hospital settings were carried out by Wang et al. [354] in Taiwan and by van Gaever et al. [355] in Belgium. Khodakarami and Nasrollahi reviewed the literature on thermal comfort in hospitals [356]. An overview of thermal comfort for older people with dementia was presented by [357].

In Hong Kong, a study compared the results of thermal acceptability of the elderly in centers for older people with younger residents [358]. Results established that for every 25.3 years, a probable decay of one predicted mean vote was stated for people with 60 or more years [358]. The study by Mui et al. [359], performed in 19 elderly centers in Hong Kong, indicates that all users felt satisfaction with the conditions of the indoor thermal environment, as well as with the other three environmental conditions evaluated (air quality, lighting and noise level) [359].

Hostels

A study conducted in student hostels in Malaysia used questionnaire results to infer that students who live in rooms with projected balconies were more satisfied with their indoor environment [360]. Wafi and Ismail [361] and Dahlan et al. [362] also studied other student hostels in Malaysia. According to the work of Dhaka et al. [363] in India, there were a wide range of neutral temperatures (wider and higher than international standards) at 6 naturally ventilated student hostels. Based on the research of Guedes et al. [364], who performed a field study in offices, homes for the elderly and educational buildings in Lisbon (Portugal), people experience the sensation of thermal comfort in wider temperature ranges than specified in ASHRAE 55 [364].

THERMAL COMFORT AND PRODUCTIVITY

A study in Tokyo, Japan during the summer under mandatory electricity savings after the Great East Japan Earthquake was held in office buildings [81]. The authors imposed a variation of indoor temperature and ventilation conditions and concluded that users expressed discomfort at higher temperatures and recommended a maximum operative temperature of 27ºC [81]. The user productivity compared to the previous year's survey was estimated through a self-assessment and resulted in a loss of productivity of 6.6% [81].

Climate chamber studies were performed in Japan (users could not change their clothes, nor the environmental conditions of the room) and demonstrated in short exposure time, no change in productivity in high temperature and humidity conditions [365]; on the other hand, in longer exposure time there was a decrease in productivity in a hot and dissatisfying environment [366]. Another study in a climate chamber in a non-steady thermal environment in Denmark (users could only change their clothes) found no difference in productivity amongst the analyzed thermal conditions (19.0-26.8ºC) [367]. In a US study, subjects were exposed to cold conditions (10ºC) and then to 25ºC [368]. The authors concluded that cognitive function is reduced during the cold exposure and that such reduction persisted for one hour during the rewarmed period [368]. In China, another study involving two groups of subjects (one exposed to temperature variations and the other exposed to 26°C) concluded that a warm discomfort environment had a negative effect on performance. The study recommended an optimum range of temperatures for performance: 22ºC to 26ºC [369]. Also in China, another study evaluated the influence of constant mechanical wind (CMW) and simulated natural wind (SNW) on human thermal comfort and performance, indicating that both airflows would increase comfort in warm environments (CMW performed better at a close to neutral condition and the SNW performed better at a warmer condition), but no differences were found in human performance [370]. In Lithuania, three groups of subjects exposed to constant (22ºC), rising (22ºC to 26ºC; +0.1ºC/h) and dropping (22ºC to 18ºC; -0.1ºC/h) air temperatures were assessed with respect to office work performance; regarding the constant temperature conditions, the case with a rising temperature showed a decrease in performance of 2.5% and the case with a dropping temperature an increase of 1.6% [371].

A climate chamber study using task-ambient conditioning (TAC) evaluated productivity and concluded that TAC does not affect the task performance in relation to a neutral environmental condition [372]. Another study on productivity using TAC was conducted in an office building in Japan, where users were exposed to different environmental conditions (TAC off, TAC on and TAC controlled by users) [373]. When users controlled the TAC, they reported fewer symptoms and had a lower loss of vitality level, so the use of TAC is important to maintain the vitality level [373]. In another survey conducted in a climate chamber operating with personalized ventilation (PV), Bogdan et al. [374] determined thermal conditions (ambient room temperature and PV air supplied temperature) for summer and winter which led to better productivity results.

In Singapore and Thailand, in office rooms with air-conditioning (a semi-controlled environment) productivity studies were conducted [375,376]. In Singapore, despite causing lower thermal sensation and reduced thermal comfort, a lower air temperature (moderate cold exposure of 20ºC) increased mental arousal and increased performance in activities requiring attention [376]. In Thailand, research indicates that in order to maintain and increase productivity, indoor temperatures should be higher in the morning (26-28ºC, warmer thermal condition than PMV-ISO 7730) than in the afternoon and evening (24.5-26ºC) [375]. This finding may be related to the results obtained by Kakitsuba and White [377] in climate chamber experiments in Japan. The authors evaluated the core temperature of the human body (Tc, which is lowest during wake up in the morning and increased during the daytime) -circadian rhythm- and concluded that the best outcomes for thermal comfort and thermal sensation were obtained through daytime temperature variations - with higher air temperatures during the morning and lower temperatures in the afternoon.

In a Finnish study on productivity carried out in an office building during the summer, self-estimated work efficiency decreased when the temperature was above 25ºC [378]. In a Japanese call center an increase in air temperature from 25 to 26ºC resulted in a decrease in performance of 1.9% [379].

Katafygiotou and Serghides [205] studied the perceived learning performance (PLP) by comparing air-conditioned and fan-assisted naturally ventilated environments (FANV) in schools in the hot and humid climate of Cyprus. Students with uncomfortable thermal sensation reported worse PLP in FANV environments [205], but more research is needed in the area. Learning performance was also studied in a university building in Hong Kong [380]. The higher the number of IEQ complaints (including thermal comfort), the higher the student learning performance loss [380]. A performance comparison between green schools and conventional schools in Toronto, Canada shows that green buildings present improved productivity than conventional ones [381]. In addition, thermal comfort and other IEQ attributes were better at the green schools [381].

A study carried out in a climate chamber (simulating an office) in Denmark, included 12 subjects dressed with a clo of 0.9 and subjected to 22ºC (thermal neutrality) and 30ºC (Lan et al. [382] e Lan et al. [383]). The users were subjected to a series of tasks for the purpose of estimating their productivity in both thermal conditions. The authors concluded that task performance was reduced when people felt warm and that this loss was a result of elevated air temperature [382]. Such work generated discussion, resulting in a critical letter to the editor [384] and another one in response from the authors [385].

In a review paper [386] and in a letter to the editor [384], Leyten and Kurvers (and Raue, in the review article) point out the limitations of the work of Lan et al. [382]. The critique pointed out that the research was conducted in a climatic chamber and concludes that the findings of Lan et al. can not be extrapolated to real conditions in naturally ventilated buildings. In reply to Leyten and Kurvers, Lan et al. [385] argued that while there is no field work in naturally ventilated buildings proving a loss of performance of office work in high temperature conditions where the PMV and the adaptive model differ, they are satisfied with their conclusions.

A short time later, Wyon and Wargocki [387], two of the authors of the discussed article (Lan et al. [382]), wrote a letter to the editor criticizing a review article on thermal comfort of de Dear et al. [388], which contains a chapter on thermal comfort and productivity. Wyon and Wargocki [387] again argued that if the indoor operative temperatures vary according to the adaptive model, the productivity can not be maintained and would instead be reduced. In response, de Dear et al. [389] together with Leyten and Kurvers, asserted that the conclusions of Wyon and Wargocki should be limited to the experimental conditions of their study (Lan et al. [382]) performed in a climate chamber.

In this context, it is evident that the relationship between thermal comfort and productivity requires more attention from researchers. Typically, research in the area uses different methods to estimate productivity, therefore hindering any comparison between studies. The standardization of methods to estimate productivity would result in a better understanding of the subject.

OVERVIEW OF PHYSIOLOGICAL MODELS

In the field of physiological modeling, studies conducted have shown great progress. Review papers about physiological modeling are available in the literature [25]. A review about the human thermoregulatory behavior was presented by [390]. According to the review articles of de Dear et al. [388] and Cheng et al. [391], the first thermoregulation models of the human body and thermal comfort divided the human body between one (whole body) [43] and 15 segments [44–46]. Each part of the body was again divided into nodes, with a minimum of two nodes to the model of Gagge, Stolwijk and Hardy [43] and Gagge, Stolwijk and Nishi [47]: the Pierce two-node model. The nodes compose anatomical segments (fingers, hands, head, etc.) and have inherent physical properties (conductivity, for example) which are modeled numerically to solve the heat balance equation [388].

The models of Stolwijk and Hardy [44] and Stolwijk [46] laid the foundation for several more current physiological models such as Fiala et al. [48,392], UC Berkeley [49], Tanabe et al. [50], ThermoSEM [51,393] and JOS-2 [394], which use between 15 and 19 segments and hundreds of nodes.

Another promising field of research, 3-D human body models, is more complex and requires better computer resources using thousands of nodes [391].

The physiological models have been validated by experimental studies (subjective responses) in order to predict the thermal sensation and thermal comfort of each body part, as well as of the whole body. A great effort in this direction has been conducted by researchers at UC Berkeley [395–397]. Recently, in partnership with Tsingua University, UC Berkeley further reviewed and refined their comfort model [398,399], which can be used in uniform and non-uniform, transient and steady-state environments. In another study, a predictive model of local and overall thermal sensations for non-uniform environments was proposed based on studies with subjects in a climate chamber in China [400].

In recent years a number of new approaches have been proposed, for example, a new adaptive predicted mean vote (aPMV) model was developed with the goal of extending the application of PMV in free-running buildings [401]. The aPMV uses an adaptive coefficient that is based on field study. Such a coefficient was determined in naturally ventilated buildings at Chongqing University in China [401]. A new framework for modeling occupants' adaptive thermal comfort that considers adaptive actions probability, as well as feedback of users' perceived comfort from these actions, was developed and applied in a building in Switzerland [402]. A new simplified three-node model for non-uniform thermal sensation (bare and clothed parts of the human body) was developed based on Gagge's model [403]. A new approach (multi-segmental -MS- Pierce model) to predicting the local skin temperatures of individual body parts was proposed based on the Pierce two-node model [404], which later was used as the thermoregulatory control mode for thermal manikins [405]. A new predictive thermal response index was proposed for use in steady-state and transient conditions based on the 1991 Ring and de Dear model [406]. A new simplified predict thermal sensation equation - using only the air temperature and water vapor pressure - was proposed based on field work in office buildings [407]. Another new model for predicting thermal sensation based on the neurophysiology of thermal reception was developed and validated through subject experiments in the Netherlands [408]. A new equation for the prediction of whole-body thermal sensation in the uniform and non-steady state based on skin temperature was built and validated through subject experiments in climate chambers in Japan [409]. Revised and new PMV-PPD curves for offices representing the relationship between PMV and direct thermal acceptability and preference ratings were developed using Bayesian probit analysis [410]. A novel two-stage regression model of thermal comfort was developed and validated in an office building in the United States [411]. In China, a data-driven method describing personalized dynamic thermal comfort was proposed and tested [412]. A new methodology to evaluate the thermal environment based on operative temperature thermal levels (decitherms, analogous to decibels in acoustics) was proposed by Jokl [413]. A new PMV (nPMV) based on the adaptive comfort theory was proposed and compared with the original PMV and with the actual thermal sensation of subjects in an air-conditioned office building in South Korea show better results than the original PMV [414].

In 2011, Foda et al. [415] compared the predictions of skin temperature from three different models of human thermoregulation (Fiala, UC Berkeley and MS Pierce model) with experimental data, showing that the MS Pierce model presented a good performance. The model was then coupled with the UC Berkeley comfort model to predict the local thermal sensation and the results were compared with subjective votes, showing a positive match for most body segments [415]. In 2013, Schellen et al. [416] compared experimental data in a climate chamber with Fanger's, ThermoSEM and UC Berkeley models (the latter before the 2014 review [398]). Results confirmed that when local effects have significant influence, the PMV is not a good predictor of the body's overall sensation [416]. The combination of ThermoSEM and UC Berkeley models is promising to predict local and overall thermal sensations in steady-state non-uniform environments [416].

Recently, a new approach using exergy analysis instead of energy analysis (commonly used by thermal comfort prediction methods) was proposed, showing interesting results [417–424]. A review about the exergy balance equation can be found at [425]. This may be a field of research with a promising future.

THERMAL COMFORT IN OUTDOOR AND SEMI-OUTDOOR ENVIRONMENTS

Outdoor thermal comfort models

In outdoor environments people are directly exposed to local microclimate conditions of solar radiation, shading and changes in wind direction and speed [426]. Despite these dynamic conditions, the use of PMV-PPD index is common for the evaluation of thermal comfort outdoors [426]. As pointed out in a review paper by Chen and Ng [426], the use of the PMV-PPD in the outdoors leads to considerable discrepancies between the actual sensation vote (ASV), collected subjectively through questionnaires of thermal comfort, and the PMV. Another static method that has been widely used, but that has presented better results than the PMV in outdoor environments, is PET (Physiological Equivalent Temperature) [426]. However, static methods have the limitation of not taking into account the dynamic adaptive aspects of human beings [426]. Thus, specific indices for outdoor environments are being developed and are presenting improved results [426]. In order to assist with future research in the area, Chen and Ng [426] proposed a general framework for outdoor thermal comfort assessment, which covers the physical, physiological, psychological and social/behavioral aspects.

More recently, a new outdoor thermal index indicating universal and separate effects on human thermal comfort for uniform conditions (ETVO) [427] and for non-uniform conditions (the universal effective temperature – ETU) [428] were proposed by Nagano and Horikoshi. Another proposed thermal index is the Universal Thermal Climate Index (UTCI) based on an advanced multi-node model of thermoregulation [429].

Another outdoor thermal comfort model (COMFA) was assessed in field tests (walking, running, and cycling activities) in Canada [430,431] and improvements to the model were also made [432]. A new conceptual model of direct and indirect influence of place-related parameters on human responses was proposed and applied in a outdoor space in Gothenburg [433]. A new thermal index for outdoor environments (ETFe-enhanced conduction-corrected modified effective temperature) was proposed by Kurazumi et al. [434] based on ETF (conduction corrected modified effective temperature) index [435] and the new index was compared to subjective responses from field studies during the summer [436] and winter [437,438] in outdoor places in Nagoya (Japan).

Outdoor field studies

Field surveys at 14 different outdoor sites, across five different countries in Europe, led to the finding that at least 75% of people are comfortable on a yearly basis [439]; the actual thermal sensation votes were compared with PET, the Temperature-Humidity Index (cTHI) and the wind chill index (K) [440].

Field studies were conducted at outdoor sites in Gothenburg (Sweden) and Matsudo (Japan) [441,442], in Lisbon (Portugal) [443], in Matsudo [444], Tajimi [445] and 14 forests and urban areas in Japan [446], in Taichung [447–450] and Chiayi

[451] (Taiwan), in Marrakech (Morocco) and Phoenix (US) [452], in the Hague, Eindhoven and Groningen (Netherlands) [453–455] and in Beirut (Lebanon) [456]. Additional field studies were also conducted in Xi'na [457], Guangzhou [458], Nanjing [459], Chengdu [460], Tianjin [461], Wuhan [462] and others [463] (China), in Cairo (Egypt) [464], in Curitiba (Brazil) [465–467], in Hong Kong [468,469], in Szeged (Hungary) [470,471], in Malaysia [472,473], in Athens [474–477] and Crete [478] (Greece), in Damascus (Syria) [479], in Glasgow (UK) [480], in Singapore [481,482], in Mendoza (Argentina) [483], in Barranquilla (Colombia) [484], in the Caribbean islands of Barbados, Saint Lucia and Tobago (with beach tourists) [485] and in Israel [486]. The results were analyzed through PET and/or other indices (UTCI, OUT_SET-outdoor standard effective temperature, for example) and variables (air velocity, solar radiation, clothing, for example). Another study measured the solar absorptance of the clothed human body in Japanese subjects [487]. In outdoor environments and based on data from field studies conducted in Taiwan, Tung et al. [488] concluded that women are less tolerant of heat and, for cultural reasons, protect their skin more from solar radiation [488].

The literature includes review papers on outdoor comfort studies [489] about different approaches for outdoor thermal comfort [490] and about the mean radiant temperature for outdoor places [491]. Another review paper examines the instruments and methods used to assess outdoor thermal comfort and subjective thermal perception [492].

Semi-outdoor studies

Regarding transitional spaces, Chun, Kwok and Tamura [52] defined them as spaces in between outdoor and indoor. This includes balconies, lobbies and bus stations: areas that are influenced by the prevailing weather conditions, but that are limited by a construction. In these spaces, the transitional zone is modified without mechanical control systems [52]. These types of environments are also commonly referred to as semi-outdoor environments. In order to avoid possible confusion, as pointed out by Chun, Kwok and Tamura [52] through the use of the term “transitional” and “transient”, in this review paper we chose to use the term “semi-outdoor environments”. The regulations and existing standards do not provide guidelines for the thermal environment of such spaces [108] and these spaces have not been studied in great detail. Fanger's model (PMV-PPD) is not applicable for research in the area of semi-outdoor environments [52].

The review paper presented by van Hoof [108] collects some of the findings of research conducted in applying PMV model in outdoor and semi-outdoor environments. The changes in clothing, metabolic rate and the high variability of physical parameters limit the use of this model in outdoor and/or semi-outdoor environments [108]. The author also points out the validity of the model exposed by Fanger himself: PMV is only applicable for indoor spaces and constant environmental conditions [108]. Kwong et al. [493] state that in tropical climates like Malaysia the air velocity is important to maintain thermal comfort.

Thermal comfort ranges were proposed based on a field study in outdoor and semi-outdoor environments in Taiwan [494] and the effect of seasonal thermal adaptation was also studied [495]. Outdoor and semi-outdoor environments were also investigated in Wuhan (China) [496] and in Nagoya (Japan) [497].

In semi-outdoor environments in a university in Singapore (two food centers, one with misting fans and the other without misting fans, as well as one coffee store with a misting line system), a field survey was conducted. The survey concluded that for the same outdoor effective temperature (ET*), lower votes of thermal sensation were achieved by using misting fans [498]. A field study in a workshop in a university in Beirut was used to validate a thermal comfort model proposed for semi-outdoor environments [499].

CONCLUSIONS

In this paper a review of human thermal comfort in the built environment was performed. The review focused on articles published in the last 10 years however remarkable works and some standards were also discussed.

The methodology used to select the literature allowed the authors to identify the difficulties that still exist in the selection of keywords and writing for abstracts. The term "thermal comfort" is often used indiscriminately, which hindered the process of searching for articles by area of interest. The abstracts themselves also had inadequacies. Many of them did not include enough information to facilitate the identification of the type of building used in the study (real environment or climate chamber or simulation, for example), the period of the study, the results and the main conclusion. In many cases it was necessary to read parts of the article to be able to extract such basic information about the work.

Over the past 10 years, several research topics involving thermal comfort have emerged, as the occupant behavior studies and the exergy analysis in physiology. Still others were rescued, such as the growing interest in naturally ventilated and mixed-mode buildings and personalized conditioning systems, the development of more complex and accurate physiological models, the increased interest in thermal comfort in the outdoors and studies aimed at productivity. The latter is deserving of more attention from researchers. Also in the last 10 years, different authors in many countries around the world developed several new adaptive thermal comfort models and others worked to correct or adjust the PMV/PPD model for actual building types and different conditioning modes. These new data have been contributing to the improvement of models of thermal comfort. While there have been many field studies bringing valuable information from the people conducting their activities in their everyday environments, including research into the person-environment relationship and the factors that affect thermal comfort in the built environment, studies are still numerous in controlled environments and analyze issues individually. In some situations thermal comfort cannot be fully explained by the classical six variables (two human and four environmental). There are a number of other factors that influence the sensation of thermal comfort, like cultural and behavioral aspects, age, gender, space layout, possibility of control over the environment, user's thermal history and individual preferences. Static and homogeneous environments leading to thermal monotony, an expensive solution, previously preferred, are giving way to dynamic environments, in which wider ranges of indoor temperature are preferred and the natural ventilation is desired. The use of personalized conditioning systems is probably the best ways to increase user acceptability with the thermal environment. Thermal comfort is a complex topic and we are far from understanding all its interrelated aspects.

Through this review of the literature it became evident that there is a gap in thermal comfort studies in relation to interdisciplinary research. The association with other professionals like psychologists, physiologists, sociologists, philosophers and even with other building related ones (architects and engineers that work with visual, aural and olfactory comfort) could be of great value for the development of an integral (systemic/holistic) research approach that may help to a better comprehension about sensation, perception and thermal comfort and its physiological and psychological dimensions.

If the trend of exponential growth of papers in the area continues in the coming years, it is likely that research into many subjects in the area will be deepened and new ways of looking at thermal comfort will be explored. We certainly need a better understanding of thermal comfort to face climate change and the demands for more energy efficient buildings.

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3. MÉTODO

Neste capítulo é descrito o método proposto para alcançar os objetivos desta pesquisa. O trabalho foi baseado em estudos de campo sobre conforto térmico em edificações de escritórios com ventilação híbrida e com sistema central de ar-condicionado, localizadas no clima subtropical úmido de Florianópolis. Os estudos de campo foram realizados durante os anos de 2014 a 2016 e envolveram a participação voluntária de ocupantes das edificações. Os usuários responderam a questionários de conforto térmico ao mesmo tempo em que medições ambientais dos espaços eram efetuadas.

Os resultados dos levantamentos de campo foram devidamente tabulados e analisados dentro do contexto dos objetivos desta tese. Cabe ressaltar que nem todos os dados, tanto dos questionários quanto das variáveis ambientais, foram utilizados nesta tese; poderão ser utilizados em trabalhos futuros.

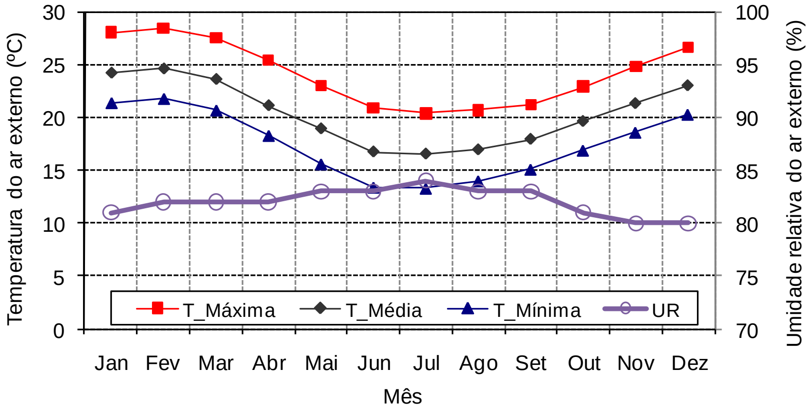
O método de coleta de dados desta tese foi adaptado do método de De Vecchi (2015). A coleta de dados durante o ano de 2014 foi realizada em conjunto com a pesquisadora e os dados coletados neste período foram utilizados por De Vecchi (2015) em sua tese de doutorado.

3.1 CARACTERÍSTICAS CLIMÁTICAS DE FLORIANÓPOLIS

A cidade de Florianópolis (latitude 27º36’ S, longitude 48º33’O e altitude de 7m), localizada no Estado de Santa Catarina, possui clima subtropical úmido, com verões quentes e invernos amenos e com ocorrência de precipitação ao longo do ano (sem período de seca), sendo rotulada como Cfa, segundo a classificação climática de Köppen-Geiger (ALVARES et al., 2013; KOTTEK et al., 2006). De acordo com o zoneamento bioclimático brasileiro, a cidade está localizada na Zona Bioclimática 3 (ABNT, 2005), dentre as 8 zonas existentes.

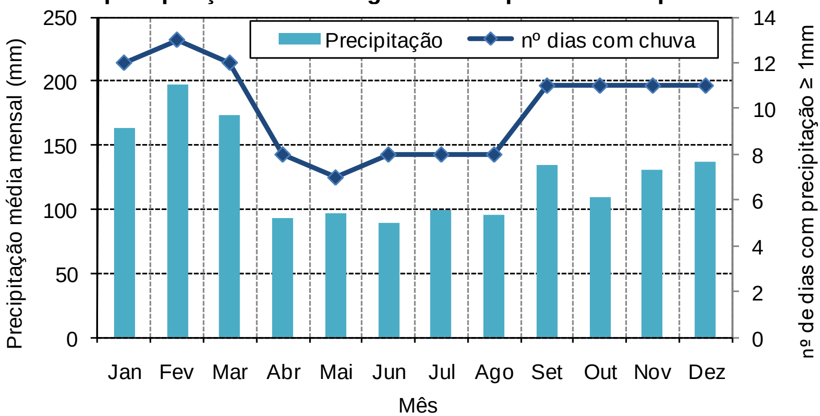
A ilha de Florianópolis é banhada pelo oceano atlântico e devido a esta proximidade com o mar, altas umidades relativas do ar são observadas ao longo do ano, com médias mensais superiores a 80% (Figura 2). A precipitação média anual é de 1518mm e as precipitações médias mensais variam entre 90 e 197mm, conforme mostrado na Figura 3, que também apresenta o número de dias com precipitação maior ou igual a 1 mm, para cada mês (anualmente são 120 dias com chuva). As precipitações são maiores durante os meses de dezembro a março, quando as temperaturas externas também são maiores (chuvas de verão). Porém, no mês de setembro também há precipitação considerável.

Figura 2: Temperaturas máximas, médias e mínimas mensais do ar externo e umidade relativa média mensal do ar externo para Florianópolis.



Fonte: Normais Climatológicas (1961-1990) (BRASIL, 1992).

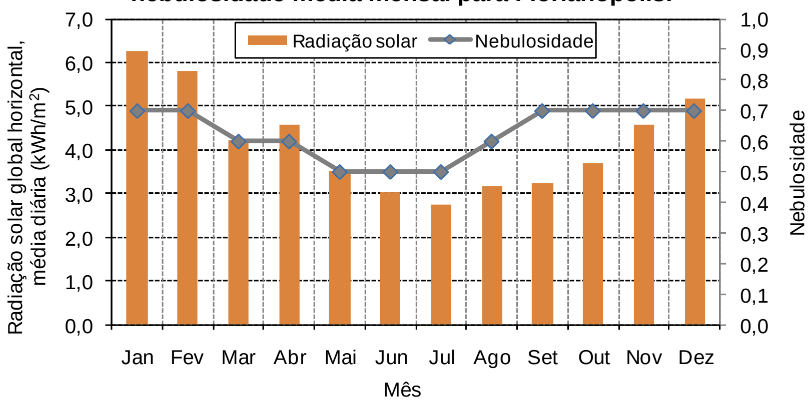
Figura 3: Precipitação média mensal e número de dias com precipitação maior ou igual a 1mm para Florianópolis.



Fonte: Normais Climatológicas (1961-1990) (BRASIL, 1992).

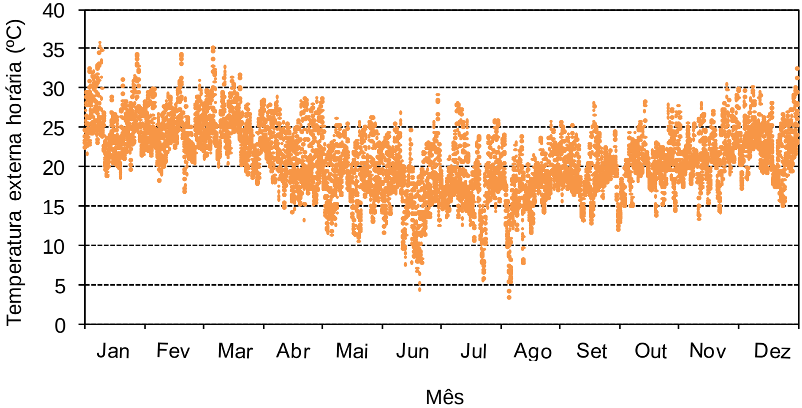
A temperatura do ar externa mensal (média, máxima e mínima), bem como a radiação solar global horizontal variam conforme as estações do ano e podem ser visualizadas nas Figuras 2 e 4, respectivamente. Na Figura 5 podem ser visualizados os dados de temperatura do ar externa em base horária provenientes do arquivo climático de Florianópolis TRY 1963. As temperaturas médias do ar externo atingem 24,6ºC durante o mês de fevereiro (verão) e 16,5ºC no mês de julho (inverno), com média anual de 20,4ºC. A amplitude térmica média das máximas mensais é de 13,5ºC, a mínima de 2,9ºC e a média de 7,6ºC. A máxima radiação solar global horizontal (média diária) ocorre no mês de janeiro (6,27 kWh/m^2) e a mínima radiação solar (2,73 kWh/m^2) ocorre no mês de julho. Condições de céu encoberto são comuns em Florianópolis e a nebulosidade média anual é de 0,6 (Figura 4).

Figura 4: Radiação solar global horizontal (média diária) e nebulosidade média mensal para Florianópolis.



Fonte: Arquivo climático de Florianópolis TRY 1963 (LabEEE, 2015a) e Normais Climatológicas (1961-1990) (BRASIL, 1992), respectivamente.

Figura 5: Temperatura do ar externo em base horária para Florianópolis. Cada ponto representa uma das 8760 horas de um ano.



Fonte: Arquivo climático de Florianópolis TRY 1963 (LabEEE, 2015a).

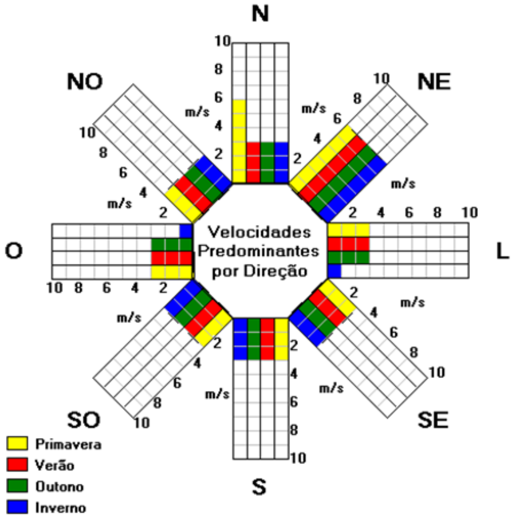
Com relação aos ventos em Florianópolis, as maiores velocidades predominantes (6 m/s) são encontradas na orientação nordeste durante as quatro estações e durante a primavera, na orientação norte (Figura 6a). Estas duas orientações, de modo geral, apresentam as maiores frequências de ocorrência de ventos durante o ano todo (Figura 6b) e estão associadas às massas de ar (quentes) tropicais marítimas (MENDONÇA; LOMBARDO, 2009). A orientação sudoeste apresenta frequências de ocorrência de ventos (porém, com velocidades menores) similar à orientação nordeste, com exceção do verão, onde as ocorrências de vento são menores a sudoeste. Os ventos provenientes do quadrante sul estão associados às massas de ar polar marítimo do Atlântico e sua ocorrência indica a entrada de frentes frias (MENDONÇA; LOMBARDO, 2009). Nas demais orientações, as velocidades predominantes são menores (3 m/s) e menos frequentes. Destaca-se que durante o inverno, nas orientações oeste e leste, as velocidades predominantes são ainda menores (1 m/s) e a ocorrência de ventos nessas direções é baixa (2,2%).

As condições gerais do clima de Florianópolis não descrevem as mudanças bruscas do tempo atmosférico que ocorrem ao longo do ano, em função da entrada de frentes frias polares que se chocam com as massas de ar tropicais marítimas

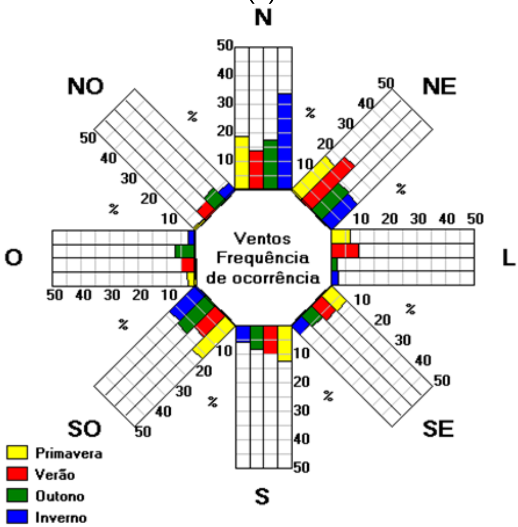
(MENDONÇA; LOMBARDO, 2009). As grandes amplitudes térmicas diárias observadas em Florianópolis ocorrem, portanto, devido à atuação da massa de ar polar atlântica (MENDONÇA; LOMBARDO, 2009). Na Figura 7 são apresentadas as temperaturas do ar externo para nove dias consecutivos no verão e no inverno, como exemplificação da atuação de frentes frias ao longo do ano, causando grandes mudanças nas condições atmosféricas.

Devido ao clima de Florianópolis, em edificações de escritórios é comum o uso de ar-condicionado para resfriamento durante as épocas mais quentes do ano; aquecimento não é normalmente empregado (SANTANA, 2006). Porém, existem edificações que operam com sistema central de ar-condicionado durante o ano todo. Uma comparação entre o consumo de energia de diferentes ambientes de escritórios operando com ar-condicionado durante um ano climático típico e ambientes com ventilação híbrida foi realizada em Florianópolis (RUPP; GHISI, 2013). Os ambientes foram estudados por meio de simulações termoenergéticas no programa EnergyPlus. O consumo de energia dos ambientes híbridos foi reduzido em (i) até 32%, em comparação aos ambientes condicionados artificialmente, considerando a energia total (equipamentos, ar-condicionado e iluminação artificial) e (ii) até 72%, analisando-se somente o dispêndio de ar-condicionado. Assim, há potencial de economia de energia em edificações de escritórios com ventilação híbrida em Florianópolis, em comparação a edifícios que operam somente com sistema de ar-condicionado.

Figura 6: Rosa dos ventos das (a) velocidades médias do ar predominantes e da (b) frequência de ocorrência dos ventos para cada estação do ano em diferentes orientações.



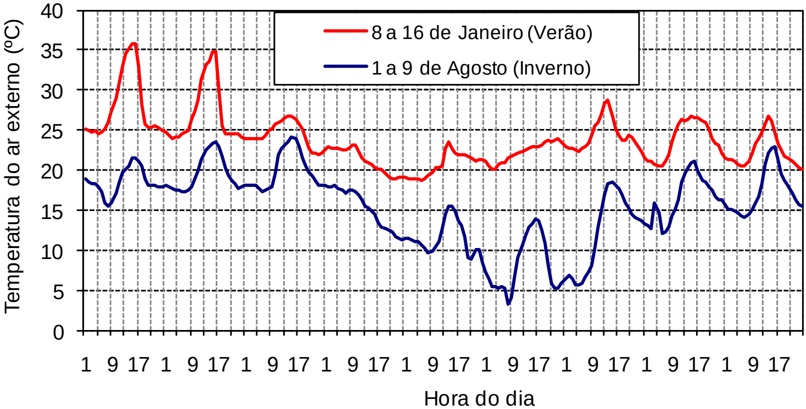
(a)



(b)

Fonte: Programa SOL-AR (LabEEE, 2015b), utilizando o arquivo climático de Florianópolis TRY 1963.

Figura 7: Temperatura do ar externo para nove dias consecutivos no verão e inverno.



Fonte: Arquivo climático de Florianópolis TRY 1963 (LabEEE, 2015a).

3.2 AS EDIFICAÇÕES ESTUDADAS

Para a realização deste trabalho foram contatadas dez empresas instaladas em edificações de escritórios, localizadas nas regiões centrais (Bairro Centro, Itacorubi, João Paulo e Pantanal) de Florianópolis. Das dez edificações, duas delas operam totalmente com sistema de ar-condicionado central e as restantes são edificações com ventilação híbrida.

Quatro das empresas contatadas autorizaram a realização do trabalho, sendo três edificações com ventilação híbrida. Foi acordado com as empresas que as informações coletadas nos edifícios são sigilosas. Portanto, não foram mostradas plantas, imagens, nem a localização precisa dos edifícios estudados. Os nomes das empresas também não foram divulgados e neste trabalho são denominadas por edificações H1, H2 e H3 (com ventilação híbrida) e CC (com sistema de condicionamento central de ar). Em três das quatro edificações estudadas foi empregado um “estudo transversal repetido” [11] de conforto térmico; em uma das edificações (H2) um “estudo transversal” foi realizado.

As edificações estudadas estão localizadas entre 1,1 e 5,4km de distância entre elas, conforme pode ser observado na Tabela 8.

Tabela 8: Distâncias em linha reta entre as quatro edificações estudadas.

Distâncias entre edificações em linha reta (km)				
Edificações	CC	H1	H2	H3
CC	-	3,3	3,7	2,8
H1	3,3	-	5,4	4,3
H2	3,7	5,4	-	1,1
H3	2,8	4,3	1,1	-

[11] Os dados podem ser coletados por estudos transversais ou longitudinais (NICOL, F.; HUMPHREYS; ROAF, 2012). Nos estudos transversais, a maioria da população alvo de estudo participa respondendo aos questionários de conforto térmico uma única vez. Esta abordagem pode evitar problemas estatísticos relacionados a amostragens não representativas da população. Porém, se um estudo transversal é conduzido em um período curto de tempo (um dia, por exemplo), as variações climáticas podem ser pequenas, impossibilitando a obtenção das respostas subjetivas em diferentes condições térmicas. Nos estudos longitudinais, uma pequena parcela da população retorna múltiplas respostas subjetivas durante um período extenso de tempo (semanas, meses ou até anos). Neste caso, os participantes necessitam de um maior envolvimento na pesquisa. Diferenças na percepção térmica entre indivíduos podem ser identificadas por este tipo de abordagem. Porém, a amostragem pode não ser representativa da população. As duas maneiras de coleta de dados podem ser empregadas de maneira complementar. Nesta abordagem, denominada de estudo transversal repetido, a mesma população participa do trabalho de campo várias vezes durante um período estendido de tempo (uma vez por mês ou uma vez a cada estação climática do ano). Assim, uma gama maior de condições climáticas é coberta, o que é importante, principalmente, em locais com estações do ano definidas.

Em cada edificação foram adotados alguns critérios gerais para a seleção de ambientes para o estudo:

- Os usuários do espaço deveriam estar desempenhando atividades de escritório (1,0 – 1,2 met), realizadas através do uso de computadores;

- Os usuários do ambiente não deveriam ser obrigados a utilizar uniforme da empresa, sendo a vestimenta escolhida por eles mesmos. Porém, algumas restrições poderiam existir, por exemplo, o uso obrigatório de calças pelos homens (mais detalhes são fornecidos no decorrer deste capítulo na descrição de cada edificação);

- Somente os ambientes de trabalho com atividades de escritório foram considerados. Assim, desconsideraram-se os *halls* de acesso, as recepções, as salas de reuniões, os banheiros, as copas, os depósitos, as circulações internas e outros ambientes transitórios;

- Ambientes com atendimento ao público também foram desconsiderados;

- Ambientes com baixa densidade de pessoas (menos de três pessoas), tais como salas de diretores, gerentes e afins não foram considerados.

Além destes critérios gerais, foram adotados outros critérios específicos para a definição dos ambientes de estudo da edificação com ar-condicionado central:

- Possuir sistema de condicionamento de ar central, sendo este o modo de climatização predominante durante o ano todo;

- Não possuir janelas operáveis.

Outros critérios específicos para a definição dos ambientes de estudo das edificações com ventilação híbrida foram:

- Possuir sistema de ar-condicionado instalado;

- Possuir janelas acessíveis e operáveis pelos usuários, permitindo a entrada direta do ar externo. Portanto, ambientes centrais da edificação ou localizados no subsolo, sem nenhuma fachada em contato direto com o exterior, não foram considerados neste trabalho;

- O sistema de ar-condicionado e/ou a ventilação natural pela operação de janelas poderiam ser utilizados de acordo com a preferência dos usuários.

Nas edificações com ventilação híbrida, a maioria dos espaços estudados permitia a ventilação natural unilateral. Porém, alguns espaços localizados nos cantos das edificações, com duas fachadas em contato com o exterior, possuíam a possibilidade de ventilação cruzada. A maioria das janelas nas edificações com ventilação híbrida era do tipo máximo ar. Porém, em alguns espaços das edificações H1 existiam janelas de correr.

3.2.1 Edificações H1

A edificação H1 é composta por três blocos. Eles foram estudados agrupados, pois se tratam de edificações de uma mesma empresa com padrões construtivos similares, localizados em um único lote urbano[12]. Os estudos de campo nestas edificações foram realizados durante os anos de 2014 a 2016. Uma caracterização das edificações estudadas pode ser visualizada na Tabela 9.

Próximo da fachada nordeste do bloco 1 existe um talude que causa sombreamento parcial no edifício e pode influenciar nas correntes de vento. A fachada sudeste é sombreada por outro edifício térreo não estudado neste trabalho.

No bloco 2, principalmente próximo da fachada principal, existe a presença de árvores que ajudam a sombrear as aberturas na fachada noroeste.

No bloco 3, apesar da fachada principal estar orientada a noroeste, as salas estudadas possuem fachadas voltadas a sudeste.

A maioria dos espaços estudados possui persianas verticais internas operadas pelos usuários.

Nos três blocos da edificação H1 os usuários possuem liberdade na escolha da vestimenta.

Em algumas estações de trabalho observou-se a presença de ventiladores portáteis individuais, controlados pelos ocupantes.

[12] No lote ainda existem outras três construções que servem para outras atividades (não de escritório), as quais não foram consideradas neste trabalho.

Tabela 9: Características das edificações H1.

Edificação	Bloco 1	Bloco 2	Bloco 3
Características gerais			
Ano de construção	Década de 1990		
Ano da última reforma	-		
Área construída apoximada (m^2)	1000	4200	1000
Número de pavimentos	1	2	1
Forma	Retangular	Formato H	Retangular
Orientação da fachada principal	Sudoeste	Noroeste	Noroeste
Padrão construtivo	Concreto armado		
Revestimento externo de paredes	Alvenaria de tijolos aparentes		
Tipo de vidro	Vidro incolor (alguns espaços c/ película aplicada)		
Proteções solares externas	-		
Características internas			
Ambientes de escritórios	Planta livre com divisórias internas		
Altura do pé-direito (m)	2,6		
Ocupação			
Número de ocupantes (aprox.)	60	220	40
Horário de ocupação (aprox.)	7-18h	8-18h	8-18h
Sistema de ar-condicionado e/ou ventilação natural			
Ventilação natural	Janelas operáveis pelos usuários		
Sistema de ar-condicionado	Aparelhos de janela e *splits* (maioria)		

3.2.2 Edificação H2

A fachada principal da edificação H2 possui menor dimensão. Assim, apesar da orientação principal do edifício ser sudoeste, a maior área de envoltória está voltada a sudeste e noroeste. Na Tabela 10 podem ser observados alguns dados da edificação. A circulação vertical é localizada no núcleo central. A edificação H2 foi estudada durante o ano de 2014.

Tabela 10: Características da edificação H2.

Características gerais	
Ano de construção	Década de 1990
Ano da última reforma	-
Área construída (m^2)	8244
Número de pavimentos	12 pavimentos + 1 subsolo
Forma	Retangular
Orientação da fachada principal	Sudoeste
Padrão construtivo	Concreto armado
Revestimento externo de paredes	Alvenaria rebocada e pintada na cor bege
Tipo de vidro	Vidro incolor (alguns espaços c/ película aplicada)
Proteções solares externas	Elementos da fachada (proteção do AC)
Características internas	
Ambientes de escritórios	Planta livre com divisórias internas
Altura do pé-direito (m)	2,6
Ocupação	
Número de ocupantes (aprox.)	350
Horário de ocupação (aprox.)	13-19h
Sistema de ar-condicionado e/ou ventilação natural	
Ventilação natural	Janelas operáveis pelos usuários
Sistema de ar-condicionado	Aparelhos de janela (maioria) e *splits*

A maioria dos ambientes possui equipamentos de janela para resfriamento do ar, porém, sistemas do tipo *split* também foram observados. A unidade externa dos sistemas *split* ou a parte externa dos aparelhos de janela são protegidas da radiação solar por um elemento opaco na fachada, com venezianas para ventilação. Tal elemento, presente em todas as fachadas, sombreia parte das janelas em algumas horas do dia. A fachada nordeste também é sombreada por outras edificações próximas.

Os ambientes de escritório possuem cortinas ou persianas internas, operadas pelos usuários.

Nesta edificação a vestimenta pode ser escolhida livremente pelos ocupantes.

3.2.3 Edificação H3

A edificação H3 foi reformada em 2012, o que incluiu a melhoria e atualização dos sistemas de iluminação e de ar-condicionado. A Tabela 11 apresenta alguns dados sobre o edifício. A forma do edifício é retangular, mas a proporção geométrica do edifício é quase quadrada (1,0:1,1). No núcleo central estão localizadas as escadas e elevadores. Na edificação H3 os estudos de campo aconteceram durante os anos de 2015 e 2016.

Tabela 11: Características da edificação H3.

Características gerais	
Ano de construção	Década de 1990
Ano da última reforma	2012
Área construída (m^2)	3090
Número de pavimentos	5 pavimentos + 1 subsolo
Forma	Retangular
Orientação da fachada principal	Sul
Padrão construtivo	Concreto armado
Revestimento externo de paredes	Concreto aparente
Tipo de vidro	Vidro incolor com película aplicada
Proteções solares externas	Vidro recuado da fachada
Características internas	
Ambientes de escritórios	Planta livre com divisórias internas
Altura do pé-direito (m)	2,6
Ocupação	
Número de ocupantes (aprox.)	250
Horário de ocupação (aprox.)	8-18h
Sistema de ar-condicionado e/ou ventilação natural	
Ventilação natural	Janelas operáveis pelos usuários
Sistema de ar-condicionado	*Splits*

As janelas são recuadas com relação à fachada com acabamento em concreto aparente. Assim, as áreas envidraçadas são sombreadas parcialmente, dependendo da orientação.

O último andar e o subsolo não foram considerados neste trabalho, pois abrigam somente os presidentes e diretores e, estacionamentos e auditórios, respectivamente.

Algumas estações de trabalho possuem ventiladores portáteis individuais, sendo a operação realizada pelo ocupante da estação correspondente. Persianas verticais também operadas pelos usuários foram observadas em todas as aberturas.

Nesta edificação os homens possuem certa restrição de vestimenta, pois são obrigados a usar calças.

3.2.4 Edificação CC

Em 2008 a edificação CC foi reformada e os sistemas de iluminação e ar-condicionado central foram modernizados. A edificação CC recebeu etiqueta A de eficiência energética pelo Procel Edifica, avaliada pelo RTQ-C - Requisitos Técnicos da Qualidade para o Nível de Eficiência Energética de Edifícios Comerciais, de Serviços e Públicos. Os estudos de campo na edificação CC foram conduzidos entre 2014 e 2016.

A edificação possui um átrio central fechado com domo zenital para aproveitamento da luz natural. No átrio também se localizam as escadas e elevadores. Mais informações sobre a edificação são encontradas na Tabela 12.

Os ambientes com ocupação permanente são localizados perimetralmente, mas também há ambientes em contato com o átrio central sem fachadas voltadas ao exterior.

No térreo existem poucos ambientes com atividades de escritório. Os escritórios desse pavimento também foram estudados neste trabalho. Estes possuem pé-direito de 2,5m.

No primeiro piso há espaços perimetrais com pé-direito duplo e outras salas com pé-direito simples. No segundo piso, todos os ambientes internos têm pé-direito simples e estão em contato somente com outros ambientes internos e/ou possuem uma das fachadas em contato com o exterior através de varandas. No primeiro e segundo pisos foram realizadas a maior parte da coleta de dados sobre conforto térmico.

O sistema de ar-condicionado do tipo central possui *setpoint* de temperatura igual a 24ºC, sendo a distribuição do ar realizada pelo teto. Os usuários não têm controle sobre as condições ambientais. Porém, ventiladores portáteis individuais, controlados pelos usuários, foram observados em algumas estações de trabalho.

O uso de calças pelos homens é obrigatório nesta edificação.

Tabela 12: Características da edificação CC.

Características gerais	
Ano de construção	1979
Ano da última reforma	2008
Área construída (m^2)	27432
Número de pavimentos	3 pavimentos + 2 subsolos
Forma	Quadrada
Orientação da fachada principal	Sudeste
Padrão construtivo	Concreto armado
Revestimento externo de paredes	Concreto aparente
Tipo de vidro	Vidro fumê
Proteções solares externas	Brises metálicos - controle manual
Características internas	
Ambientes de escritórios	Planta livre com divisórias internas
Altura do pé-direito (m)	2,5 (porém existem áreas com pé-direito duplo)
Ocupação	
Número de ocupantes (aprox.)	1200
Horário de ocupação (aprox.)	7-19h
Sistema de ar-condicionado e/ou ventilação natural	
Ventilação natural	Janelas seladas (fixas)
Sistema de ar-condicionado	Central

3.3 INSTRUMENTO DE COLETA DE DADOS SUBJETIVOS

Para a coleta de dados subjetivos foi utilizado um questionário eletrônico, desenvolvido em linguagem de programação Java por Karran Besen, Renata de Vecchi e Ricardo Forgiarini Rupp, pesquisadores do Laboratório de Eficiência Energética em Edificações (LabEEE) da UFSC. O aplicativo (questionário) foi enviado aos participantes da pesquisa através de e-mail ou disponibilizado na rede interna de cada edificação, sendo que somente os usuários presentes em cada ambiente, no momento de cada experimento de campo, podiam ter acesso ao programa. O questionário eletrônico pode ser visualizado no Apêndice A.

3.3.1 Funcionamento do questionário

O questionário eletrônico ao ser executado pela primeira vez no computador pessoal abria uma janela com opções para o agendamento do horário inicial. Nos estudos realizados no período da manhã, os usuários foram instruídos a agendar o início do questionário às 9h e nos estudos conduzidos no período da tarde o horário de início do questionário foi às 14h. Nos horários agendados, uma janela abria automaticamente no computador pessoal com a primeira rodada de perguntas a serem respondidas pelos usuários.

Após a primeira rodada de perguntas, os usuários eram informados pelo próprio aplicativo que deveriam aguardar 20 minutos para a próxima etapa da pesquisa e que uma nova janela abriria automaticamente contendo as próximas questões. O aplicativo continuava rodando em segundo plano em cada computador e os usuários podiam continuar exercendo suas atividades corriqueiramente. Passados os 20 minutos desde a última rodada de perguntas, uma nova janela abria automaticamente na tela do computador, avisando as pessoas que já podiam responder a próxima etapa da pesquisa (segunda rodada de perguntas). Essa rotina foi repetida mais quatro vezes (mais quatro rodadas de perguntas), totalizando seis rodadas de perguntas.

A cada resposta das pessoas, as mesmas foram enviadas via internet a um servidor interno da UFSC, no qual todas as informações foram armazenadas (banco de dados). A qualquer momento, as informações do banco de dados podiam ser acessadas por meio de um endereço eletrônico e/ou baixadas através de planilhas eletrônicas.

3.3.2 Questionário eletrônico

As perguntas do questionário foram baseadas no apêndice K da ASHRAE 55 (2013), no apêndice E do livro "*Performance measurement protocols for commercial buildings: best practices guide*" da ASHRAE (2012) e nos apêndices B e C do documento "*Data Collection Methods for Assessing Adaptive Comfort in Mixed-Mode Buildings and Personal Comfort Systems*", publicado pelo CBE da Universidade da Califórnia em Berkeley (ACKERLY; BRAGER; ARENS, 2012). Eventuais alterações foram realizadas de modo a ajustar as perguntas aos interesses desta pesquisa.

O questionário eletrônico é composto por quatro partes (Apêndice A):

Primeira parte do questionário (dados pessoais e características gerais): questões relativas às características antropométricas (peso e altura), idade e gênero, vestimenta, tempo de trabalho no local e atividade realizada.

Segunda parte do questionário (hábitos e preferências pessoais): questões relacionadas ao estado de humor, condição física e saúde, preferência por modo de condicionamento (natural e/ou mecânico) e histórico térmico.

Terceira parte do questionário (avaliação em tempo real): questões sobre sensação, preferência e aceitabilidade térmica, do movimento do ar e da umidade do ar, conforto térmico e qualidade do ar. As escalas utilizadas para as diferentes questões desta parte do questionário são apresentadas na Tabela 13. Também contêm questões sobre possíveis mudanças na vestimenta, atividade e ingestão de alimentos e bebidas.

Tabela 13: Escalas utilizadas para diferentes questões do questionário.

Descrição da escala	Valor na escala						
	+3	+2	+1	0	-1	-2	-3
Sensação térmica	Com muito calor	Com calor	Levemente calor	Neutro	Levemente frio	Com frio	Com muito frio
Preferência térmica			Mais aquecido	Assim mesmo	Mais resfriado		
Aceitabilidade térmica			Aceitável	Inaceitável			
Conforto térmico			Confortável	Desconfortável			
Aceitabilidade do movimento do ar			Aceitável	Inaceitável			
Preferência quanto ao movimento do ar			Mais movimento de ar	Não mudar	Menos movimento de ar		
Sensação de umidade*	Muito seco	Seco	Pouco seco	Neutro	Pouco úmido	Úmido	Muito ùmido
Preferência quanto à umidade*			Aumentar a umidade	Não mudar	Diminuir a umidade		
Aceitabilidade da umidade*			Aceitável	Inaceitável			
Qualidade do ar	Muito satisfeito	Satisfeito	Pouco satisfeito	Indiferente	Pouco insatisfeito	Insatisfeito	Muito insatisfeito

*As questões sobre umidade possuem uma opção extra, na qual a pessoa pode assinalar "Não sei responder".

Quarta parte do questionário (questões para serem respondidas após a última rodada de perguntas): questões que tratam sobre produtividade incluindo uma auto-avaliação da produtividade, sintomas (síndrome do edifício doente), sugestões para melhorias e comentários sobre o ambiente térmico e a qualidade do ar no espaço.

Para facilitar a compreensão do procedimento de aplicação do questionário, as quatro partes do questionário foram agrupadas em rodadas de perguntas, de acordo com a quantidade de vezes que os usuários foram solicitados a responder o questionário em cada experimento:

- Primeira rodada de perguntas: Partes 1 e 2;
- Segunda à quinta rodada de perguntas: Parte 3;
- Sexta rodada de perguntas: Partes 3 e 4.

O Apêndice A apresenta o questionário eletrônico com as quatro partes do mesmo e as seis rodadas de perguntas. Algumas das perguntas do questionário são fechadas e outras são mistas, onde os usuários possuem como opções de resposta algumas questões fechadas (fixas), porém têm a opção de incluírem informações com suas próprias palavras (questões abertas). Além disso, algumas perguntas têm condicionantes e somente são realizadas se o usuário assinala a opção correspondente:

Segunda parte do questionário – primeira rodada de perguntas - Questão 6 (Figura A.2): somente se a pessoa assinala a opção “Sim” as demais perguntas de “quando”, “onde” e “por quanto tempo” são realizadas.

Terceira parte do questionário – segunda a sexta rodada de perguntas - Questão 4 (Figura A.3): Caso a pessoa assinale dentre as opções “desconfortável por frio” ou “desconfortável por calor”, uma nova janela aparece com as respectivas questões sobre desconforto por frio ou por calor.

Terceira parte do questionário – segunda a sexta rodada de perguntas - Questão 13 (Figura A.4): Caso o usuário marque qualquer um dos três últimos pontos do lado de “Muito Insatisfeito” (Figura A.4), novas perguntas sobre a qualidade do ar são realizadas (Figura A.5).

Durante os estudos de campo conduzidos no ano de 2014, as questões 7, 8 e 9 (Figura A.4) sobre sensação, preferência e aceitabilidade da umidade não constavam no questionário. Tais questões foram adicionadas posteriormente nos estudos realizados durante os anos de 2015 e 2016. Outra modificação realizada no questionário para os estudos pós-2014 foi com relação à questão sobre conforto térmico (Questão 4). Na Questão 4 foram incluídas as opções descritas acima, ou seja, caso a pessoa assinale alguma das duas alternativas de desconforto, uma imagem aparece e a pessoa pode marcar as partes do corpo que estão desconfortáveis e também pode descrever o motivo do desconforto, caso julgue necessário.

Nos "estudos transversais repetidos" realizados em 2015, outras duas questões foram administradas aos usuários com o intuito de avaliar suas disposições térmicas (HEALEY, 2014; HEALEY; WEBSTER-MANNISON, 2012):

I. *Comparado aos seus colegas de trabalho, você se considera uma pessoa:*

( ) Mais sensível ao frio (friorenta)
( ) Mais sensível ao calor (calorenta)
( ) Sensível a ambos (tanto ao frio, quanto ao calor)
( ) Pouco ou não sensível a ambos (nem ao frio, nem ao calor)

II. *De modo geral, você prefere qual estação do ano:*

( ) Verão
( ) Inverno
( ) Primavera
( ) Outono

3.4 PROCEDIMENTO DE COLETA DE DADOS

Os estudos de campo foram realizados em diferentes épocas do ano. Em cada experimento de campo foram realizadas medições das variáveis ambientais de cada espaço estudado, concomitantemente à aplicação de questionários eletrônicos.

As temperaturas do ar externo foram levantadas a partir da estação meteorológica do INMET - Instituto Nacional de Meteorologia, localizada na parte continental urbana de Florianópolis. De Vecchi (2015) comparou as medições diárias de temperatura do ar externo refentes ao ano de 2014 da estação do INMET, da Epagri (Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina) localizada no bairro Itacorubi e da estação do LEPTEN (Laboratório de Engenharia de

Processos de Conversão e Tecnologia de Energia da UFSC) localizada no bairro Trindade. A autora não observou diferenças significativas entre os dados das diferentes estações meteorológicas.

3.4.1 Equipamentos utilizados

Para as medições das variáveis ambientais internas (temperatura do ar, temperatura de globo, umidade relativa e velocidade do ar) foram utilizadas cinco estações microclimáticas SENSU (confortímetros) desenvolvidas pelo LMPT - Laboratório de Meios Porosos e Propriedades Termofísicas da Universidade Federal de Santa Catarina (UFSC). As estações microclimáticas são compostas por sensor de temperatura de bulbo seco, termoanemômetro omnidirecional, sensor de umidade relativa do tipo capacitivo e sensor de temperatura de globo (esfera metálica com diâmetro de 15cm) de acordo com a norma ISO 7726 (1998). As especificações técnicas dos confortímetros SENSU podem ser visualizadas na Tabela 14.

Tabela 14: Especificações técnicas das estações microclimáticas SENSU.

Equipamento	Estação microclimática			
Modelo	Confortímetro SENSU (Produzido no LMPT - UFSC)			
Marca				
Parâmetro	Temperatura do ar	Temperatura de globo	Umidade relativa	Velocidade do ar
Faixa de medição	0-60 ºC	0-60 ºC	5-96%	0-3 m/s
Exatidão	± 0,2 ºC	± 0,2 ºC	± 3 %	± 3 %
Resolução	0,1 ºC	0,1 ºC	0,1%	0,01 m/s

As medições realizadas durante o ano de 2014 somente utilizaram duas estações microclimáticas, as quais são compostas por conjunto de sensores e registrador de dados (computador) em uma mesma unidade. Posteriormente, uma destas estações foi reformada pelo LMPT e a outra foi temporariamente desativada por problemas técnicos e três novas estações foram adquiridas. Os confortímetros novos (Figura 8a) são compostos por conjunto de sensores e módulo de rádio[13], os quais transmitem as informações para outro módulo de rádio (receptor) que é conectado via USB a um computador portátil. Assim, permitindo uma maior versatilidade na realização dos estudos de campo, pois o registrador de dados não precisa estar ao lado do conjunto de sensores. As informações são então processadas por um programa computacional desenvolvido em linguagem de programação C++ pelo LMPT, gravadas em arquivo de texto e podem ser observadas em tempo real. Dessa maneira, nas medições realizadas durante os anos de 2015 e 2016, quatro confortímetros foram utilizados.

As velocidades do ar e as temperaturas do ar também foram medidas pontualmente próximas aos usuários localizados perto das saídas de ar do sistema de ar-condicionado ou das aberturas voltadas ao exterior (ventilação natural). Estas medições pontuais também foram realizadas quando os usuários utilizavam ventiladores portáteis (sistema de condicionamento personalizado). As medições pontuais foram realizadas por meio do uso de termoanemômetro portátil da marca Airflow (Figura 8b). Na Tabela 15 são apresentadas as especificações técnicas do termoanemômetro portátil.

A concentração de dióxido de carbono (CO_2) foi medida em alguns ambientes utilizando-se de um analisador de CO_2, que pode ser visualizado na Figura 8c e suas especificações técnicas são mostradas na Tabela 15. Tais medições não foram realizadas em todos os ambientes devido à indisponibilidade de equipamentos para tal fim.

Todos os equipamentos de medição foram calibrados periodicamente no LMPT ou via empresa especializada, no caso do equipamento de medição de CO_2.

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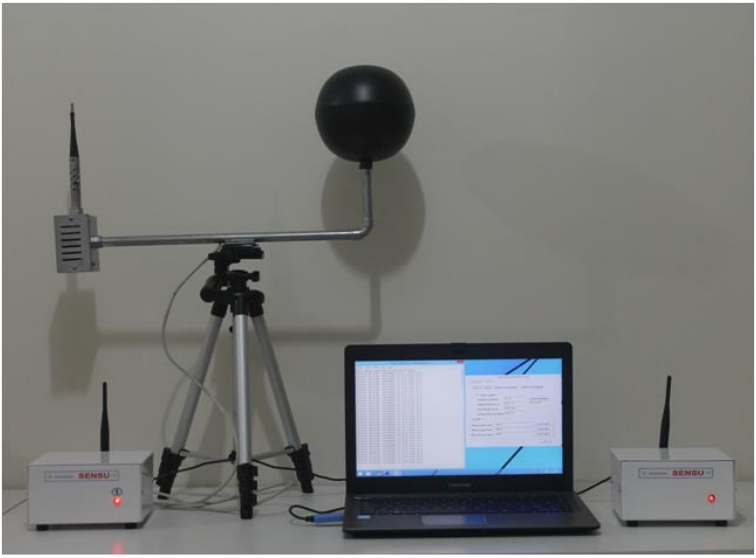
[13] Em ambientes interiores de edificações, o alcance do sinal dos módulos é de 610m entre qualquer um dos módulos, pois cada módulo pode re-enviar as informações para outro.

Figura 8: Equipamentos utilizados para as medições em campo: a) estação microclimática SENSU, b) termoanemômetro portátil e c) analisador de dióxido de carbono.



(a)

(b)

(c)

Tabela 15: Especificações técnicas do termoanemômetro portátil e do sensor de dióxido de carbono.

Equipamento	Termoanemômetro		Analisador de CO_2
Modelo	AirFlow TA 35		435-2
Marca	TSI Inc.		Testo
Parâmetro	Temperatura do ar	Velocidade do ar	Concentração de CO_2
Faixa de medição	0-80 ºC	0-20 m/s	0-10.000 ppm
Exatidão	± 1 ºC	± 3 %	± 75 ppm
Resolução	0,1 ºC	0,01 m/s	1 ppm

3.4.2 Protocolo experimental

Durante a realização dos estudos de campo tentou-se interferir o mínimo possível nos ambientes de trabalho. Na Figura 9 pode ser visualizado o protocolo experimental de cada estudo de campo. Os estudos de campo tiveram uma duração média de 200min, nos quais quatro procedimentos foram realizados (Figura 9): procedimentos iniciais, medição ambiental, observação do comportamento dos usuários e aplicação do questionário eletrônico.

Procedimentos iniciais (0-60min): tempo destinado à instalação dos equipamentos e estabilização dos sensores. Normalmente, a instalação dos equipamentos inicia-se antes da jornada de trabalho regular das pessoas. Desta maneira, este tempo inicial também é necessário para aguardar que os usuários cheguem ao ambiente de trabalho e comecem oficialmente a sua jornada de trabalho - estabilização do metabolismo a níveis correspondentes a atividades de escritório (GOTO et al., 2006). Após a instalação dos equipamentos e chegada das pessoas no ambiente de trabalho foi feita uma contextualização do trabalho perante os usuários e explicação do questionário eletrônico e procedimentos experimentais[14]. Foi explicado aos usuários, que a realização dos estudos de campo não iria impor restrição alguma ao desenvolvimento de suas atividades, possibilitando às

[14] Especial ênfase foi dada na explicação para os participantes de que eles deveriam avaliar as suas próprias percepções térmicas e não as condições térmicas da sala.

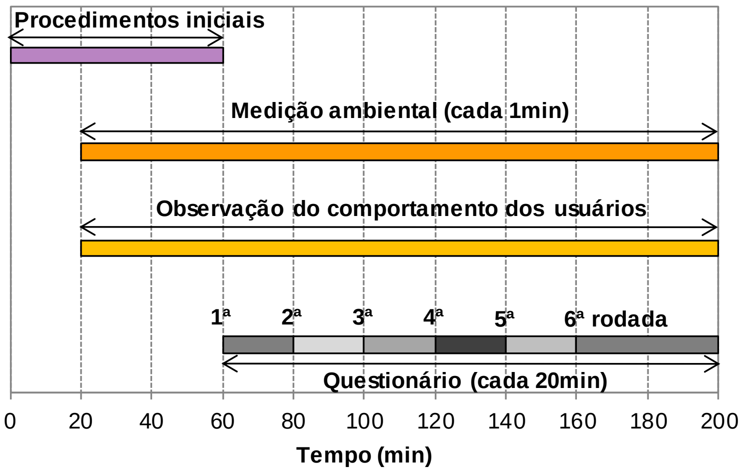
pessoas que agissem de maneira habitual. Portanto, os usuários poderiam alterar as condições do espaço (operação de aberturas e do sistema de ar-condicionado, no caso dos edifícios com ventilação híbrida) e de vestimenta de acordo com suas preferências. Durante este tempo inicial também foi realizado um croqui de cada espaço, indicando a localização de cada usuário e dos equipamentos de medição, bem como das aberturas e sistemas de condicionamento artificial. Porém, tais croquis não foram apresentados devido ao acordo prévio com as empresas sobre a não divulgação de informações que poderiam identificar as edificações.

Medição ambiental (20-200min): Nas estações microclimáticas, as variáveis ambientais (temperatura do ar, temperatura de globo, umidade relativa do ar e velocidade do ar) foram registradas a cada 1min. Essas medições foram realizadas de acordo com as recomendações apresentadas no capítulo 7 e apêndice K da norma ASHRAE 55 (2013), com os sensores posicionados a uma altura de 60cm em relação ao piso (altura correspondente ao nível do abdômen de uma pessoa sentada em cadeira) e, sempre que possível, localizados próximo ao centro geométrico dos ambientes. Medições pontuais de velocidade do ar e temperatura do ar também foram realizadas por meio de termoanemômetro portátil, conforme descrito anteriormente. As medições de CO_2 foram realizadas a uma altura de 1,5m do piso com o sensor distante entre 1,5 e 2,0m das paredes e das pessoas conforme recomendações da norma ISO 16000:1 (2004) e ISO 16000:26 (2012).

Observação do comportamento dos usuários (20-200min): Durante todo o período de medição ambiental foi observado continuamente o comportamento dos usuários (operação de aberturas e/ou sistema de ar-condicionado, operação de ventiladores portáteis individualizados, operação de elementos de proteção solar externos e/ou cortinas internas, mudança de vestimenta, alteração do metabolismo). As informações comportamentais foram registradas pelos pesquisadores em planilhas.

Aplicação do questionário eletrônico (60-200min): Simultaneamente às medições ambientais, foi solicitado aos usuários o preenchimento de um questionário eletrônico, descrito anteriormente, uma vez a cada 20min, totalizando cinco rodadas de perguntas sobre a percepção térmica e a qualidade do ar, mais a rodada inicial com perguntas gerais (características antropométricas, preferências, vestimenta, etc.). Ao final da última rodada de perguntas (160min), aguardou-se mais 40min com o intuito de esperar as pessoas que ainda não haviam finalizado o questionário. Após os 200min, solicitou-se aos usuários que não conseguiriam completar a todas as rodadas de perguntas encerrar o programa (questionário), assim somente as respostas já dadas foram consideradas.

Figura 9: Protocolo experimental do trabalho de campo.



3.5 TRATAMENTO DOS DADOS

Os dados coletados foram organizados em planilhas eletrônicas e analisados no programa computacional R (2017). O R é uma linguagem de programação e um ambiente de desenvolvimento integrado para cálculos estatísticos e gráficos. O programa R é totalmente gratuito e funciona em diversos sistemas operacionais, incluindo Linux, Windows e Macintosh.

3.5.1 Cálculos de parâmetros a partir de dados medidos

A partir dos dados coletados em campo, alguns parâmetros foram calculados para a realização das análises estatísticas.

3.5.1.1 Temperatura média radiante

A temperatura média radiante foi determinada através da medição *in loco* da temperatura de globo, da temperatura do ar e da velocidade do ar, de acordo com a ISO 7726 (1998) - Eq. 1[15].

$$T_r = \left[\left(T_g + 273 \right)^4 + 2,5x10^8 . V_a{}^{0,6} . \left(T_g - T_a \right) \right]^{1/4} - 273 \qquad \textbf{Eq. 1}$$

Onde:
T_r é a temperatura média radiante (ºC);
T_g é a temperatura de globo (ºC);
V_a é a velocidade do ar (m/s);
T_a é a temperatura do ar (ºC).

3.5.1.2 Temperatura operativa

A temperatura operativa foi calculada com base na temperatura do ar, velocidade do ar e na temperatura média radiante (Eq. 2) para cada registro de dados realizado através dos equipamentos de medição em cada experimento de campo. Este procedimento de cálculo é recomendado pela ASHRAE 55 (2013; 2017).

[15] Esta equação para o cálculo da temperatura média radiante é válida quando se utiliza um globo padrão (diâmetro de 15cm) e coeficiente de transferência de calor por convecção forçada (ISO 7726, 1998). Em nenhuma das situações de cálculo o valor do coeficiente de transferência de calor por convecção natural foi maior que o coeficiente por convecção forçada. Portanto, somente a equação da temperatura média radiante para convecção forçada foi apresentada.

$$T_o = A.T_a + (1 - A).T_r \quad \textbf{Eq. 2}$$

Onde:
T_o é a temperatura operativa (ºC);
A = 0,5 para V_a menor que 0,2 m/s;
A = 0,6 para V_a entre 0,2 e 0,6 m/s;
A = 0,7 para V_a entre 0,6 e 1,0 m/s.

3.5.1.3 Temperatura média predominante do ar externo

A temperatura média predominante do ar externo foi calculada a partir dos dados climáticos obtidos da estação meteorológica do INMET (Florianópolis), de acordo com a ASHRAE 55 (2013; 2017). A temperatura média predominante do ar externo deve ser baseada na temperatura média diária externa do ar dos últimos sete dias, no mínimo, e no máximo de 30 dias. A média predominante do ar externo pode ser calculada como a média aritmética das temperaturas médias diárias ou por meio de um método de ponderação, conforme Eq. 3 (ASHRAE 55, 2013; 2017).

$$T_{mpa(ext)} = (1 - \alpha).\left[T_{ext(d-1)} + \alpha.T_{ext(d-2)} + \alpha^2.T_{ext(d-3)} + \alpha^3.T_{ext(d-4)} + \cdots\right] \quad \textbf{Eq. 3}$$

Onde:
d é o dia em questão para o qual será calculada a $T_{mpa(ext)}$;
$T_{ext(d-1)}$ é a temperatura média do dia anterior ao dia em questão (ºC); $T_{ext(d-2)}$ é a temperatura média do dia anterior ao dia anterior (ºC); e assim por diante;
α é uma constante que varia entre 0 e 1 e é utilizada como ponderação das temperaturas externas dos últimos dias (adm). A ASHRAE 55 (2013; 2017) recomenda valores de α entre 0,6 e 0,9. Para climas com pouca variabilidade diária de temperatura externa, como o clima tropical úmido, o valor de 0,9 para α é recomendado. Em latitudes médias um menor valor de α pode ser mais apropriado.

Neste trabalho, a temperatura média predominante do ar externo foi baseada na temperatura média diária externa do ar dos últimos sete dias e o valor de 0,6 foi adotado para a constante de ponderação (α).

3.5.1.4 PMV/PPD e SET

Os valores de PMV/PPD e SET (temperatura efetiva padrão) foram calculados no programa R utilizando-se dos *scripts* desenvolvidos e validados por Silva, Ghisi e Lamberts (2016). Para o cálculo do PMV/PPD e SET são necessários os seguintes dados de entrada: temperatura do ar interno, temperatura média radiante, umidade relativa do ar interno, velocidade do ar interno, isolamento térmico da vestimenta e taxa metabólica dos ocupantes.

3.5.2 Análise estatística

Primeiramente, os dados brutos foram verificados contra potenciais erros oriundos dos levantamentos de campo. Os erros observados foram devidos às respostas dos usuários às perguntas abertas (idade, altura e peso) do questionário. Quando foram observados erros (incluindo, por exemplo, altura dada em centímetros ao invés de metros), estes foram corrigidos ou removidos do banco de dados.

Cada resposta subjetiva de um participante em determinado momento foi combinada com as condições ambientais medidas no momento da resposta. Assim, em uma planilha eletrônica, cada linha de dados contém uma resposta subjetiva instantânea (vestimenta, metabolismo, voto de sensação térmica, conforto térmico, dentre outros) associada às condições ambientais (temperaturas, umidade do ar, velocidade do ar, dentre outros) e aos índices calculados (PMV, SET, por exemplo).

Uma análise estatística descritiva foi empregada com o intuito de resumir e contextualizar os dados coletados.

Análises estatísticas simples foram realizadas comparando as variáveis ambientais e pessoais com os votos subjetivos (sensação, preferência, conforto e aceitabilidade).

Gráficos de frequência de ocorrência de cada variável estudada também foram confeccionados. Correlações entre as diferentes variáveis ambientais foram estudadas.

Para as análises estatísticas, as informações foram agrupadas em diferentes subconjuntos de dados, conforme descrito nos artigos. Demais tratamentos estatísticos estão discriminados nos próprios artigos.

As análises estatísticas foram realizadas no Brasil (LabEEE-UFSC) e durante o período de doutorado sanduíche na Austrália, realizado no *Indoor Environmental Quality Laboratory* da *University of Sydney*.

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4. RESULTADOS

Neste capítulo são apresentados os três artigos, dois publicados na revista *Energy and Buildings* e um publicado na revista *Building and Environment*, desenvolvidos durante o período de doutorado. Devido às exigências da Universidade Federal de Santa Catarina quanto à formatação da versão final da tese em formato A5, os artigos são apresentados em suas versões finais, porém, sem a diagramação do próprio periódico internacional.

Apesar de terem sido coletados dados sobre a concentração de dióxido de carbono, estes não foram mostrados neste trabalho. Também não foram apresentados os resultados da coleta de dados subjetivos sobre sensação, preferência e aceitabilidade do movimento do ar e da umidade do ar, nem sobre disposição térmica, qualidade do ar, produtividade, síndrome do edifício doente e comentários dos usuários sobre o ambiente térmico e a qualidade do ar. Estas informações poderão ser utilizadas em trabalhos futuros.

4.1 ARTIGO 1: ADEQUABILIDADE DOS MODELOS ANALÍTICO E ADAPTATIVO

RUPP, R. F.; GHISI, E. Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate. **Energy and Buildings**, v. 144, p. 152–166, 2017. doi: 10.1016/j.enbuild.2017.03.039

Este artigo está relacionado ao primeiro objetivo específico desta tese. Neste artigo foi examinada a adequabilidade dos modelos existentes de conforto térmico da ASHRAE 55 (tanto analítico quanto adaptativo) para aplicação em edificações de escritórios localizadas no clima subtropical úmido de Florianópolis. Os resultados do trabalho também contribuíram para um melhor entendimento sobre a percepção térmica de ocupantes nos diferentes modos de operação de edificações de escritórios com ventilação híbrida e com sistema central de condicionamento artificial.

Declaração de contribuição de coautores

Ricardo Forgiarini Rupp: como primeiro autor, Ricardo foi o responsável pela coleta de dados -realizada em conjunto com pesquisadores do LabEEE-UFSC- e por todo o processo de redação do artigo, incluindo a revisão da literatura, tratamento e análise dos dados, resultados e conclusões.

Enedir Ghisi: como coautor, Enedir supervisionou todo o processo de produção do artigo e contribuiu com discussões durante a redação do artigo. O artigo também foi revisado e editado por Enedir.

Predicting thermal comfort in office buildings in a Brazilian temperate and humid climate

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Abstract

This paper aims to compare thermal comfort responses from office workers in both fully air-conditioned and mixed-mode buildings against both the analytical and adaptive models of thermal comfort of ASHRAE 55-2013. Occupants were asked to record their thermal perception in questionnaires delivered online while instantaneous instrumental measurements were taken in situ (air temperature, radiant temperature, air velocity and humidity). Three buildings were investigated in a temperate and humid climate, i.e., in Florianópolis, southern Brazil. Two buildings have mixed-mode operation and one building has central air-conditioning. Almost two thousand six hundred questionnaires were collected during field studies. Actual thermal sensation and acceptability votes were compared against two predictive models of thermal comfort: the analytical model and the adaptive model. The 80% and 90% acceptability limits of indoor operative temperature used in the adaptive model were calculated using the prevailing mean outdoor air temperature. The analytical model overestimated the cold sensation of users, mainly for natural ventilation mode, and did not properly predict the percentage of thermal dissatisfaction of users. The analytical model could be used only when air-conditioning is operating; and a wider range of indoor thermal conditions than recommended by ASHRAE 55-2013 is recommended to be adopted during air-conditioning operation. The application of the adaptive model seems to be inappropriate for fully air-conditioned buildings. This work was not conclusive about the use of the adaptive model when the air-conditioning is on in mixed-mode buildings due to few data collected in this mode of operation. Under natural ventilation operation in mixed-mode buildings, occupants adapted to temperature fluctuations as predicted by the adaptive model, however, occupants appear to be more tolerant to cool conditions. The adaptive model may be used in mixed-mode buildings, when the air-conditioning is not on.

Keywords: thermal comfort; PMV; adaptive model; mixed-mode, offices.

INTRODUCTION

Currently the American standard for thermal comfort (ASHRAE 55-2013 [1]) assesses thermal conditions according to two theories about thermal comfort: the analytical model and the adaptive model. The analytical model of thermal comfort should be used for general environments (air-conditioned or not). The adaptive model could be used just for occupant-controlled naturally ventilated spaces without air-conditioning. The standard did not specify an evaluation procedure for mixed-mode buildings. However, it could be implied that for such buildings the analytical model should be used [1].

The analytical model of thermal comfort was developed by Ole Fanger in the 1970s based on studies carried out in climatic chambers [2]. The PMV index (Predicted Mean Vote) aims to predict the average thermal sensation of a group of people indoors and in theory could be used for any type of space irrespective to the use of air-conditioning. However, with the emergence of the adaptive model of thermal comfort, the limitations of Fanger's model became evident, mainly about its applicability in naturally ventilated environments [3-5]. However, limitations on the applicability of the PMV model in air-conditioned buildings have also been reported [6-12]. In such studies, PMV differed from the actual mean vote of thermal sensation (AMV) of people. PMV and AMV did not correlate well according to field studies conducted during different seasons in air-conditioned office buildings located in several climate locations such as Beijing (China) [12], northern Italy [11], Belgium [9] and Hong Kong [6]. Other comparative studies showing the differences between PMV and AMV may be found in the review article of Rupp et al. [13].

The adaptive model of ASHRAE 55-2013 [1] was derived from the ASHRAE RP-884 database [14], which contains around 21,000 subjective responses of thermal comfort, coming from field studies in 160 office buildings located in nine countries on four continents (data from Brazil are not included). The adaptive model relates the indoor comfort temperatures to the outdoor climate (higher outdoor temperatures allow higher indoor temperatures and vice versa).

Some studies stated that the PMV model suits well to thermal sensation of occupants in air-conditioned buildings or during the operation of air-conditioning in mixed-mode buildings. On the other hand, the adaptive method describes thermal sensation of users more appropriately in naturally ventilated buildings or during natural ventilation operation in mixed-mode buildings [5, 12, 15, 16]. However, there is no consensus about this.

In recent researches on thermal comfort conducted in mixed-mode buildings, two approaches have been employed: studies that separated mixed-mode buildings according to the operation mode (thus, adaptive models of thermal comfort were used for natural ventilation mode and other models were used when air-conditioning was on [17, 18]) and other studies that determined a single adaptive model, specific for mixed-mode buildings [19, 20-22].

The development of adaptive models, others than shown in ASHRAE 55, is mainly due to cultural and behavioural aspects, typical of each region. For example, in India, Indraganti et al. [17, 18] found that the Indians are much more tolerant to warmer conditions than prescribed by the adaptive model of ASHRAE 55.

Studies performed in China [23], for example, have shown that current standards are inappropriate for that country and maybe for any other developing country, where thermal comfort expectations are different than those for the developed countries, which are accustomed to artificially air-conditioned environments (not experiencing higher or lower indoor temperatures).

Therefore, this paper aims to compare thermal comfort responses from office workers in both fully air-conditioned and mixed-mode buildings located in a Brazilian temperate and humid climate (Florianópolis city) against the analytical and adaptive models of ASHRAE 55-2013 [1]. Mixed-mode office buildings are usually found in Florianópolis [24]. Rupp and Ghisi [25] concluded that energy savings due to mixed-mode strategy in office buildings in Florianópolis may be around 30-35% in comparison to fully air-conditioned buildings.

Few studies comparing PMV and AMV were performed in Brazil [26]. In Brazilian mixed-mode office buildings there is only the work of Vecchi [27], which is known for analysing the differences between the predicted and the actual thermal sensation votes, and comparing the results of field studies with the adaptive model of thermal comfort. Therefore, further analyses are necessary.

METHOD

Field studies on thermal comfort were carried out from March to October 2014 in three office buildings located in Florianópolis, southern Brazil. Florianópolis is an island located at the latitude -27º36’ and longitude -48º33’. The city has a temperate and humid climate with warm and humid summers (December to March) and cool winters (June to September). Heating is not commonly used in office buildings in Florianópolis and cooling is mostly used over summer [24].

Subjective data were collected via electronic questionnaires at the same time that environmental variables (air temperature, relative humidity, globe temperature and air velocity) were measured using microclimate stations. Outdoor environmental conditions were taken from a meteorological station located near the buildings. Data collection was performed by a team of researchers and more detailed information about it can be found in Vecchi [27].

The field data were analysed and comparisons against analytical and adaptive models of ASHRAE 55-2013 were also performed.

The office buildings

Building A

Building A is a concrete construction with three storeys and about 28,000m^2 of floor plan area. The studied spaces are open plan offices with lightweight partition materials. The building has a central air-conditioning system with strict temperature control (around 24°C). There is no possibility of opening windows as they are all sealed. However, users are allowed to manually adjust window shading devices.

Building B

Building B is a low-rise building (5,000m^2 of floor plan area) with mixed-mode operation (split air-conditioners and operable windows controlled by users). Windows are partially shaded by trees and other buildings. Indoor spaces (open plan offices) are separated by lightweight partition materials.

Building C

Building C is a mixed-mode 12-storey building with approximately 8,000 m^2. There are no window shading devices. Office spaces are open plan with lightweight partition materials. Users are free to control the split air-conditioners (or the window air-conditioners) or open the windows.

Thermal comfort questionnaire

The electronic questionnaire contained questions about anthropometric data and other characteristics of users (clothing, metabolic activity) and on thermal comfort (sensation, preference and acceptability). Table 16 shows the scales used in the questionnaires.

Table 16: Scales used in the questionnaires.

Scale	-3	-2	-1	0	+1	+2	+3
Thermal sensation	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Thermal preference	-	-	Cooler	No change	Warmer	-	-
Thermal acceptability	-	-	-	Accepta-ble	Unaccep-table	-	-
Thermal comfort	-	-	-	Comfor-table	Uncom-fortable	-	-

The estimation of clothing insulation considered all the garments people were wearing in the day the field study took place. An incremental value of +0.10 Clo was included in the clothing insulation in order to consider the chair people sit on.

The metabolic activity of users was estimated as recommended by ASHRAE 55-2013. The following values were assumed according to each activity:

- 1.0 met: reading (seated) or writing;
- 1.1 met: typing;
- 1.2 met: filling (seated);
- 1.4 met: filling (standing).

Anthropometric data were used to calculate the body mass index (BMI). BMI was obtained dividing the body mass by the square of the body height. It was assumed that the normal weight classification is the range between 18.5 and 25.0 kg/m^2.

Measurement instruments

Instruments used for monitoring the indoor environmental variables were microclimate stations and portable anemometers. Microclimate stations included air temperature sensor, omnidirectional thermo-anemometer sensor, relative humidity sensor (capacitive type) and globe temperature sensor (metallic sphere with a diameter of 15cm in accordance with ISO 7726 [28]). Such variables were recorded every 1 min and the measurements were performed according to Appendix K of ASHRAE 55-2013 [1]. Microclimate stations were installed in the geometric centre of the environments. Portable thermo-anemometers were used to mapping indoor air velocity near users. Technical specifications of instruments are shown in Table 17.

Table 17: Technical specifications of instruments used for monitoring the indoor environmental variables.

Parameter	Microclimate stations			Thermo anemometer		
	Range	Accuracy	Resolution	Range	Accuracy	Resolution
Air temperature	0-60 ºC	± 0.2 ºC	0.1 ºC	0-80 ºC	± 1 ºC	0.1 ºC
Air velocity	0-3 m/s	± 3 %	0.01 m/s	0-20 m/s	± 3 %	0.01 m/s
Globe temperature	0-60 ºC	± 0.2 ºC	0.1 ºC	-	-	-
Relative humidity	5-96%	± 3 %	0.001	-	-	-

Conducting field studies

During the field campaigns, occupants were asked to evaluate their thermal perception on their workstations, responding to the questionnaire once every 20 minutes, which totalled six rounds of questions in a work shift; the first round had questions about anthropometric, clothing and metabolic activity, and the other five rounds had questions about thermal comfort. In the meantime, the first 60 minutes were used for installing the equipment and waiting for the stabilization of both sensors and metabolism of occupants. While the occupants responded to the questionnaires and measurements of environmental variables were recorded by microclimate stations, observations about the environment, operation and behaviour of users were collected in standard spreadsheets by the researchers. Measurements of environmental variables were recorded at the same point in time and space as the subjective measurements. The experimental procedure is shown in Fig. 10.

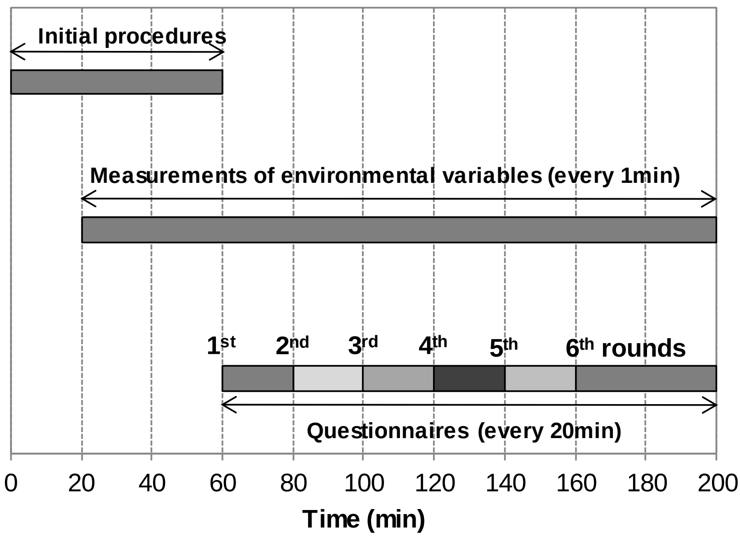


Fig. 10: Measurement protocol used in the field experiments.

Data analysis

The database was organized into spreadsheets, where each comfort vote was linked to human and environmental variables. The spreadsheets used in this study correspond to those used by Vecchi [27]. Data were separated according to building and mode of operation.

The calculation of the PMV/PPD was performed using the online calculator from the Center for the Built Environment (CBE) developed by Hoyt et al. [29]. PMV/PPD were calculated for each individual set of measurement and mean values were also obtained for each field study and for each building.

Actual mean vote (AMV) is the average of users' thermal sensation votes and it was calculated considering each field study and each building separately. Actual percentage of dissatisfied (APD) was calculated considering thermal comfort votes for each field study and for each building.

Comparisons between predicted (PMV and PPD) and actual (AMV and APD) parameters were performed considering each field study, building and mode of operation.

The adaptive model of ASHRAE 55-2013 [1] was used to perform the analysis in this work. The prevailing mean outdoor air temperature (exponentially weighted, running mean of daily temperature) was calculated as recommended by ASHRAE 55-2013. ASHRAE 55-2013 recommends α equal to 0.9 in the tropics and a lower value for mid-latitude climates. The prevailing mean outdoor air temperature may be calculated considering the minimum of seven and the maximum of 30 sequential days prior to the day to be analysed [1]. In this work, an α equal to 0.6 and the past seven days were considered. Thus, the equation presented in ASHRAE 55-2013 takes the form of Eq. 4. Indoor thermal conditions were separated as acceptable or unacceptable to users and they were related to the adaptive model of ASHRAE 55.

$$\boldsymbol{t_{pma(out)}} = (\mathbf{1}-\boldsymbol{\alpha}).\left[\boldsymbol{t_{e(d-1)}} + \boldsymbol{\alpha}.\boldsymbol{t_{e(d-2)}} + \boldsymbol{\alpha^2}.\boldsymbol{t_{e(d-3)}} + \boldsymbol{\alpha^3}.\boldsymbol{t_{e(d-4)}} + \ldots + \boldsymbol{\alpha^6}.\boldsymbol{t_{e(d-7)}}\right] \qquad \textbf{Eq. 4}$$

where $t_{pma(out)}$ is the exponentially weighted running mean outdoor temperature 7-days ago (ºC); α is a constant between 0 and 1, but ASHRAE 55 recommends values between 0.6 and 0.9 (it was assumed a value of 0.6) (non-dimensional); $t_{e(d-1)}$ is the mean daily outdoor temperature for the previous day (simple arithmetic mean of the hourly outdoor air temperature for the 24-hour day) (ºC), $te_{(d-2)}$ is the mean daily outdoor temperature for the day before that (ºC), and so on.

RESULTS

The surveys returned 2,589 valid votes from 317 men and 266 women.

The users of the buildings, their activities and clothes

Building A

During the surveys in building A (fall, winter and spring), questionnaires were answered by 284 people (178 men and 106 women), which resulted in 1,236 valid votes. Some personal characteristics of users are shown in Table 18.

Table 18: Average profile of users in building A.

Gender	Users	Weight (kg)	Age (years)	Height (m)	BMI (kg/m^2)	Clo	Met
Male	178	82.13	41.18	1.76	26.4	0.64	1.06
Female	106	62.38	35.78	1.64	23.2	0.71	1.03
Total	284	72.26	38.48	1.70	25.2	0.68	1.05

Building B

The field studies in building B were conducted during winter and autumn and included the participation of 179 people (104 men and 75 women), which resulted in 823 valid votes (26% of them under air-conditioned operation and 74% under natural ventilation operation). The average profile of users is shown in Table 19.

Table 19: Average profile of users in building B.

Gender	Users	Weight (kg)	Age (years)	Height (m)	BMI (kg/m^2)	Clo	Met
Male	104	82.98	40.34	1.76	26.7	0.73	1.03
Female	75	62.12	40.82	1.63	23.4	0.76	1.02
Total	179	72.55	40.58	1.70	25.3	0.75	1.03

Building C

Questionnaires were applied to 126 people over winter only (41 men and 85 women), which totalled 530 valid votes (22% of them under air-conditioning operation and 78% under natural ventilation operation). Table 20 shows some personal characteristics of the participants.

Table 20: Average profile of users in building C.

Gender	Users	Weight (kg)	Age (years)	Height (m)	BMI (kg/m^2)	Clo	Met
Male	41	82.78	41.85	1.76	26.5	0.71	1.02
Female	85	66.13	38.27	1.63	25.3	0.70	1.02
Total	126	71.58	39.44	1.67	25.7	0.70	1.02

Metabolic activity and clothing insulation

The metabolic activity of users was typical of office workers. The seated activities included reading, writing, typing and filling. In a few situations, some users were filling while standing. The average metabolism was close to 1 met for users in all buildings (Tables 18-20).

Clothing insulation varied approximately between 0.4 and 1.4 in all buildings, even in building C where data were collected just in winter. Overall, men, unlike women, wore very similar garments. Despite that, the average clothing insulations were similar between males and females (Tables 18-20).

Typical summer ensembles for men were trousers, short-sleeve shirts and shoes; and for women were skirt, scoop-neck blouse and sandals/shoes or short-sleeve shirtdress and sandals/shoes. In winter, the typical ensembles were trousers, long-sleeve shirt, jacket/long-sleeve sweater and shoes for men; and trousers, long-sleeve shirt, jacket/long-sleeve sweater and boots/shoes or skirt, panty hose, long-sleeve shirt, jacket/long-sleeve sweater and boots/shoes for woman. It was observed that a considerable amount of people (mainly women) leaved a jacket or a sweater on their chairs irrespective to the season (in cooler seasons it worked as extra protection when moving from inside to outside or during cooler hours of the day; in warmer seasons it was usually used as extra insulation against the cooler air from air-conditioners).

Indoor thermal conditions and response of users

An overview of indoor thermal conditions of each building during field experiments can be seen in Tables 21-23. In general, low air velocity with little variability was obtained in the experiments.

In building A, the operative temperature varied little during field experiments (Table 21). Fig. 11(a) shows the total percentage of sensation votes of users in building A. The majority of votes (58.0%) focused on the neutral category, while 30.4% of users said they were feeling slightly cool to cold and only 11.6% reported thermal sensations of slightly warm to warm. Most people (72.0% of the votes) preferred to keep the current conditions of the thermal environment (Fig. 11(b)). However, a significant number of users (18.0% of the votes) preferred warmer thermal conditions, while 10.0% would prefer a cooler environment. The thermal acceptability of users was 94.9%.

Table 21: Overview of indoor thermal conditions during field experiments in building A (1,236 votes).

Parameter	Operative temperature (ºC)	Relative humidity (%)	Air velocity (m/s)	PMV	AMV	PPD (%)	APD (%)
Average	22.92	62.17	0.12	-0.59	-0.23	16	9
Standard deviation	0.30	6.60	0.02	0.17	0.13	5	8
Maximum	24.46	76.23	0.30	+0.44	+2.00	30	26
Minimum	21.75	23.05	0.10	-1.60	-3.00	8	0

In building B a greater variation of indoor operative temperatures was observed (Table 22). The distribution of thermal sensation votes separated by operating mode can be seen in Fig. 12(a). Neutral sensations were reported by 56.3% of people, slightly warm to hot sensations were reported by 18.6% of users and 25.2% of the participants felt slightly cool to cold sensations. The thermal preferences of users indicated that 74.0% of people preferred to keep the current conditions of the thermal environment (Fig. 12(b)). The thermal acceptability of users was 96.7%. Notably, during air-conditioning operation, thermal sensation of the occupants tended more to the cold side of the 7-point scale (almost 40.0% of the votes) and the preference for warmer conditions also increased. However, 94.4% of users accepted the thermal conditions during operation of the air-conditioning. During the use of natural ventilation, thermal acceptability was 97.5%.

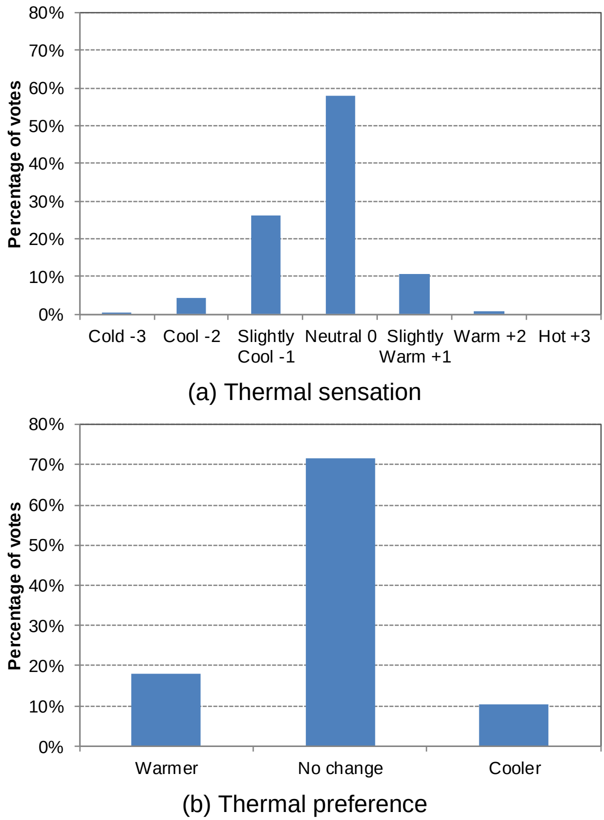
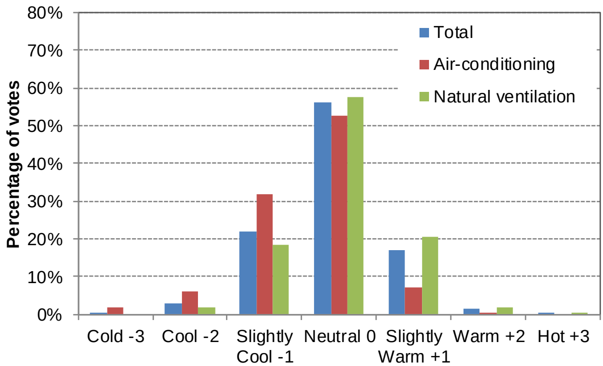


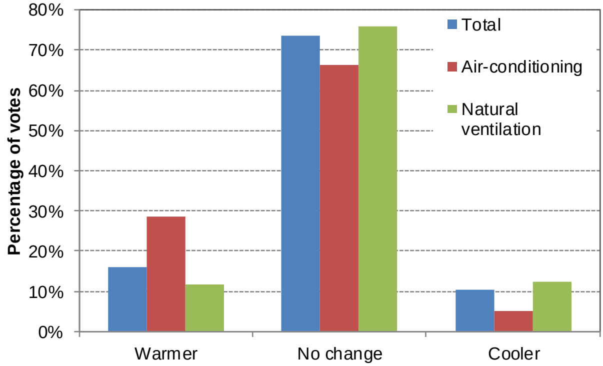
Fig. 11: Thermal sensation and thermal preference of users in building A (central air-conditioning).

Table 22: Overview of indoor thermal conditions during field experiments in building B (823 votes).

Parameter	Operative temperature (ºC)	Relative humidity (%)	Air velocity (m/s)	PMV	AMV	PPD (%)	APD (%)
Average	22.63	62.54	0.14	-0.61	-0.07	19	5
Standard deviation	1.61	8.66	0.03	0.51	0.43	14	9
Maximum	25.71	82.25	0.30	+0.81	+3.00	64	42
Minimum	16.95	47.10	0.10	-2.95	-3.00	5	0



(a) Thermal sensation



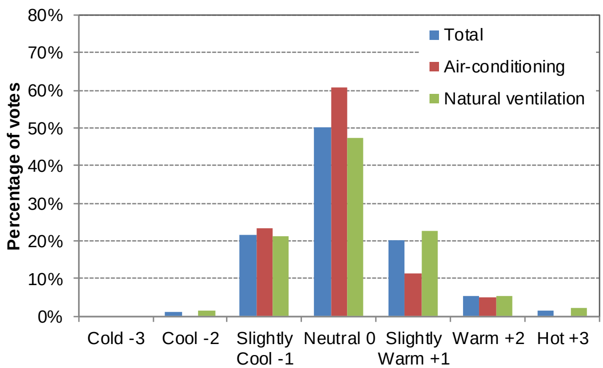
(b) Thermal preference

Fig. 12: Thermal sensation and thermal preference of users in building B (mixed-mode operation).

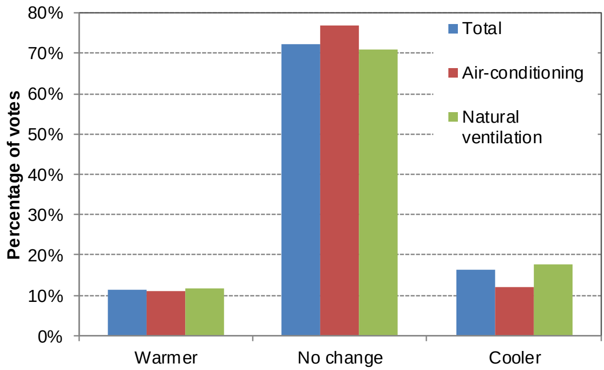
During the winter in building C, the minimum indoor operative temperature reached 21.1ºC and the maximum temperature was 26.9ºC (Table 23). Thus, there have been periods where users turned the air-conditioning system on. Most of the people (50.3%) felt the thermal environment as neutral, 22.8% expressed slightly cool to cold sensations and 27.0% reported thermal sensations ranging from slightly warm to hot (Fig. 13(a)). Most people (72.0% of the votes) preferred to keep the current conditions of the thermal environment (Fig. 13(b)). In general, thermal acceptability of users was 95.3% and reached 99.2%, when considered only the air-conditioning mode (thermal acceptability was 94.0% for natural ventilation mode). The higher thermal acceptability during air-conditioning operation was followed by a higher concentration of neutral thermal sensations (61% of the votes).

Table 23: Overview of indoor thermal conditions during field experiments in building C (530 votes).

Parameter	Operative temperature (ºC)	Relative humidity (%)	Air velocity (m/s)	PMV	AMV	PPD (%)	APD (%)
Average	23.82	59.04	0.17	-0.48	+0.14	15	7
Standard deviation	1.05	9.52	0.02	0.33	0.48	6	12
Maximum	26.90	75.50	0.30	+1.02	+3.00	26	44
Minimum	21.11	20.47	0.10	-1.92	-2.00	7	0



(a) Thermal sensation



(b) Thermal preference

Fig. 13: Thermal sensation and thermal preference of users in building C (mixed-mode operation).

Comparing predicted and actual sensation votes

Overall, the PMV overestimated the cold sensation of users, tending more to the negative side of the 7-point thermal sensation scale than the actual sensation of people.

Building A

The mean values of PMV and AMV for building A were -0.59 and -0.23, respectively (Table 21). The correlation between the predicted mean votes and actual mean votes of each field study resulted in a coefficient of determination (R^2) equal to 0.25 and all points were above the bisector (line that represents a perfect match between PMV and AMV) (Fig. 14). Fig. 14 also shows the range of acceptable thermal conditions of ASHRAE 55-2013 (PMV ± 0.5); it can be noticed that only 32.0% of the studied cases comply with the standard. However, in all situations AMV ranged between -0.5 and 0.5, and the actual thermal acceptability was 94.9%. Considering the three central points of the 7-point thermal sensation scale (as originally proposed by Fanger [2], i.e., PMV ranging from -1.0 to +1.0) as those that provide thermal acceptability to the people, it can be stated that 96.0% of users would be satisfied with the thermal environment (value similar to the actual thermal acceptability).

Building B

In building B, PMV overestimated the cold sensations of people (comparison between the means of PMV and AMV) as shown in Table 22. However, the greatest differences were found during the operation of natural ventilation (AMV=+0.03 and PMV=-0.63); the average values of PMV (-0.68) and AMV (-0.42) were closer during air-conditioning operation.

The correlation between the predicted mean votes and actual mean votes obtained in each field experiment can be seen in Fig. 15. During the air-conditioning operation the PMV overestimated the warm sensation of people in only two situations. These situations occurred in two small rooms with only four people each: one of the rooms was occupied only by women whose average age was 31.2 years, which resulted in a PMV equal to -0.17 and AMV equal to -0.38; in the other room, thermal sensation was affected by the responses of a 63-year-old woman who always reported slightly cool sensation (the votes of the other three people resulted in an AMV equal to 0.27, similar to PMV equal to 0.23). It has been discussed in the literature that women and older people tend to feel the environment cooler than men and young people, respectively [30-33]. Thus, these two situations may be explained by these individual differences. In all other cases the PMV overestimated the cold sensation of people. For the air-conditioning mode, indoor temperatures varied little in comparison with the period of natural ventilation. Considering the acceptable thermal conditions as proposed by ASHRAE 55-2013 [1], thermal acceptability of 66.7% during air-conditioning operation and 38.5% during natural ventilation operation was obtained. The three central points of the 7-point thermal sensation scale resulted in thermal acceptability of 100.0% (air-conditioning) and 73.1% (natural ventilation). The actual thermal acceptability was 94.4% (air-conditioning) and 97.5% (natural ventilation). Again, the narrow acceptable ranges of ASHRAE 55 predicted unacceptable conditions when in fact they were acceptable by the occupants. During operation of natural ventilation differences were even greater and, thus, the PMV model should not be used under these operating conditions.

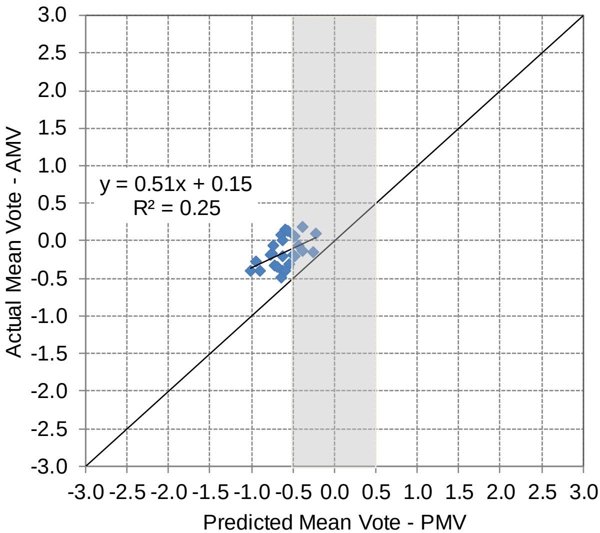


Fig. 14: Correlation between the predicted mean vote (PMV) and the actual mean vote (AMV) in building A. Acceptable thermal conditions as proposed by ASHRAE 55-2013 are shown in grey. Each dot represents the mean vote obtained in each field study.

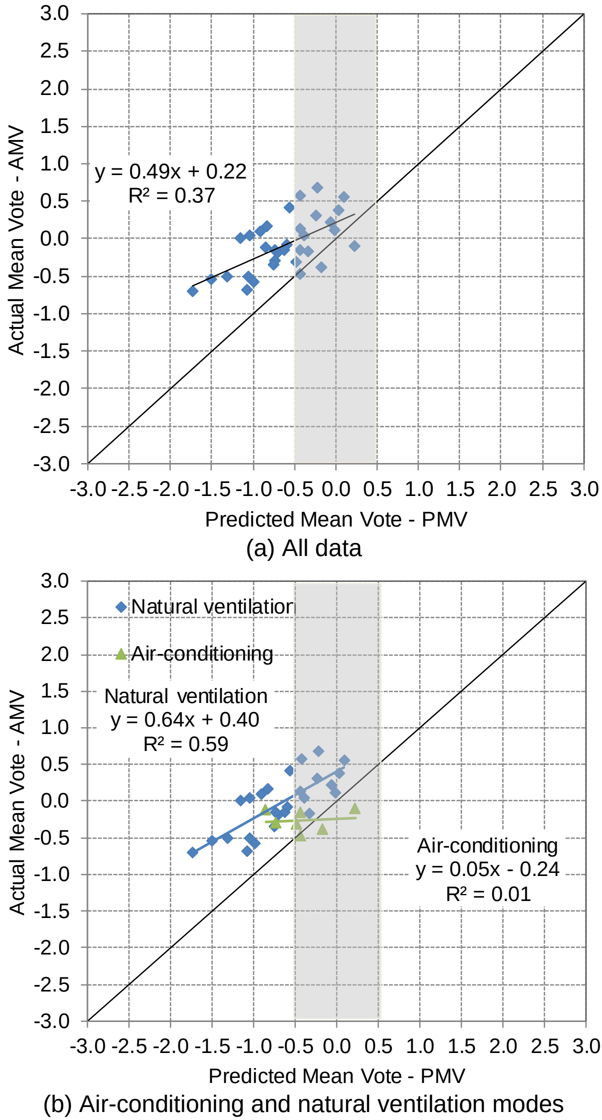


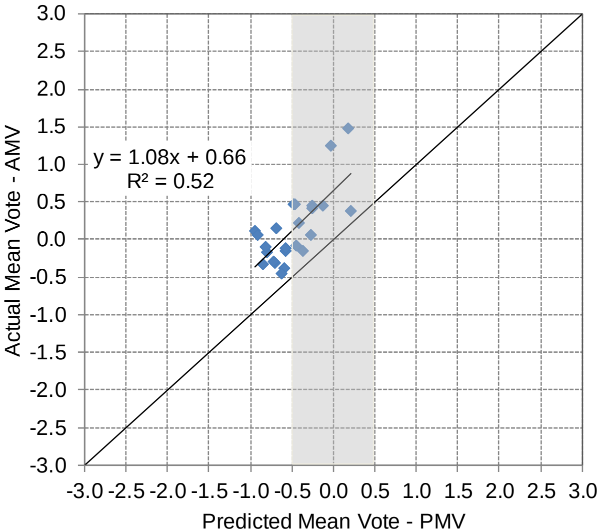
Fig. 15: Correlation between the predicted mean vote (PMV) and the actual mean vote (AMV) in building B considering all data and air-conditioning and natural ventilation modes. Acceptable thermal conditions as proposed by ASHRAE 55-2013 are shown in grey. Each dot represents the mean vote obtained in each field study.

Building C

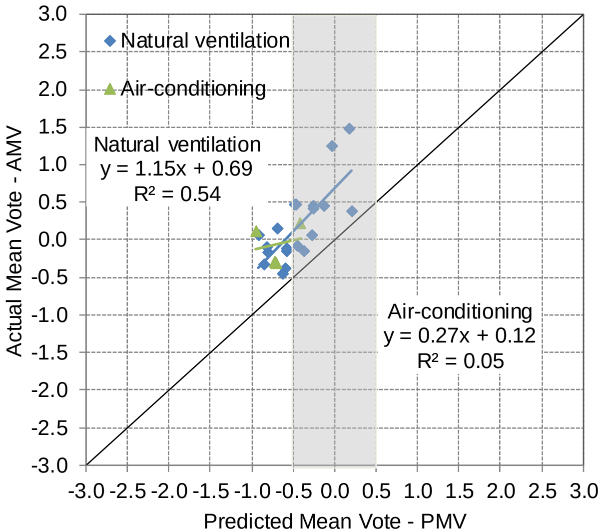
The PMV (-0.48) and AMV (+0.14) averages indicate that the analytical model overestimated the cold sensation of occupants on both operating modes in building C (Table 23): PMV equal to -0.44 and AMV equal to +0.18 for natural ventilation, and PMV equal to -0.69 and AMV equal to -0.06 for the air-conditioning mode. Few data were collected during air-conditioning operation. The PMV and AMV of each experiment are shown in Fig. 16, where it can be seen that all points are above the bisector. Considering a variation of the PMV between -1 and +1, the thermal acceptability was 100% in both modes of operation. Predicted thermal acceptability was 25% for air-conditioning mode and 55% for natural ventilation (actual acceptability was 99.2% and 94.0%, respectively) with a variation of the PMV between -0.5 and +0.5.

Analysing each comfort vote

Fig. 17 shows the acceptable thermal conditions expressed by each individual calculated PMV in relation to the indoor operative temperature and the outdoor climate. In Fig. 17 data of all buildings were separated according to operation mode. During air-conditioning operation, PMV as low as -2.74 and +0.72 were considered acceptable by users. In natural ventilation mode, the ranges of acceptable PMV are even wider, i.e., -2.76 to +1.02. For each outdoor temperature there is a wide range of acceptable conditions indoors, in both modes of operation. There is no evidence to justify a mandatory PMV between -0.5 and +0.5, as proposed by ASHRAE 55-2013 [1]. It is worth mentioning that in this work field experiments were not conducted during the summer. Therefore, the upper ranges of acceptable PMV could have been greater.

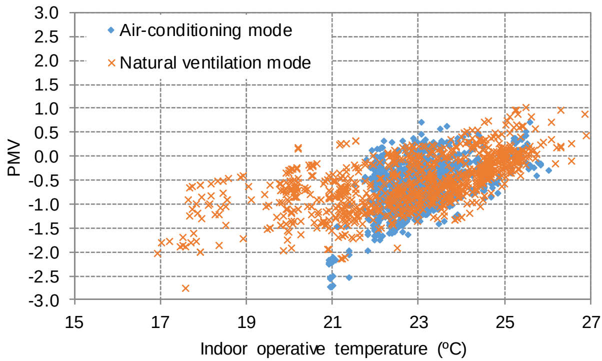


(a) All data

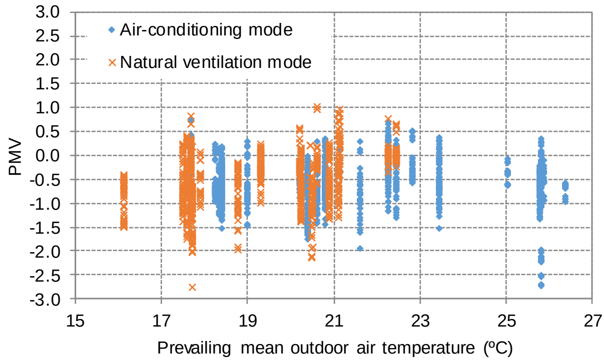


(b) Air-conditioning and natural ventilation modes

Fig. 16: Correlation between the predicted mean vote (PMV) and the actual mean vote (AMV) in building C considering all data and air-conditioning and natural ventilation modes. Acceptable thermal conditions as proposed by ASHRAE 55-2013 are shown in grey. Each dot represents the mean vote obtained in each field study.



(a) PMV vs. indoor operative temperature



(b) PMV vs. outdoor air temperature

Fig. 17: Acceptable thermal conditions expressed through PMV separated by operation mode and related to indoor and outdoor climate.

Comparing predicted and actual percentage of dissatisfied

A comparison between PPD and APD as a function of PMV for each field study is given in Figs. 18-20, corresponding to buildings A, B and C, respectively. PPD differs from APD in most situations considering all buildings.

For building A, the mean difference between PPD and APD was 7%; however, there were differences of up to 19%. The mean PPD was 16%, while the mean APD was 9% (Table 21).

The mean difference between PPD and APD was 14% and 8% for buildings B and C, respectively. Such buildings experienced higher differences of up to 64% and 35%, respectively. The means also differed: PPD means were 19% and 15% for buildings B and C and, accordingly, APD means were 5% and 9% (Tables 22-23). This result corroborates the studies comparing the PPD and APD in Brazil [26], demonstrating that PPD does not predict the APD properly.

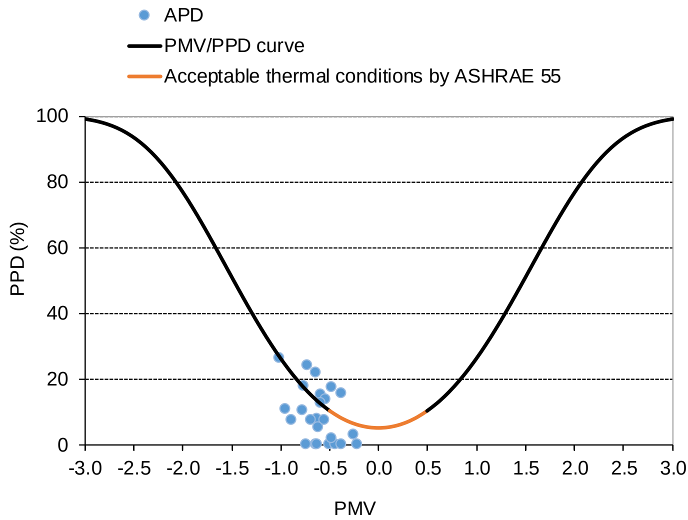


Fig. 18: Predicted percentage of dissatisfied (PPD) and actual percentage of dissatisfied (APD) as a function of predicted mean vote (PMV) – Building A.

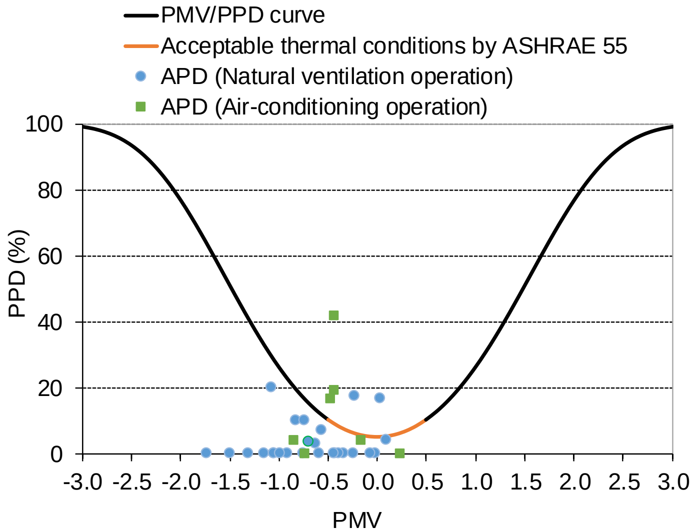


Fig. 19: Predicted percentage of dissatisfied (PPD) and actual percentage of dissatisfied (APD) as a function of predicted mean vote (PMV) – Building B.

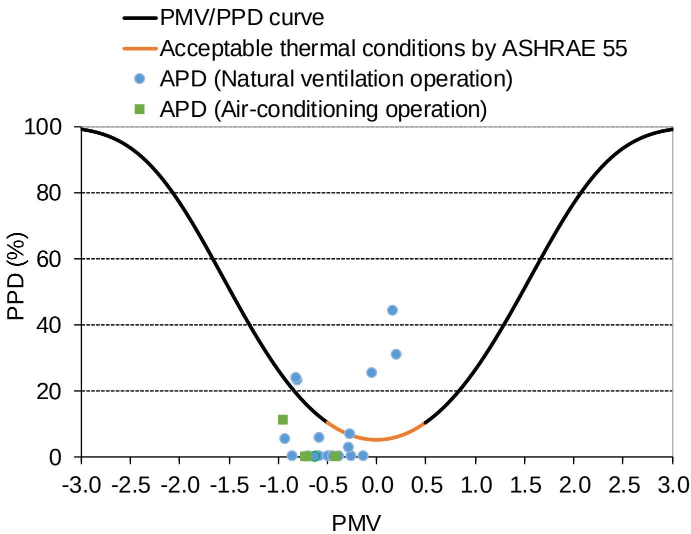


Fig. 20: Predicted percentage of dissatisfied (PPD) and actual percentage of dissatisfied (APD) as a function of predicted mean vote (PMV) – Building C.

Although PPD does not match APD (neither PMV matches AMV), it is interesting to note how close the PMV/PPD curve is to a curve fitting between the values of AMV and APD. Fig. 21 shows the relation between AMV and APD for all buildings together and also shows the PMV/PPD curve for comparison. However, the curve fitting process generated a R^2 value of just 0.25, what may be explained by the great variability in APD values for a certain AMV. Fanger's model [2] predicted that a minimum 5.0% of users in a space will be thermally dissatisfied, which was very similar to the minimum value of dissatisfaction of the curve fitting process (4.8%) in this work. But, considering each field study, APD values of zero (0.0%) were achieved in almost half (49%) of the field studies (AMV ranged between -0.70 and + 0.53 in those situations).

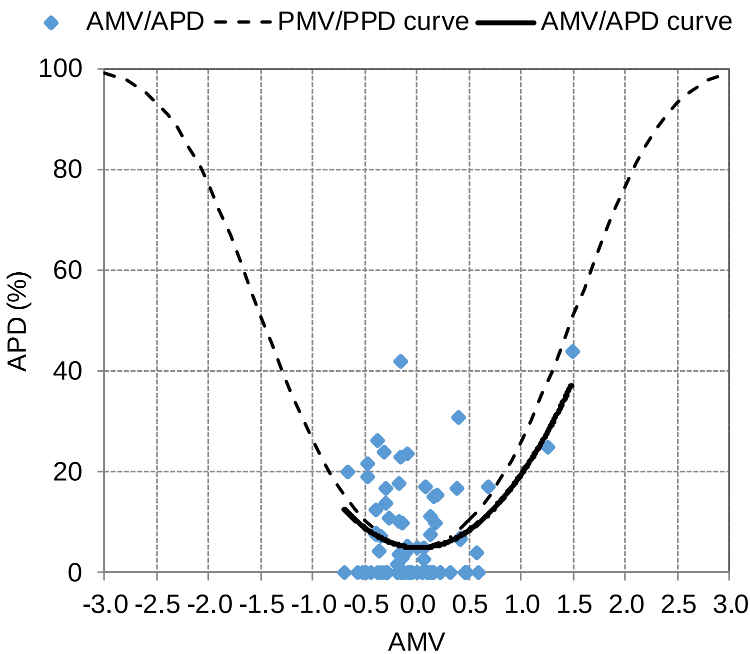


Fig. 21: Actual percentage of dissatisfied (APD) as a function of actual mean vote (AMV) – all data.

Comparing predicted and actual thermal acceptability

Indoor operative temperatures assessed as acceptable or unacceptable by users were correlated to the prevailing mean outdoor air temperatures in each field campaign.

Building A

Fig. 22 shows the results for building A considering the thermal acceptability ranges (80% and 90%) of the adaptive model proposed by ASHRAE 55-2013 [1]. All points were within the range for 80% thermal acceptability (Table 24). For 90% acceptability, 92.5% of the points were within the ranges. In situations with higher outdoor temperatures, the adaptive model predicted slightly less thermal acceptability than that reported by people. The indoor thermal conditions were controlled in a narrow range of temperatures, regardless of the season. Thus, for fully air-conditioned buildings, the application of the adaptive model seems to be inappropriate.

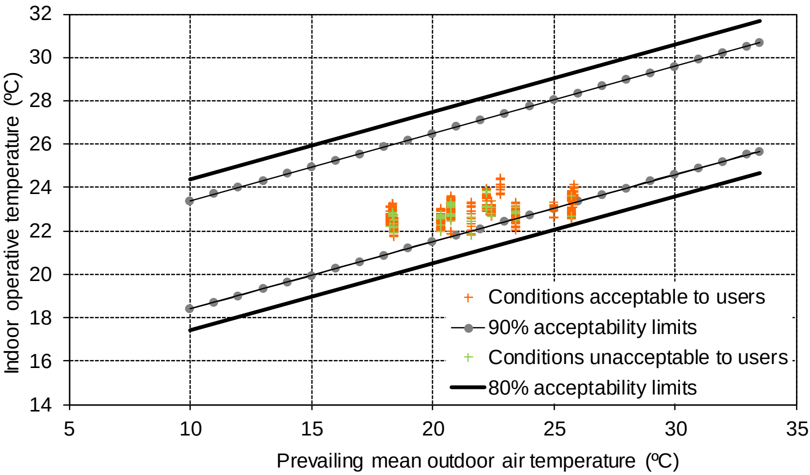


Fig. 22: Indoor operative temperature according to the prevailing mean outdoor air temperature in building A.

Building B

In building B, during the use of air-conditioning, indoor operative temperatures ranged between 20.9 and 25.5ºC. However, it appears to be no relationship between indoor and outdoor temperatures (Fig. 23(a)). In fact, it appears the contrary:

the higher the prevailing mean outdoor air temperature, the lower the indoor operative temperature. But there were few data in air-conditioning mode, thus, no definite conclusion can be made about this.

Indoor operative temperatures ranged between 16.9 and 25.7ºC for periods with natural ventilation (Fig. 23(b)). The indoor temperatures followed the changes in outdoor climate. The adaptive model predicted more people dissatisfied with the thermal environment than the actual thermal acceptability (Table 24), especially considering the range of 90% thermal acceptability for natural ventilation mode. In such occasions, the adaptive model of ASHRAE 55 predicted only 68.5% of acceptability and the actual thermal acceptability was 97.5%. Fig. 23(b) shows that people accepted temperatures lower than the lower limits of the adaptive model. Thus, the acceptable votes were divided into two groups of clothing insulation: greater than and less than or equal to 1.0 clo (Fig. 23(c)) – 1.0 clo is the limit of applicability of the adaptive model, according to ASHRAE 55-2013 [1]. Most acceptable votes outside the acceptability ranges of the adaptive model were related to users with higher clothing insulation (clo > 1.0). This may be one reason for the differences. Furthermore, in office buildings in Florianópolis, the use of heating is not common. Thus, people may be adapted to indoor temperatures lower than the predictions of the adaptive model (there is no data from Brazilian field studies in ASHRAE 55 adaptive model).

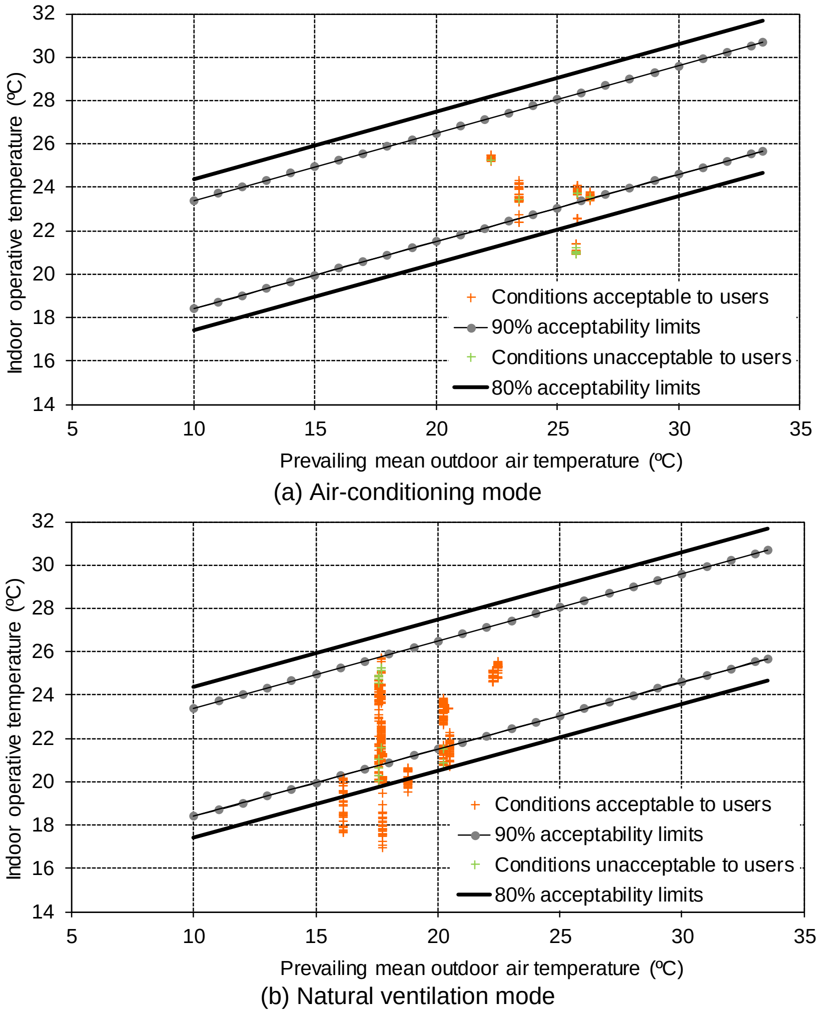
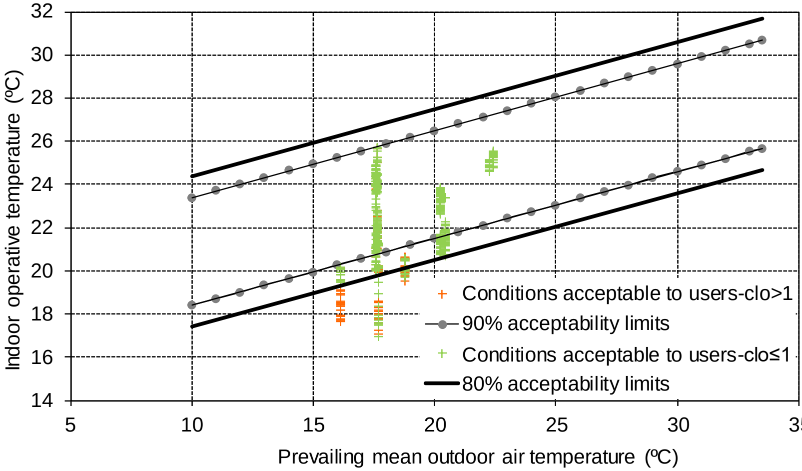


Fig. 23: Indoor operative temperature according to the prevailing mean outdoor air temperature in building B for air-conditioning mode, natural ventilation mode and for natural ventilation mode (acceptable votes separated according to clo).



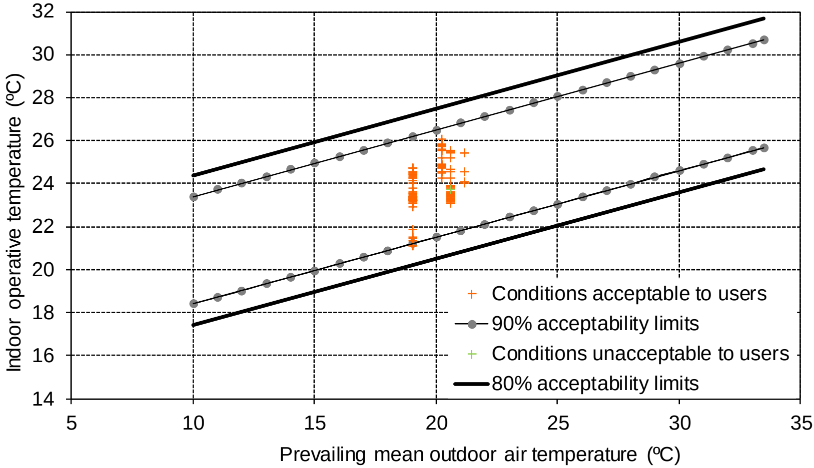
(c) Natural ventilation mode (acceptable votes separated according to clo)

Fig. 23: Indoor operative temperature according to the prevailing mean outdoor air temperature in building B for air-conditioning mode, natural ventilation mode and for natural ventilation mode (acceptable votes separated according to clo) (continuation).

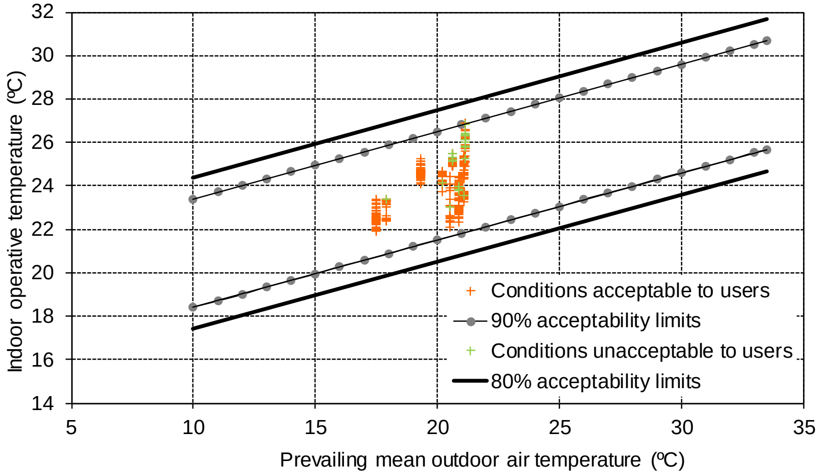
Thus, for this type of mixed-mode building, during natural ventilation operation, the adaptive model could be used; however, it should be taken into account that people tolerate lower temperatures during cooler outdoor conditions.

Building C

Fig. 24 shows the relationship between the indoor operative temperatures and the prevailing mean outdoor air temperatures for building C, in both operating modes. It is noticed that in both operating modes with higher outdoor temperatures, indoor temperatures were also higher. The experiments in building C were carried out only during the winter. Thus, the adaptive model appears to be suitable to be applied in both modes of operation for this specific mixed-mode building during the winter. However, few data were collected during air-conditioning operation, which does not allow to make any conclusion about this.



(a) Air-conditioning mode



(b) Natural ventilation mode

Fig. 24: Indoor operative temperature according to the prevailing mean outdoor air temperature in building C for air-conditioning mode and natural ventilation mode.

Table 24: Thermal acceptability predicted by the adaptive model and the actual one for the studied buildings.

Building	Operation mode	Thermal acceptability (%)		
		Adaptive model		Actual
		80% limits	90% limits	
A	Full HVAC	100.0	92.5	94.9
B	Air-conditioning	85.5	78.5	94.4
	Natural ventilation	88.2	68.5	97.5
C	Air-conditioning	100.0	98.4	99.2
	Natural ventilation	100.0	99.1	94.0

DISCUSSION

One implication of the findings of this work is that both fully air-conditioned and mixed-mode buildings could operate in a wider range of indoor temperatures other than that recommended by both the analytical and the adaptive models of ASHRAE 55-2013. Thus, such implication may contribute to energy efficiency in buildings. Moreover, due to the seasonality of the climate in Florianópolis and the high actual thermal acceptability (Table 24) reported in all buildings, there is no reason to design office buildings operating with air-conditioning during the whole year. Mixed-mode buildings could save energy without compromising thermal comfort.

Users of the fully air-conditioned building were exposed to similar indoor thermal conditions in the different seasons and even in those conditions they reported varying thermal sensations, as shown in Fig. 25. Fig. 25 shows the individual thermal sensation votes with the corresponding indoor operative temperature and the prevailing mean outdoor air temperature. The studied population was a heterogeneous one and this may show the interindividual differences on subjective responses.

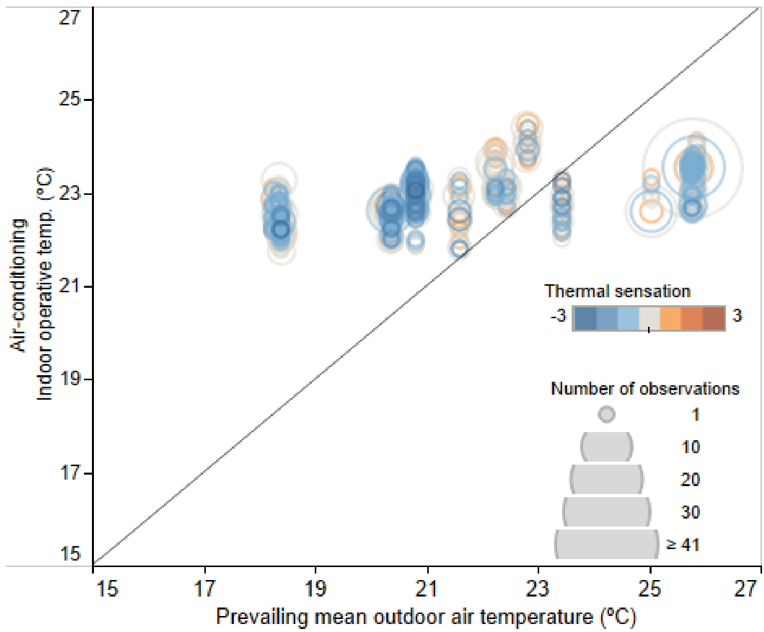


Fig. 25: Individual thermal sensation votes with the corresponding indoor operative temperature and the prevailing mean outdoor air temperature in building A.

Building A operated all year long with air-conditioning and users were unable to control the thermal environment according to their preferences. Mixed-mode buildings provided more freedom to users due to the fact that they could operate windows and the air-conditioning system. For instance, Fig. 26 shows the mode of operation of the mixed-mode buildings related to the season and time of the day and to clothing insulation. In building B it becomes evident that users changed the mode of operation between seasons. Air-conditioning operated during the warmer season (spring) and natural ventilation was used in cooler seasons (winter and fall). Clothing insulation also changed according to the season (users wore more clothes in winter and fall than in spring), showing an adaptive behaviour of people. In building C, as the field studies were performed just in one season (winter), such behaviour was not observed. As it can be observed in Fig. 26, people changed the mode of operation during a work shift in two days only: in building B it occurred on August 7 (afternoon) and in building C on August 26 (afternoon). In those situations, people used natural ventilation, changed to air-conditioning mode during middle afternoon and then changed again to natural ventilation. Thus, people tend not to change the mode of operation on a work shift.

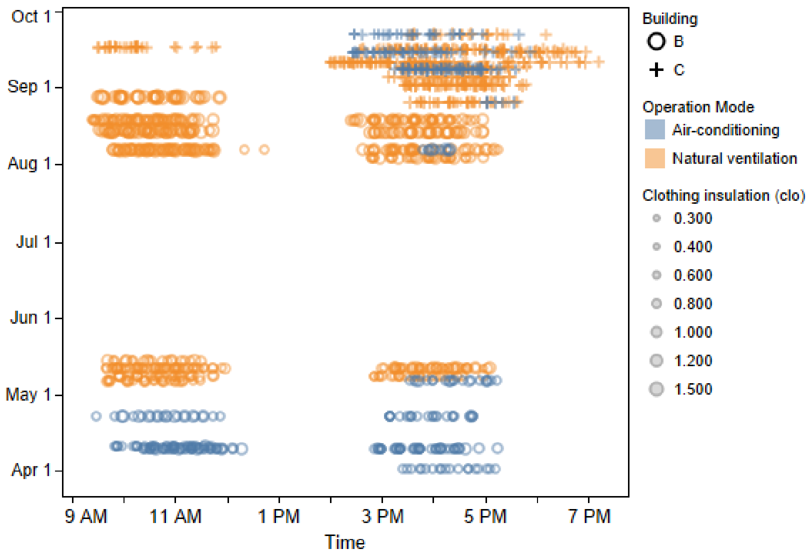


Fig. 26: Mode of operation in mixed-mode buildings, clothing insulation and time of day of each field study in buildings B and C.

Furthermore, in building B the air-conditioning was in use mostly when the prevailing mean outdoor air temperatures were higher than nearly 22ºC (Fig. 27). When air-conditioning was in operation, cool (-2) and cold (-3) thermal sensations were only reported when the indoor temperature was lower than the prevailing mean outdoor air temperature.

The reason for turning on the air-conditioners in building C was related to higher indoor temperatures due to poor shading of windows (Fig. 28). For example, with a prevailing mean outdoor air temperature equal to 19ºC, an indoor operative temperature of up to 24.7ºC was recorded while air-conditioning was turned on in cooling mode (it is noteworthy to mention that artificial heating was not available).

Hot (+3) and warmer (+2) thermal sensations were only expressed by users experiencing indoor temperatures 4ºC higher than the prevailing mean outdoor air temperature during natural ventilation in buildings B and C. During air-conditioning operation in the mixed-mode buildings, warmer (+2) thermal sensations were reported only when indoor temperatures were 3ºC higher than the prevailing mean outdoor air temperature.

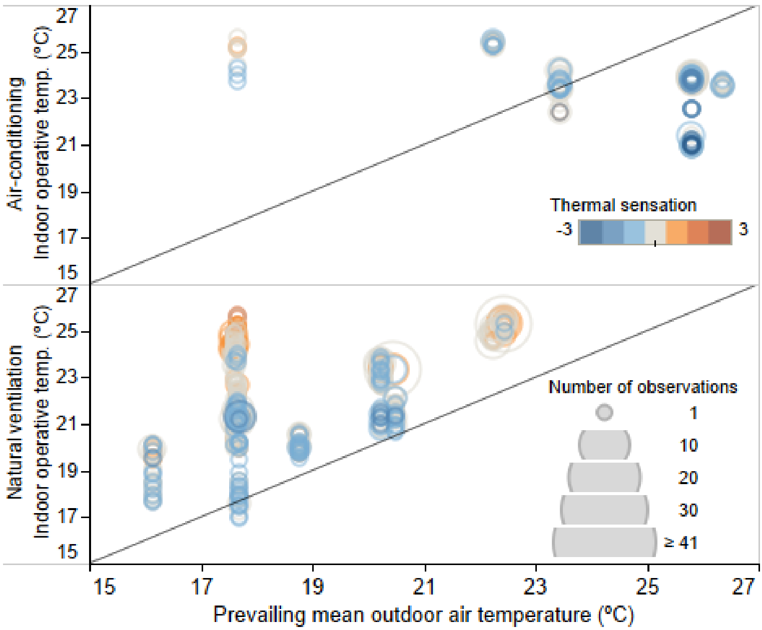


Fig. 27: Individual thermal sensation votes separated by mode of operation and with the corresponding indoor operative temperature and the prevailing mean outdoor air temperature in building B.

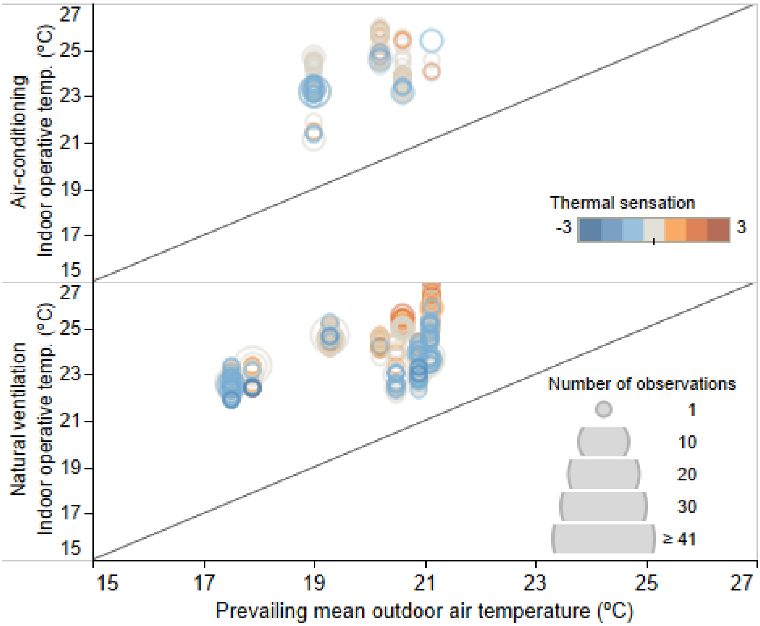


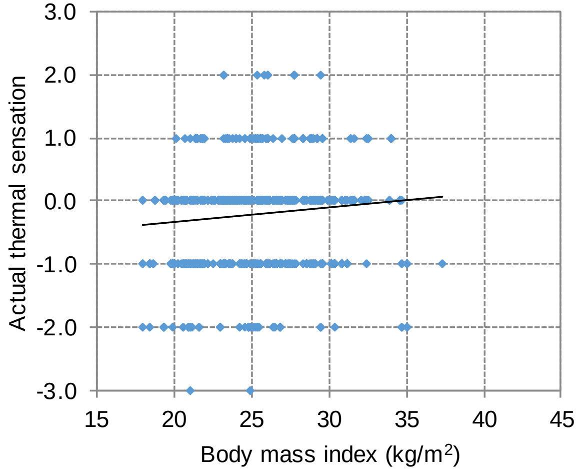
Fig. 28: Individual thermal sensation votes separated by mode of operation and with the corresponding indoor operative temperature and the prevailing mean outdoor air temperature in building C.

A note about adaptive opportunities

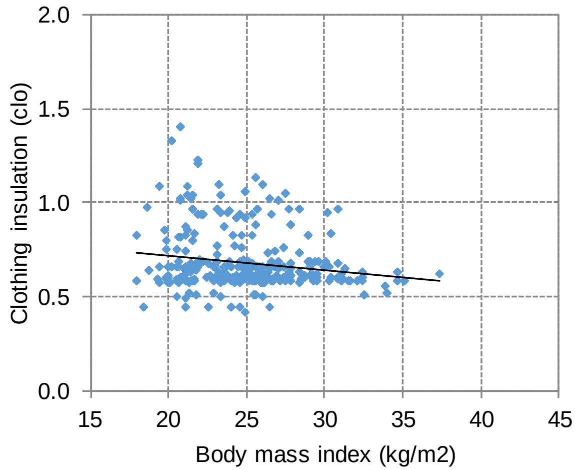
The buildings (B and C) with operable and accessible windows provide the adaptive opportunity for users to control natural ventilation. In cooler outdoor environmental conditions and in the absence of artificial heating, users maintained, in most cases, the windows closed. In such situations, the actual thermal acceptability was 100%, i.e., users' actions met their expectations.

A note about body mass index (BMI)

One factor that could affect the subjective responses is the BMI. If it is assumed that BMI links to the fat layer influencing the heat transfer of the body, overweight people could need lower temperatures than normal weight people due to higher tissue insulation caused by the subcutaneous fat layer between muscles and skin [32]. Tables 18-20 showed the average BMI of users in each building. The average values were very similar amongst buildings, being 25.2 kg/m^2 in building A, 25.3 kg/m^2 in building B and 25.7 kg/m^2 in building C. Those values are above the upper limit for normal weight (25.0 kg/m^2), thus, indicating overweight. Overall, males had higher BMIs than females. An interesting result was obtained when correlating the individual body mass index with the actual thermal sensation for each building separately.



(a) BMI vs. actual thermal sensation



(b) BMI vs. clothing insulation

Fig. 29: Correlations between body mass index and actual thermal sensation votes and clothing insulation in building A.

For all buildings, there was a tendency in which the greater the body mass index the higher the actual thermal sensation (Fig. 29(a) shows the correlation between BMI and the actual thermal sensation of users in building A). So, to compensate the higher body mass index, these users could wear clothes lighter than people with lower BMI in order to decrease their thermal sensation. When a comparison between BMI and clothing insulation (Fig. 29(b) presents such correlation for building A) was made, one observed a tendency showing that the greater the BMI the lower the clothing insulation – and this was noticed in all buildings. Thus, despite the lower clothing insulation, people with a greater BMI were experiencing higher thermal sensations.

CONCLUSIONS

This work presented the results of field studies conducted during 2014 in three office buildings located in a Brazilian temperate and humid climate. Two buildings have mixed-mode operation through opening windows and unitary air-conditioning system for cooling. The third building has a central air-conditioning system used throughout the year. Comparisons between thermal comfort responses from office workers in fully air-conditioned and mixed-mode buildings against the analytical and adaptive models of ASHRAE 55-2013 were also performed.

In this study, the maximum prevailing mean outdoor air temperature was 26.4ºC (summer season was not considered) and the minimum was 16.1ºC. Bearing this in mind, the following were the main findings:

• The actual thermal acceptability in all buildings considering the two modes of operation was greater than 94%. The majority of people expressed sensations of thermal neutrality and preferred to keep the current conditions of the thermal environment. Personalized conditioning systems could be used to improve thermal comfort in workstations, reducing differences in thermal sensation related to the subjectivity of the users;

• A significant finding of the work is that the studied population (southern Brazilians) appear to be more tolerant to cool conditions than predicted by the adaptive model proposed by

ASHRAE 55-2013. The clothing has an important role in the adaptation of people in those cooler situations;

• During natural ventilation mode, occupants adapted to temperature fluctuations as predicted by the adaptive model. Thus, the adaptive model may be used in mixed-mode buildings, when the air-conditioning is not operating;

• Overall and considering each building and operating mode, the PMV model overestimated the cold sensation of users. The greatest differences were found for natural ventilation mode. Fanger’s model did not properly predict the percentage of thermal dissatisfaction of users either;

• There is no evidence to justify acceptable thermal conditions when PMV varied in a narrow range between -0.5 and +0.5, as prescribed by ASHRAE 55-2013. A wider range could be used during air-conditioning operation, and this would allow greater energy savings in buildings.

More field studies need to be conducted in southern Brazil, and during summer, for a better understanding of thermal comfort in this specific context. Furthermore, Brazil needs to develop its own thermal comfort evaluation approach, as other developing countries are doing.

ACKNOWLEDGEMENTS

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4.2 ARTIGO 2: CONFORTO TÉRMICO EM EDIFICAÇÕES COM VENTILAÇÃO HÍBRIDA

RUPP, R. F.; DE DEAR, R.; GHISI, E. Field study of mixed-mode office buildings in Southern Brazil using an adaptive thermal comfort framework. **Energy and Buildings**, v. 158, p. 1475–1486, 2018. doi: 10.1016/j.enbuild.2017.11.047

Este artigo está relacionado ao segundo e terceiro objetivos específicos desta tese. Neste artigo verificou-se a necessidade de um modelo de conforto térmico específico para descrever a percepção térmica dos usuários de edificações operando com ventilação híbrida e foram identificadas relações entre a temperatura predominante externa e as temperaturas operativas internas de neutralidade térmica (modelo adaptativo de conforto térmico) para cada modo de operação (ventilação natural e ar-condicionado). Os resultados do trabalho também contribuíram para melhor compreensão sobre a percepção térmica de ocupantes nos diferentes modos de operação de edificações de escritórios com ventilação híbrida.

Declaração de contribuição de coautores

Ricardo Forgiarini Rupp: como primeiro autor, Ricardo foi o responsável pela coleta de dados -realizada em conjunto com pesquisadores do LabEEE-UFSC- e por todo o processo de redação do artigo, incluindo a revisão da literatura, tratamento e análise dos dados, resultados e conclusões.

Richard de Dear: como coautor, Richard supervisionou todo o processo de produção do artigo e contribuiu com discussões durante a redação do artigo. O artigo também foi revisado e editado por Richard.

Enedir Ghisi: como coautor, Enedir supervisionou todo o processo de produção do artigo e contribuiu com discussões durante a redação do artigo. O artigo também foi revisado e editado por Enedir.

Field study of mixed-mode office buildings in Southern Brazil using an adaptive thermal comfort framework

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Abstract

Studies about thermal comfort in mixed-mode buildings have been performed in order to better understand this type of building and its influence on occupants' thermal perception. However, there is still no consensus amongst researchers regarding whether mixed-mode buildings should be evaluated separating each mode of operation (natural ventilation or air-conditioning) and whether adaptive thermal comfort theory applies to both modes of operation. Does the mode of operation of a mixed-mode building, *ceteris paribus*, influence occupant thermal comfort perception? Trying to answer such questions, field studies on thermal comfort were conducted in three mixed-mode office buildings in the city of Florianópolis (a temperate and humid climate), Southern Brazil. Buildings were equipped with mechanical cooling systems and operable windows, both controlled by occupants. Thermal comfort questionnaires were collected at the same time and location that environmental variables were measured by microclimate instruments. Almost 5,500 questionnaires were answered by occupants of the three buildings in both modes of operation over the four seasons. Analysis of the results indicated that occupants' thermal perception was influenced by the mode of operation. Adaptive thermal comfort models were developed for natural ventilation and air-conditioning mode of mixed-mode buildings. This work found no evidence to support a single adaptive model for mixed-mode buildings. During natural ventilation mode, occupants adapted to indoor temperature fluctuations as predicted by the adaptive thermal comfort theory. On the other hand, during air-conditioning operation a weak adaptive relation (indoor comfort temperature vs. outdoor climate) was observed – a range of about 4ºC of indoor temperature fluctuation may be used for the operation of the air-conditioning system without compromising thermal comfort, which could help saving energy. This work is a first step towards building an adaptive model of thermal comfort for Brazilian subtropical climate.

Keywords: human thermal comfort; offices; adaptive model; mixed-mode buildings; hybrid buildings.

INTRODUCTION

Mixed-mode buildings, also known as hybrid buildings, integrate natural ventilation (NV) and air-conditioning (AC) in order to provide thermal comfort and save energy [1-3]. Generally, mixed-mode buildings are classified depending on the control strategy used:

• Concurrent: when AC and NV operate at the same time in the same space;
• Changeover: when AC and NV operate in different times in the same space;
• Zoned: when some spaces of the buildings run in NV and others in AC.

The control of mixed-mode buildings depends on outdoor and indoor thermal conditions and in the changeover control strategy, the shift between modes of operation can be either triggered automatically by a building management system or manually by users [4-13].

In the field of thermal comfort, mixed-mode buildings have been analysed in different ways by researchers [14]. Some authors considered the mixed-mode strategy as a new type of building operation, different from a naturally ventilated or artificially conditioned space. Thus, they proposed a single adaptive model [16] (linear regression equation between indoor temperature and outdoor climate) for mixed-mode buildings [7, 8]. Other researchers understand that mixed-mode buildings should be analysed depending on the mode of operation and proposed adaptive models of thermal comfort for each mode (natural ventilation and air-conditioning) [9-12]. Furthermore, two of the main international standards on thermal comfort (ASHRAE 55 and EN15251) also considered mixed-mode buildings differently. EN 15251-2007 [15] evaluates mixed-mode buildings by using two models, depending on the operation mode. In ASHRAE 55-2013 [16], mixed-mode buildings should be assessed using the analytical model (Fanger's PMV model – Predicted Mean Vote [17]), even during natural ventilation operation, which is a very conservative approach and probably discourages many early design-stage decisions from going the mixed-mode route. Therefore, there is still no consensus regarding how mixed-mode buildings should be assessed. Should changeover mixed-mode buildings be evaluated separately by mode of operation (natural ventilation or air-conditioning)? Does adaptive thermal comfort theory apply to both modes of operation in a mixed-mode building? Such questions beg another question: does the mode of operation of a mixed-mode building, *ceteris paribus*, influence occupant thermal comfort perception?

One research strategy to answer this last question is to perform climate chamber experiments, eliminating confounding variables and isolating the mode of operation as the key variable. Climate chamber experiments provide greater control of variables and high internal validity [18]. But, no matter how good the chamber design simulates/emulates a real environment, confining people in a contrived, experimentally controlled environment could affect subjective responses. On the other hand, field studies consider the complexity of real-life environments and offer superior external validity [18]. In the present study, field studies were conducted in mixed-mode office buildings using an adaptive thermal comfort framework.

[16] The adaptive thermal comfort model relates the indoor comfort temperature to the outdoor climate. Higher indoor temperatures are allowed in higher outdoor temperatures and vice versa.

ASHRAE 55-2013 [16] adopted the adaptive model of thermal comfort naturally ventilated subsample within the ASHRAE RP-884 database [19-20]. The database contains almost 21,000 questionnaire responses regarding thermal comfort from field studies conducted in 160 buildings located in the UK, USA, Canada, Bangkok, Thailand, Australia, Pakistan, Greece and Singapore. Most of the data in naturally ventilated buildings was obtained during summer season or in warmer climates [19-20]. EN 15251-2007 [15] uses the adaptive thermal comfort model from the European project Smart Controls and Thermal Comfort (SCATs) [21], which collected around 5,000 subjective thermal responses from field studies in 26 office buildings located in France, Greece, Portugal, Sweden and the UK. Thus, the adaptive thermal comfort model from ASHRAE 55 is biased to warmer outdoor conditions and the adaptive model from EN15251 considered data only from Europe, where heating systems are commonly available [21]. In Southern Brazil, specifically in the city of Florianópolis (a temperate and humid climate), mixed-mode office buildings are common [22]. However, heating systems are not usually found in commercial buildings. Thus, natural ventilation systems are used almost the entire year[17], except during warmer conditions (mostly in summer). Given this unique context, this work also aims to explore adaptive thermal comfort models in mixed-mode office buildings in Florianópolis.

METHOD

This work is based on analysis of data from field studies using an adaptive thermal comfort framework. Field studies were carried out in three mixed-mode office buildings located in Florianópolis (latitude -27º36’ and longitude -48º33’), Southern Brazil from 2014 to 2016. Typically, office buildings in Florianópolis do not rely on heating systems; and cooling systems are used in summer [22, 23]. In the selected buildings, heating was not available at all.

[17] A study conducted in office buildings in Florianópolis showed that energy savings provided by mixed-mode buildings ranges from 30-35% in comparison to HVAC buildings [23].

Data gathering was performed by a team of researchers from the Laboratory of Energy Efficiency in Buildings (Federal University of Santa Catarina - Brazil).

The mixed-mode buildings

Three mixed-mode office buildings with manual user control (changeover) of the mode of operation (natural ventilation through operable windows or air-conditioning via split cooling system) were investigated in Florianópolis. An overview of the buildings' characteristics is shown in Table 25. Building H1 is composed of three separate blocks: two of them are one-storey with a rectangular shape and the other is a two-storey building with an H-shape. As they are all on the same site and have the same characteristics and users (same company), we treated all three buildings as "Building H1". Table 26 presents some characteristics of office workers, showing a heterogeneous population with about 52% of the participants being males and 48% being females.

Field studies

Participants were invited to answer an electronic questionnaire about thermal sensation, preference, acceptability and comfort (Table 27) during a work shift. The electronic questionnaire is composed of six stages. The first one contains questions about anthropometric data, clothing and metabolic activity. The following five stages contain the questions about thermal comfort. Thus, each subject answered the questionnaires (thermal comfort questions) up to five times. The electronic questionnaire was set in each user's personal computer to begin at the same time during a work shift. Then a pop-up window opened at the scheduled time. After the first stage, a minimum time of 20 minutes was required for the answering of the next stage, when a new pop-up window containing the next round of questions opened.

Table 25: Overview of the surveyed buildings.

Building	H1	H2	H3
General features			
Construction year	1990'	1990'	1990'
Retrofit	-	-	2012
Total floor plan area (m^2)	6200	8244	3090
Number of blocks	3	1	1
Number of floors	1, 1 and 2	12	5
Shape	Rectangular, rectangular and H-shape	Rectangular	Rectangular
Construction	Concrete	Concrete	Concrete
External walls	Apparent brick	Plastered, painted (beige)	Apparent concrete
Windows	Clear single glass	Clear single glass	Clear single glass with applied reflective film
Shading devices	Vegetation	Facade elements	Facade elements
Indoors			
Offices	Open plan with lightweight partition materials	Open plan with lightweight partition materials	Open plan with lightweight partition materials
Indoors height (m)	2.6	2.6	2.6
Occupation			
Number of occupants (aprox.)	320	350	250
Working day (aprox.)	8am - 6pm	1pm - 7pm	8am - 6pm
Air-conditioning and natural ventilation system			
Natural ventilation system	Operable windows	Operable windows	Operable windows
Air-conditioning system	Split system	Split system	Split system
Mixed-mode operation	Changeover controlled by users	Changeover controlled by users	Changeover controlled by users
Comfort surveys			
Period	2014 - 2016	2014	2015 - 2016
Season	All seasons	Winter	All seasons
Questionnaires	1567	582	3321

Researchers monitored in real-time any change in the environment, operation of windows and air-conditioning system and user's behaviour during field studies. By using a sketch of the environments, it was possible to take notes about which and when windows and air-conditioners were operated. This also allowed the identification of users in the space. The mode of operation was assumed as air-conditioning (AC) when the air-conditioning system was in operation, regardless whether windows were opened or closed (an insignificant amount of data was collected when AC was on and one of the windows in a space was partially opened; users were very concerned about energy implications of letting windows opened, when AC was on). The mode of operation was assumed as natural ventilation (NV) when the air-conditioning system was turned off, regardless whether windows were opened or closed.

The surveys happened throughout 2014–2016 in order to consider all seasons, with the exception of building H2, where field studies were performed daily during a whole month in Winter 2014.

At the same time and within the space in which the questionnaires were administered, instrumental measurements of environmental variables (globe temperature, air temperature, relative humidity and air velocity) were recorded by microclimate data loggers positioned in the geometric centre of the environments. Indoor air velocity was also measured through portable thermo-anemometers near users next to windows and evaporators (split system) or away from the microclimate stations. Measurements were performed in accordance with Appendix K of ASHRAE 55-2013 [16]. Further information about the data collection procedure and instruments can be seen in [24-26].

Data analytic method

All data underwent statistical analysis. Statistical treatment was performed using the graphical user interface R commander (Rcmdr) [27-29], a package within the R statistical software environment [30]. Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) and Standard Effective Temperature (SET) were calculated in R software using the scripts developed and validated by [31]. Indoor operative temperature (To) was calculated using the air temperature, mean radiant temperature and air velocity according to APPENDIX A of ASHRAE 55 [16].

Table 26: Overview of the occupants of each building.

Variable/building		H1	H2	H3
Number of votes	Male	827	209	1824
	Female	740	373	1497
	Total	1567	582	3321
Weight (kg)	Mean	75	73	74
	S.D.	16	15	15
	Maximum	170	110	114
	Minimum	47	43	45
Age (years)	Mean	40	39	37
	S.D.	10	11	11
	Maximum	64	68	81
	Minimum	21	18	15
Height (m)	Mean	1.71	1.68	1.70
	S.D.	0.09	0.09	0.10
	Maximum	1.92	1.92	1.97
	Minimum	1.50	1.50	1.48

Table 27: Thermal comfort questionnaire scales.

Scale	-3	-2	-1	0	+1	+2	+3
Thermal sensation (TSV)	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Thermal preference (TP)	-	-	Cooler	No change	Warmer	-	-
Thermal acceptability (TA)	-	-	-	Accepta-ble	Unaccep-table	-	-
Thermal comfort (TC)	-	-	-	Comfor-table	Uncom-fortable*	-	-

* If users expressed thermal discomfort, they were asked to state if it was caused by warm or cold sensations.

The prevailing mean outdoor air temperature, an exponentially weighted, running mean of daily temperature, was calculated following the algorithm in ASHRAE 55 [16]. ASHRAE 55 [16] recommended α values from 0.9 to 0.6; a value of 0.9

could be more appropriate for the humid tropics and lower values of α could be more appropriate for mid-latitude climates. Thus, a value of 0.6 was adopted for the constant α, considering the past seven days (Eq. 5). Hourly outdoor air temperature was collected by the National Institute of Meteorology from a meteorological station near the buildings.

$$\boldsymbol{t_{pma(out)}} = (\mathbf{1}-\boldsymbol{\alpha}).\left[\boldsymbol{t_{e(d-1)}} + \boldsymbol{\alpha}.\boldsymbol{t_{e(d-2)}} + \boldsymbol{\alpha^2}.\boldsymbol{t_{e(d-3)}} + \boldsymbol{\alpha^3}.\boldsymbol{t_{e(d-4)}} + \ldots + \boldsymbol{\alpha^6}.\boldsymbol{t_{e(d-7)}}\right] \quad \textbf{Eq. 5}$$

where $T_{pma(out)}$ is the exponentially weighted running mean outdoor temperature 7-days ago (ºC); α is a constant between 0 and 1 (adopted as 0.6) (non-dimensional); $t_{e(d-1)}$ is the mean daily outdoor temperature for the previous day (simple arithmetic mean of the hourly outdoor air temperature for the 24-hour day) (ºC), $t_{e(d-2)}$ is the mean daily outdoor temperature for the day before that (ºC), and so on.

Comfort temperature was calculated using linear regression between thermal sensation vote (dependent variable) and indoor operative temperature (independent variable), then solving the resulting equations for a value of 0 (zero) for the dependent variable. Comfort temperature was also calculated using Griffiths' method (Eq. 6). The linear regression method requires a significant amount of data in order to provide a significant relationship between the dependent and the independent variables. Thus, data grouping should be performed considering the amount of data collected and also needs to consider the adaptive thermal comfort framework. ASHRAE 55 adaptive model originally proposed a climatic month as the time-scale of thermal adaptation [32]. However, using Griffiths' method, it is not necessary to aggregate data (comfort temperatures could be estimated for each vote).

$$\boldsymbol{T_{comf}} = \boldsymbol{T_o} - \boldsymbol{TSV}/\boldsymbol{G} \quad \textbf{Eq. 6}$$

where T_{comf} is the comfort temperature (ºC); To is the indoor operative temperature (ºC); TSV is the Thermal Sensation Vote (non-dimensional); G is the Griffiths constant (ºC^{-1}).

Linear regression was performed between the indoor comfort temperature and the prevailing mean outdoor air temperature (adaptive relation between indoors and outdoors). Adaptive thermal comfort models were derived and ranges of indoor (comfort) temperature were determined using logistic regression, considering actual thermal discomfort votes. The thermal discomfort votes were also used to predict, using logistic regression, the range of thermal sensation votes people found comfortable.

RESULTS AND DISCUSSION

A total of 5,470 questionnaires were collected in the three mixed-mode buildings in Florianópolis, which were associated with environmental variables and calculated indices. Fifty-seven percent of the data were collected in natural ventilation mode and 43% in air-conditioning mode. The results and discussion from the analyses performed on the data are presented in this section.

Outdoor thermal conditions in Florianópolis

Florianópolis has a temperate and humid climate. Summers (December to March) are warm and humid, while the winters (June to September) are cool. Mean yearly outdoor air temperature is 21.7ºC and mean yearly outdoor air relative humidity is about 80%.

Outdoor mean monthly air temperatures during the years that data were obtained and the historical data are shown in Fig. 30. Surveys were conducted until March 2016, therefore in Fig. 30 data for the rest of the year are not shown. During field studies, mean outdoor temperatures were slightly higher than the historical data all year long. The mean monthly air temperatures varied from 17.5ºC (July 2014) to 26.4ºC (February 2014).

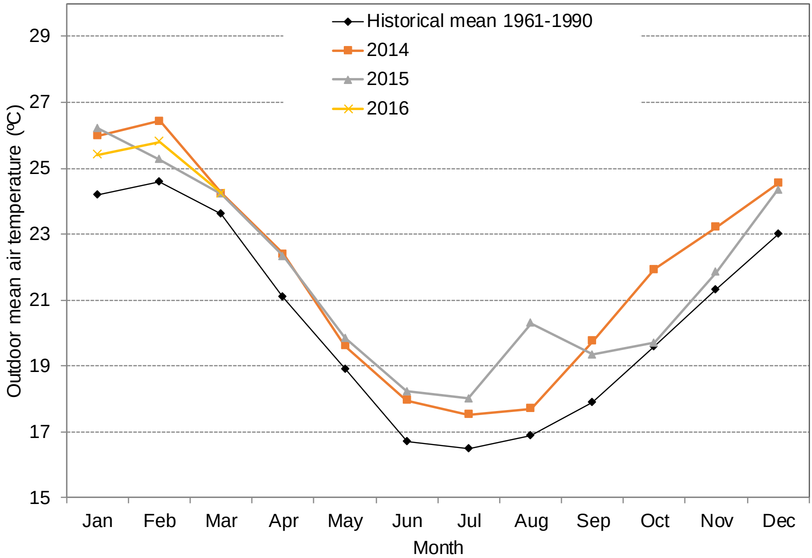


Fig. 30: Outdoor mean air temperatures over the years in which data were obtained (2014–2016) and historical mean.

Indoor thermal conditions and response of users

An overview of indoor and outdoor thermal conditions, human variables (clothing and metabolism), thermal responses and calculated indices during field studies in the three mixed-mode buildings located in Florianópolis is shown in Table 28. Mean indoor operative temperatures (To) were lower during natural ventilation (NV) operation in buildings H1 and H3 than in air-conditioning (AC) mode, because natural ventilation was mostly used when outdoor conditions were cooler (in higher outdoor temperatures the air-conditioning system was turned on by users) – Fig. 31. Similar indoor operative temperatures between modes of operation were observed for H2 building. Building H2 was surveyed only during winter and thus windows were kept partially closed when the AC was off (therefore the mean air velocity during NV mode was lower than in AC mode – Table 28); AC was turned on just in some hot days. The distribution of indoor operative temperatures per building and mode of operation can be better visualized in Fig. 32. Indoor air velocity (Va) was mostly lower than 0.25 m/s. Indoor relative humidity (RH) was lower in air-conditioning mode.

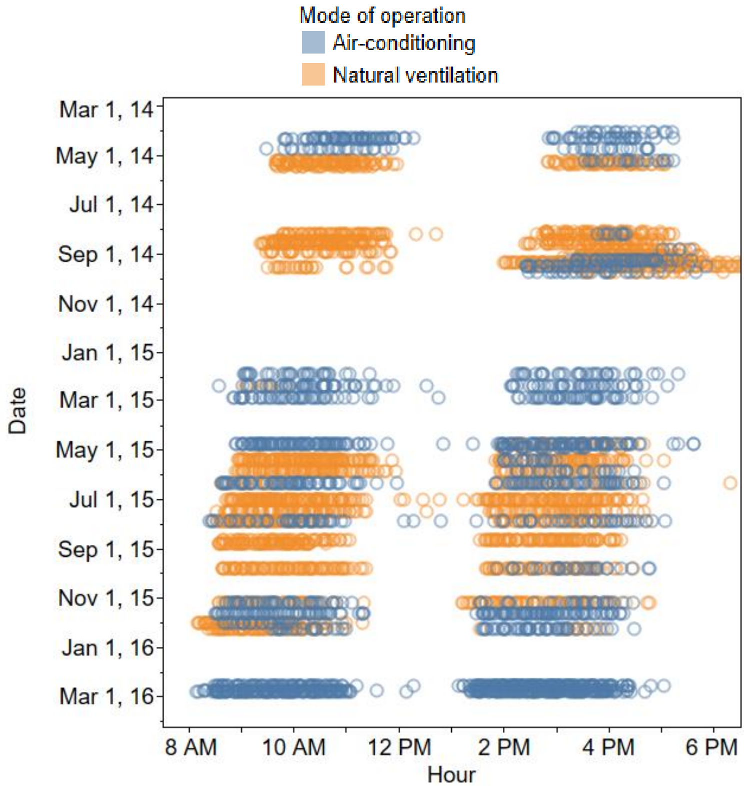


Fig. 31: Mode of operation of mixed-mode buildings according to date and hour.

As the natural ventilation mode was used in cooler weather, occupants were observed to wear more clothes during this mode of operation than in the air-conditioning mode (Table 28 and Fig. 33). Fig. 33 shows a plot of means between indoor operative temperature binned in 1ºC intervals and clothing, thermal sensation vote and PMV per mode of operation in mixed-mode buildings. In Fig. 33, the 29ºC bin contained only four observations, hence having the greatest confidence interval. Thermal responses and PMV/PPD indicated near-neutral sensations and high thermal comfort in both modes of operation (Table 28 and Fig. 33). So, by changing their clothing, occupants were adapting to the different thermal conditions due to the mode of operation.

Table 28: Summary of indoor and outdoor thermal conditions, human variables, thermal responses and calculated indices during field studies in mixed-mode buildings.

Building		H1		H2		H3	
Variable (mean)		Mode of operation		Mode of operation		Mode of operation	
		NV n=952	AC n=615	NV n=457	AC n=125	NV n=1712	AC n=1609
Indoors	To (ºC)	22.6	24.3*	23.9	23.9	24.0	24.2*
	Va (m/s)	0.14	0.13	0.16	0.20*	0.12	0.11*
	RH (%)	65	56*	61	54*	67	60*
Outdoors	$T_{pma(out)}$ (ºC)	18.4	24.0*	19.4	19.3	19.2	22.7*
Human variables	Metabolism (met)	1.10	1.13*	1.01	1.01	1.19	1.19
	Clothing (clo)	0.80	0.57*	0.70	0.65*	0.74	0.61*
Users response	TSV	0.0	-0.1*	0.2	0.0*	0.0	0.0
	TP	0.0	0.0	0.1	0.0	0.1	0.1
	TA	0.0	0.1*	0.1	0.0*	0.0	0.1*
	TC	0.1	0.1*	0.1	0.0*	0.1	0.2*
Calcula-ted indices	Griffiths' T_{comf} (ºC)	22.6	24.6*	23.6	24.0*	23.9	24.2*
	PMV	-0.3	-0.2	-0.4	-0.6*	0.2	0.0*
	PPD (%)	15	15	12	15*	9	10
	SET (ºC)	24.5	24.5	24.1	23.5*	26.3	25.4*

* Indicates significant differences between means considering $p < 0.05$ (independent t test). NV denotes Natural Ventilation; AC denotes Air-Conditioned.

In order to analyse if users of mixed-mode buildings have similar thermal responses depending on the mode of operation, linear models were developed considering thermal sensation vote and the indoor operative temperature. First, linear models were derived for each building considering all data together. Then, the mode of operation (factor variable) was added to the linear models. Table 29 shows the linear models obtained.

Comparison between models was performed using ANOVA (analysis of variance). For the three buildings, including the mode of operation significantly improved the fit of the model to the data compared to the model without this variable (Table 29). Thus, users respond differently to the thermal environment depending on the mode of operation in mixed-mode buildings. In this way, linear regressions between thermal sensation vote and indoor operative temperature were derived for each building and mode of operation (Fig. 34 and Table 30).

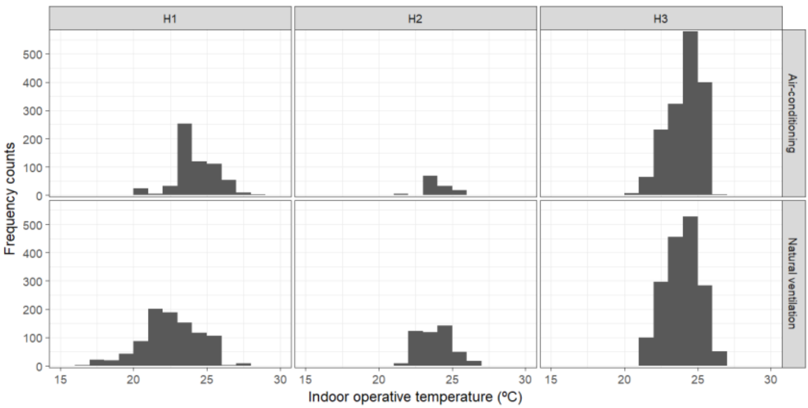
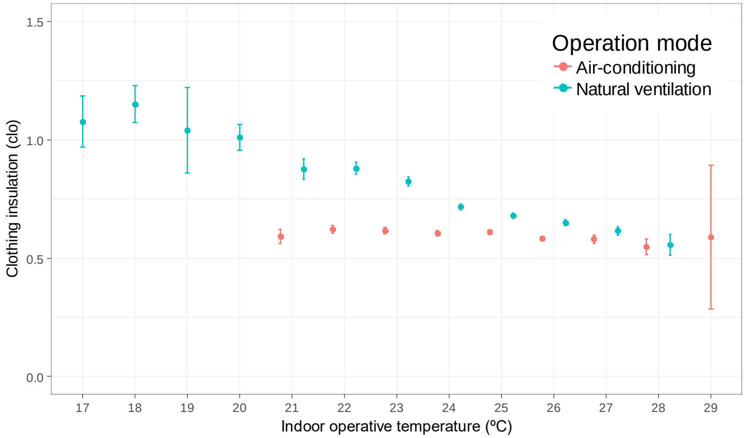
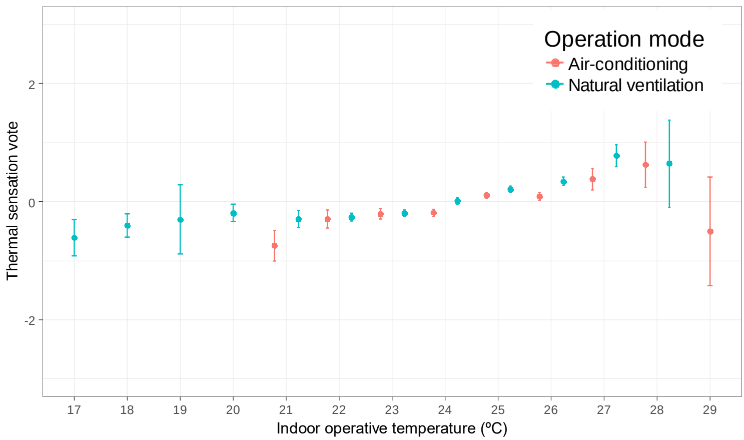


Fig. 32: Histogram of indoor operative temperature for each building and mode of operation. Indoor operative temperature was binned in 1ºC intervals.

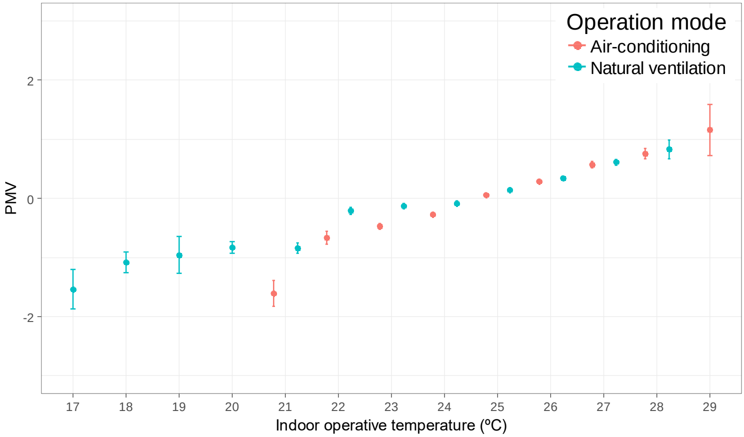


(a) Clothing vs To



(b) TSV vs To

Fig. 33: Plot of means with confidence intervals of 95% between binned indoor operative temperature and clothing, thermal sensation vote and PMV per mode of operation in mixed-mode buildings. Indoor operative temperature was binned in 1ºC intervals.



(c) PMV vs To

Fig. 33: Plot of means with confidence intervals of 95% between binned indoor operative temperature and clothing, thermal sensation vote and PMV per mode of operation in mixed-mode buildings. Indoor operative temperature was binned in 1ºC intervals (continuation).

Occupants of H1 building experienced a wider range of indoor operative temperatures than those in buildings H2 and H3 (Figs. 32 and 34). It appears that because of this, in the natural ventilation mode occupants are more tolerant to temperature variations than in air-conditioning mode (lower gradient of the linear regression equation – Table 30).

In buildings H2 and H3, users experienced a narrower range of indoor operative temperatures in both modes of operation, and it appears they are more sensitive to temperature variations in natural ventilation mode (Figs. 32 and 34 and Table 30). However, a relatively modest amount of data was collected in H2 building during air-conditioning operation, so no statistically significant conclusions could be reached for this building. In building H3 the gradients of the regression equations are similar for both modes of operation. However, looking at the coefficient of determination (R^2) during the air-conditioning mode, the indoor operative temperature explains just 3% of the variance of the thermal sensation vote, compared to 15% in natural ventilation mode.

Table 29: Linear models considering indoor operative temperature and thermal sensation vote for each building.

Building Code	Linear model		ANOVA results
	All data together	Including the mode of operation (MO)*	
H1	TSV = 0.11To – 2.63 (n=1567, R^2=0.09, p<0.001)	TSV = 0.15To + 0.40MO – 3.88 (n=1567, R^2=0.15, p<0.001)	F(1, 1524) = 103.35, p<0.001
H2	TSV = 0.38To – 8.94 (n=582, R^2=0.21, p<0.001)	TSV = 0.38To + 0.18MO – 9.09 (n=582, R^2=0.22, p<0.001)	F(1, 572) = 5.07, p<0.05
H3	TSV = 0.15To – 3.52 (n=3321, R^2=0.05, p<0.001)	TSV = 0.15To + 0.06MO – 3.62 (n=3321, R^2=0.05, p<0.001)	F(1, 3318) = 6.38, p<0.05

*MO assumes the value of 1 (one) for natural ventilation mode and 0 (zero) for air-conditioning mode.

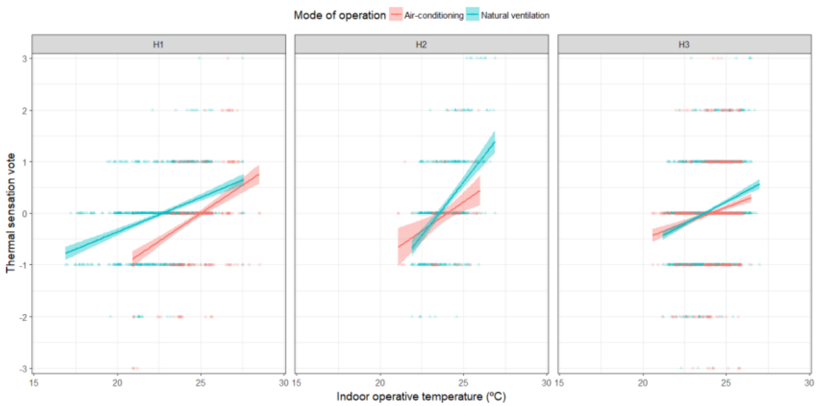


Fig. 34: Linear regression between indoor operative temperature and thermal sensation vote for each building and mode of operation. Confidence intervals of 95% are shown in blue/red colour along the regression line. Density of data may be observed by lighter/darker blue/red points.

Table 30: Linear regression equations between indoor operative temperature and thermal sensation vote for each building and mode of operation.

Building	Mode of operation	
	Natural ventilation	Air-conditioning
H1	TSV = 0.13To – 3.04 (n=952, R^2=0.14, p<0.001)	TSV = 0.22To – 5.42 (n=615, R^2=0.15, p<0.001)
H2	TSV = 0.41To – 9.75 (n=457, R^2=0.24, p<0.001)	TSV = 0.22To – 5.38 (n=125, R^2=0.09, p<0.001)
H3	TSV = 0.17To – 4.08 (n=1712, R^2=0.15, p<0.001)	TSV = 0.12To – 2.97 (n=1609, R^2=0.03, p<0.001)

Developing the adaptive model of thermal comfort for mixed-mode buildings in the humid-temperate climate zone

Developing the adaptive model of thermal comfort required the calculation of indoor comfort temperature (and the ranges of indoor temperature variability that users evaluated as comfortable) and the prevailing mean outdoor air temperature.

Estimating comfort temperatures using linear regression

Indoor comfort temperatures were determined using linear regression between thermal sensation vote and indoor operative temperature. Data were grouped for each building, mode of operation and period (month or day). Table 31 shows the number of models obtained for each building, mode of operation and period. In most cases, models did not achieve statistical significance.

The comfort temperatures derived from pooled data from all buildings for each mode of operation and period, were used to perform linear regressions against the prevailing mean outdoor air temperature. Thus, the four adaptive thermal comfort models shown in Table 32 were derived. For the air-conditioning mode, the equations did not achieve statistical significance. Due to that and also to the fact that a lot of data was not used to derive the comfort temperatures in both modes of operation, the Griffiths' method was also employed to calculate indoor comfort temperatures.

Table 31: Number of models obtained for each building, mode of operation and period (month or day) using linear regression.

Building	Description	Mode of operation: Natural ventilation	Mode of operation: Air-conditioning
H1	Low-rise office buildings with mixed-mode operation controlled by users. Occupants are free to adjust and choose their clothing. Surveys conducted during all seasons (n=1567).	Month: 8 linear models (3*) Day: 16 linear models (5*)	Month: 8 linear models (3*) Day: 14 linear models (5*)
H2	12-storey office building with mixed-mode operation controlled by users. Occupants are free to adjust and choose their clothing. Surveys conducted during winter (n=582).	Month: 2 linear models (1*) Day: 9 linear models (5*)	Month: 2 linear models (1*) Day: 4 linear models (1*)
H3	5-storey office building with mixed-mode operation controlled by users. Overall, occupants are free to adjust and choose their clothing, with the exception that it is compulsory for men to wear trousers. Surveys conducted during all seasons (n=3321).	Month: 8 linear models (5*) Day: 11 linear models (6*)	Month: 8 linear models (5*) Day: 12 linear models (7*)

* Number of models that achieved statistical significance ($p<0.05$) resulting in a comfort temperature.

Table 32: Adaptive thermal comfort models for mixed-mode buildings using comfort temperatures derived using linear regression.

Data grouping	Mode of operation: Natural ventilation	Mode of operation: Air-conditioning
Month	$T_{comf} = 0.67T_{pma(out)} + 10.73$ (n=9, R^2=0.79, $p<0.010$)	$T_{comf} = -0.02T_{pma(out)} + 24.64$ (n=9, R^2=0.01, $p>0.050$*)
Day	$T_{comf} = 0.70T_{pma(out)} + 10.12$ (n=16, R^2=0.61, $p<0.010$)	$T_{comf} = 0.01T_{pma(out)} + 24.06$ (n=13, R^2=0.00, $p>0.050$*)

* Equations that did not achieve statistical significance ($p>0.050$).

Estimating comfort temperatures by Griffiths' method

Griffiths' method was used to estimate indoor comfort temperatures following the same aggregation strategy used in the linear regression and also for each comfort vote. Table 33 shows the adaptive models of thermal comfort for mixed-mode buildings using Griffiths' method. In Table 33, Griffiths slope was assumed as 0.5/ºC[18]. For natural ventilation mode, the three equations achieved statistical significance and the equation with the highest value for the coefficient of determination is shown in Table 33 and Fig. 35 (data grouped by month). It is interesting to note that the adaptive model of thermal comfort for mixed-mode buildings during natural ventilation mode in Florianópolis ($T_{comf} = 0.56T_{pma(out)} + 12.74$) resulted in a higher regression model gradient than the ASHRAE 55 [16] adaptive model ($T_{comf} = 0.31T_{pma(out)} + 17.80$). This indicates that users in Florianópolis are more tolerant to cooler conditions when it is cooler outdoors and more tolerant to warmer conditions when it is warmer outdoors, than the ASHRAE model predicts. It is also important to mention that the model for natural ventilation mode in mixed-mode buildings obtained in this work is similar to the model recently proposed for naturally ventilated office buildings in India ($T_{comf} = 0.54T_{pma(out)} + 12.83$) [7]. The regression model gradient obtained for natural ventilation mode in Florianópolis (0.56) is also similar to the model developed: (a) for mixed-mode office buildings during natural ventilation operation in Pakistan ($T_{comf} = 0.52T_{pma(out)} + 15.40$) [13] and (b) for Japanese houses during the operation of natural ventilation ($T_{comf} = 0.53T_{pma(out)} + 12.50$) [34].

Comparing the models for natural ventilation mode from comfort temperatures using both methods, it was observed that Griffiths' method resulted in models with lower gradients and better fit to the data compared to the linear regression analytic method.

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[18] Comfort temperatures were also calculated using Griffiths slope varying from 0.1 to 0.6/ºC. Similar adaptive thermal comfort models were obtained by using Griffiths slopes ranging from 0.3 to 0.5/ºC. Thus, a Griffiths slope equal to 0.5/ºC was adopted, as recommended by [33].

Table 33: Adaptive thermal comfort models for mixed-mode buildings using comfort temperatures derived by Griffiths method. The models with best fit to the data are highlighted in grey.

Data grouping	Mode of operation	
	Natural ventilation	Air-conditioning
Month	$T_{comf} = 0.56T_{pma(out)} + 12.74$ ($n=18$, $R^2=0.89$, $p<0.001$)	$T_{comf} = 0.04T_{pma(out)} + 23.49$ ($n=18$, $R^2=0.03$, $p>0.050$*)
Day	$T_{comf} = 0.58T_{pma(out)} + 12.22$ ($n=36$, $R^2=0.73$, $p<0.001$)	$T_{comf} = 0.06T_{pma(out)} + 23.09$ ($n=30$, $R^2=0.05$, $p>0.050$*)
Vote	$T_{comf} = 0.52T_{pma(out)} + 13.57$ ($n=3121$, $R^2=0.24$, $p<0.001$)	$T_{comf} = 0.09T_{pma(out)} + 22.32$ ($n=2349$, $R^2=0.02$, $p<0.001$)

* Equations that did not achieve statistical significance ($p>0.050$).

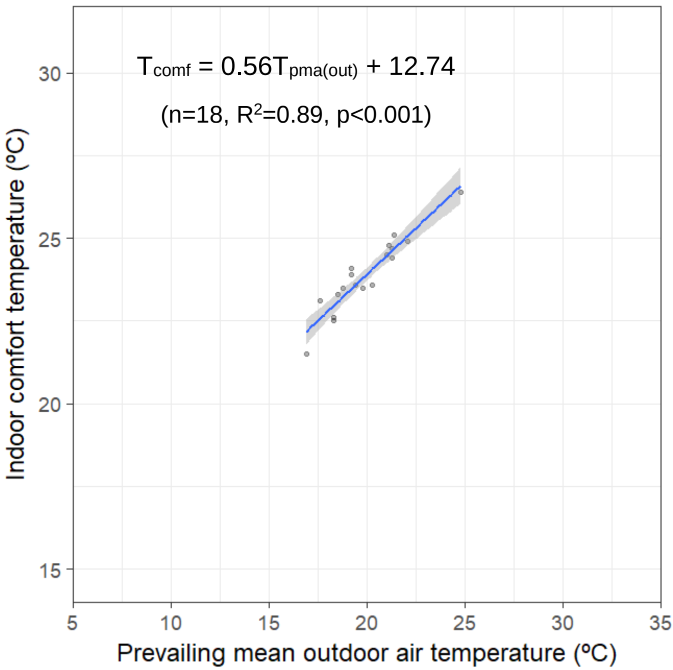

Fig. 35. Linear regression between prevailing mean outdoor air temperature and the indoor comfort temperature for natural ventilation mode in mixed-mode buildings in Florianópolis. A confidence interval of 95% is shown in grey along the regression line.

For the air-conditioning mode, the only equation that achieved statistical significance was the one considering each comfort vote (Table 33). And even in this situation, the prevailing mean outdoor air temperature explains roughly 2% of the variance of the indoor comfort temperature, i.e., a negligible adaptive relation between indoors and outdoors. Such equation ($T_{comf} = 0.09T_{pma(out)} + 22.32$) is similar to the equation shown in CIBSE Guide A [35] for cooling and heating modes ($Tc_{omf} = 0.09T_{pma(out)} + 22.60$).

Determining the range of indoor comfort temperatures

It is expected that users experiencing higher or lower indoor temperatures than the adaptive comfort temperature could be feeling thermal discomfort. Larger deviations in the indoor operative temperature from the comfort temperature could cause greater thermal discomfort [9, 11]. The concept of temperature offset from neutrality has been used in previous studies [9, 36] to consider the differences in users' thermal history (recent thermal experiences). Thermal history and current conditions influence the indoor comfort temperature [9]. The temperature offset from neutrality was calculated for each vote using Eq. 7.

$$\boldsymbol{T_{diff} = T_o - T_{comf}} \qquad \textbf{Eq. 7}$$

where: T_{diff} is the temperature offset from neutrality (ºC); T_o is the indoor operative temperature (ºC); T_{comf} is the indoor comfort temperature obtained from the adaptive model of thermal comfort for mixed-mode buildings during natural ventilation mode[19] in Florianópolis (Fig. 35).

Using the temperature offset from neutrality and the corresponding thermal comfort vote, it is possible to determine the probability of users feeling thermal discomfort by means of logistic

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[19] For comparison reasons, the temperature offset from neutrality was also calculated for the air-conditioning mode, using the linear regression model presented in Table 33 ($T_{comf} = 0.09T_{pma(out)} + 22.32$).

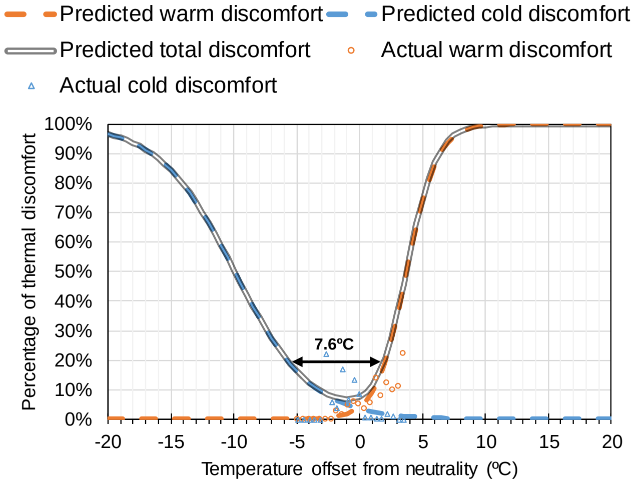
regression (Eq. 8). Previous works used probit [9] or logistic regression [11, 36] to determine the likelihood of subjects voting in each thermal sensation scale and determined that votes beyond -1 and +1 could be considered as discomfort. In this work, actual thermal discomfort votes were used.

$$\boldsymbol{P(discomfort)} = \frac{\mathbf{1}}{\mathbf{1} + \boldsymbol{e}^{-(\boldsymbol{b0}+\boldsymbol{b1}.\boldsymbol{T}_{\boldsymbol{diff}})}} \qquad \textbf{Eq. 8}$$

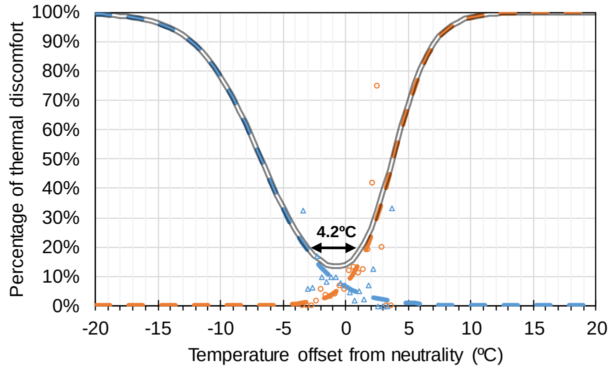
where P(discomfort) is the probability of thermal discomfort occurring; e is the base of natural logarithms; b0 is the constant of logistic regression model; b1 is the coefficient of logistic regression model; T_{diff} is the temperature offset from neutrality (the difference between the indoor operative temperature and the comfort temperature) (ºC).

Fig. 36 shows the results of logistic regression between actual thermal discomfort and temperature offset from neutrality for both modes of operation in mixed-mode buildings (the equations are presented in Table 34). The predictive curves indicate a minimum percentage of thermal discomfort equal to 7% in natural ventilation mode and 13% in air-conditioning mode, when the temperature offset from neutrality was -1.0ºC and -0.5ºC, respectively. This indicates a slightly cooler-than-neutral environment preference. It is also interesting to note that the minimum percentage of thermal discomfort was lower during natural ventilation mode.

Based on the 20% thermal discomfort on predictive curves (Fig. 36), the range of indoor comfort temperatures (upper and lower limits for 80% satisfied (comfortable)) may be established for each mode of operation. For natural ventilation mode, the range was estimated as 7.6ºC and for the air-conditioning mode as 4.2ºC. Applying these ranges to the adaptive model in natural ventilation mode (Fig. 35) resulted in Eqs. 9 and 10, which express the upper and lower limits of indoor (comfort) temperatures for NV and AC modes of ventilation. Graphically, such equations define the adaptive thermal comfort ranges for natural ventilation mode in mixed-mode buildings in Florianópolis (Fig. 37[20]).



(a) Natural ventilation mode



(b) Air-conditioning mode

Fig. 36: Percentage of actual and predicted (logistic regression) discomfort as a function of the temperature offset from neutrality for natural ventilation and air-conditioned mode in mixed-mode office buildings in Florianópolis. Actual data are presented grouped in 20 bins of equal size.

[20] In Fig. 37, the ranges for air-conditioning mode applying the 4.2ºC band to the linear regression model presented in Table 33 (T_{comf} = $0.09T_{pma(out)}$ + 22.32) was also shown. It is just to show how not adaptive is the relationship between indoors and outdoors.

Table 34: Logistic regression equations for thermal discomfort caused by warm or cold sensations (warm or cold discomfort) as a function of the mode of operation.

Discomfort	Mode of operation	
	Natural ventilation	Air-conditioning
Warm sensation	$P = \frac{1}{1 + e^{-(-3.14+0.84T_{diff})}}$ (n=3121, R^2=0.14, p<0.010)	$P = \frac{1}{1 + e^{-(-2.49+0.65T_{diff})}}$ (n=2349, R^2=0.10, p<0.001)
Cold sensation	$P = \frac{1}{1 + e^{-(-3.30-0.33T_{diff})}}$ (n=3121, R^2=0.22, p<0.001)	$P = \frac{1}{1 + e^{-(-2.68-0.40T_{diff})}}$ (n=2349, R^2=0.10, p<0.001)

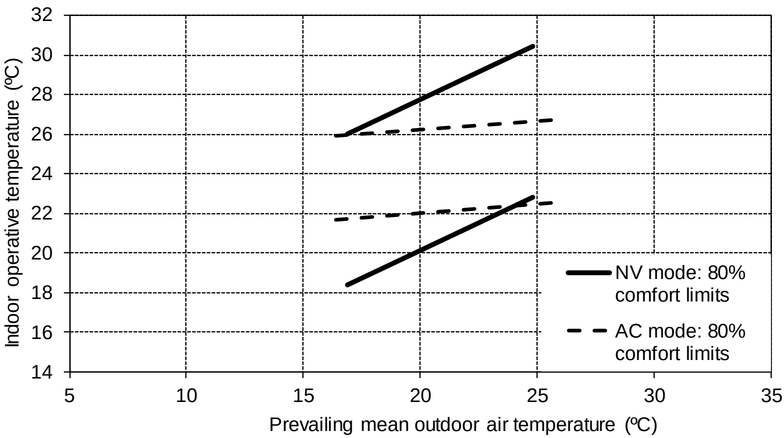


Fig. 37: Adaptive thermal comfort ranges for natural ventilation and air-conditioned mode (just for illustration) in mixed-mode buildings located in Florianópolis. Limits of prevailing mean outdoor air temperature range from 16.9 to 24.8ºC in natural ventilation mode and from 16.4 to 25.7ºC in air-conditioning mode.

Despite the fact that the adaptive model of thermal comfort for air-conditioning mode did not result in a good adaptive relation, the range of 4.2ºC shown in Fig. 37, indicates an interval of about

22 to 26ºC (up to 26.7ºC with prevailing mean outdoor air temperature of 25.7ºC) as comfortable to users – very close to the predictions of the psychrometric chart comfort standard in ASHRAE 55, which was intended for AC buildings. Such wide variation of indoor temperature could be used in the operation of the air-conditioning system, decreasing energy consumption.

Upper limits of 80% comfort (ºC) = $0.56T_{pma(out)} + 16.54$ **Eq. 9**

Lower limits of 80% comfort (ºC) = $0.56T_{pma(out)} + 8.94$ **Eq. 10**

Predicting the range of thermal sensation vote assessed as comfortable by users

When developing the PMV approach, Fanger [17] established a range of PMV between -1 and +1 as comfortable to users. If it is assumed that 20% of thermal dissatisfied (PPD) is the threshold for comfort, it results in a PMV range of ±0.85. As stated in section ”Determining the range of indoor comfort temperatures”, some authors [9, 11, 36] adopted a range between -1 and +1 on the 7-point thermal sensation scale as comfortable to users (20% of thermally dissatisfied). However, these ranges are not supported by field studies and maybe the deviations from neutral (TSV = 0), comfort conditions, are not equally distributed between the cold and warm side of the thermal sensation scale. In this work, actual thermal discomfort votes were obtained from users, which allow to predict, using logistic regression, the range of thermal sensation vote assessed as comfortable. Applying Eq. 8, using TSV instead of T_{diff}, the predictive curves of thermal discomfort and TSV for both modes of operation in mixed-mode buildings may be seen in Fig. 38. A range of TSV between -1.3 and +1.0 in NV mode and between -0.9 and +0.8 in AC mode provided thermal comfort to users, considering the threshold of 20% of dissatisfied (thermal discomfort). This coincidentally is in very good agreement with the 20% PPD level assumed for PMV values of -0.85 and +0.85. In AC mode, the comfortable TSV variation is roughly equally distributed around the neutral point. In the other hand, in the NV mode, users tolerated cooler sensations than warmer ones.

Fig. 38 also shows that smaller deviations from neutral in AC mode resulted in higher thermal discomfort than in NV mode.

For example, a TSV equal to -2 in NV mode represents 62% of thermal discomfort, while in AC mode, it represents a 96% of thermal discomfort. This supports the adaptive comfort hypothesis that occupants experiencing natural ventilation are more tolerant of thermal variability than those exposed to air-conditioning.

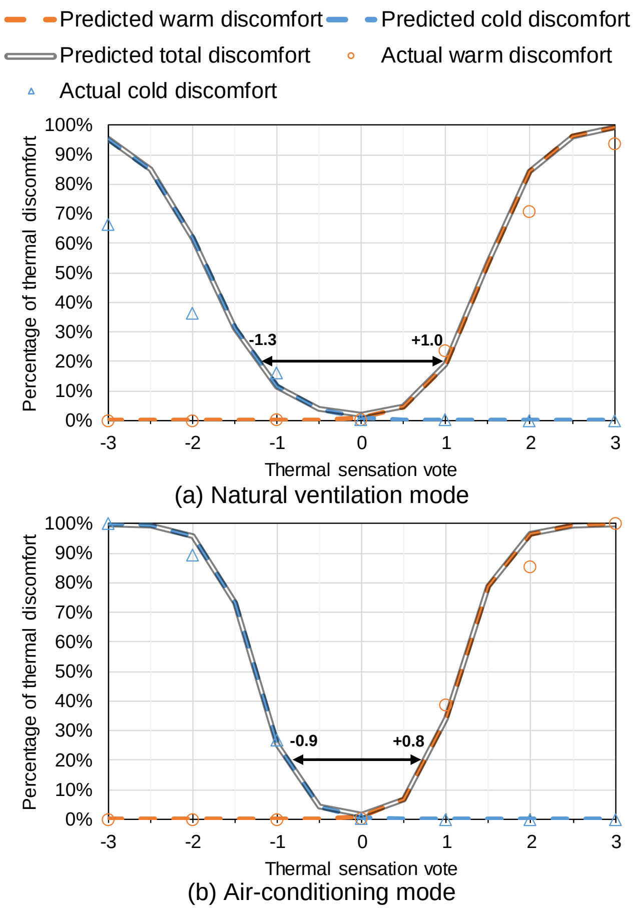


Fig. 38: Percentage of actual and predicted (logistic regression) discomfort as a function of the thermal sensation vote for natural ventilation and air-conditioned mode in mixed-mode office buildings in Florianópolis. Actual data are presented grouped in 7 bins of equal size.

CONCLUSIONS

Field studies of thermal comfort were conducted in three mixed-mode office buildings in the city of Florianópolis, Southern Brazil. More than 5,400 questionnaires with accompanying instrumental measurements were collected over the four seasons.

This work found no evidence to support either a single adaptive model for mixed-mode buildings as proposed by previous works [7, 8] or the recommendation of ASHRAE 55 [16] that mixed-mode buildings should be evaluated as HVAC buildings. It was clear that during natural ventilation operation occupants adapted, mainly due to clothing adjustments, to temperature fluctuations as predicted by adaptive thermal comfort theory – a strong relation between indoor comfort temperature and the prevailing mean outdoor air temperature was found. During air-conditioning operation, a weak relation between indoors and outdoors was observed (users were disconnected from outdoor climate). Users' thermal sensation was influenced by the mode of operation. Wider ranges of indoor temperature fluctuation were accepted by users when the building was running in natural ventilation mode. The acceptable range of thermal sensation votes between -1.3 and +1.0 in natural ventilation mode was slightly wider than the -0.9 to +0.8 range observed in air-conditioned mode, confirming the adaptive model's prediction.

The adaptive model of thermal comfort developed for mixed-mode buildings operating in natural ventilation mode in Florianópolis, Brazil:

- is limited to prevailing mean outdoor air temperature ranging from 17ºC to 25ºC.
- indicates that building occupants are more tolerant to cooler conditions during cool season and more tolerant to warmer conditions during warm season than expected on the basis of the ASHRAE 55 adaptive model.
- is similar to the adaptive model derived for naturally ventilated office buildings in India, which, like Brazil, is a member of the newly industrialized BRICS group of countries.

The adaptive model of thermal comfort developed for mixed-mode buildings operating in air-conditioning mode in Florianópolis:

- showed a weak relation between indoor thermal comfort and climatic context.
- is limited to prevailing mean outdoor air temperature ranging from 16ºC to 26ºC.
- indicated a range of indoor operative temperatures from 22ºC up to around 26ºC as comfortable to users. This closely resembles the ASHRAE 55 prescriptions for air-conditioned buildings.
- is similar to the adaptive model derived for heated/cooled office buildings in Europe (CIBSE Guide A).

This work is a first step towards building an adaptive model of thermal comfort for Brazilian subtropical climate. Other cities in the subtropical region of Brazil have outdoor climates different than that of Florianópolis, like Porto Alegre (colder in winter and warmer in summer) and Curitiba (colder over the entire year). Further field studies are necessary in order to support and enlarge the scope of application of the adaptive model developed in this work.

Another interesting field of study is related to questionnaire scales. In this work, a binary scale for thermal comfort and thermal acceptability was adopted. This may influence user's response. For example, a user feeling a slightly discomfort could have answered "Comfortable" instead of "Uncomfortable", because he/she did not have the option to choose "Slightly discomfort". These semantic and scale differences could be investigated in future works.

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4.3 ARTIGO 3: ASSOCIAÇÃO ENTRE VARIÁVEIS CONTEXTUAIS E CONFORTO TÉRMICO

RUPP, R. F.; KIM, J.; DE DEAR, R.; GHISI, E. Associations of occupant demographics, thermal history and obesity variables with their thermal comfort in air-conditioned and mixed-mode ventilation office buildings. **Building and Environment**, v.135, p. 1-9, 2018. doi: 10.1016/j.buildenv.2018.02.049

Este artigo está relacionado ao quarto objetivo específico desta tese. Neste artigo investigou-se a relação entre variáveis contextuais (gênero, idade, peso e altura, histórico térmico e estratégia de ventilação – ventilação híbrida ou ar-condicionado central) e a percepção de conforto térmico de usuários em edificações de escritórios. Os resultados do trabalho também contribuíram para maior conhecimento sobre a percepção térmica de ocupantes nos diferentes modos de operação de edificações operando com ventilação híbrida e com sistema de ar-condicionado central no clima subtropical úmido de Florianópolis.

Declaração de contribuição de coautores

Ricardo Forgiarini Rupp: como primeiro autor, Ricardo foi o responsável pela coleta de dados -realizada em conjunto com pesquisadores do LabEEE-UFSC- e pelo processo de redação do artigo, incluindo a revisão da literatura, tratamento e análise dos dados, resultados e conclusões.

Jungsoo Kim: como coautor, Jungsoo supervisionou todo o processo de produção do artigo e contribuiu com discussões durante a redação do artigo, principalmente com relação à análise estatística. O artigo também foi revisado e editado por Jungsoo.

Richard de Dear: como coautor, Richard supervisionou todo o processo de produção do artigo e contribuiu com discussões durante a redação do artigo. O artigo também foi revisado e editado por Richard.

Enedir Ghisi: como coautor, Enedir supervisionou todo o processo de produção do artigo e contribuiu com discussões durante a redação do artigo. O artigo também foi revisado e editado por Enedir.

Associations of occupant demographics, thermal history and obesity variables with their thermal comfort in air-conditioned and mixed-mode ventilation office buildings

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Abstract

Building occupants' perception of thermal comfort can be influenced by a number of contextual factors, such as their demographic and anthropometric characteristics, behavioural patterns and cultural aspects. The objective of this work is to investigate the relationship between various contextual factors and the perception of thermal comfort in workplaces, by examining the gap between the current thermal comfort criteria and the actual requirements observed for different groups of occupants. The classic thermal comfort field research design i.e. simultaneous measurements of physical environmental parameters and questionnaire surveys, was implemented for two years in both centralised HVAC and mixed-mode office buildings located in Southern Brazil. Over 7,500 questionnaires were completed by occupants of the buildings. Key variables including the participants' gender, age, body mass index, prior exposure to air-conditioning and building ventilation type were investigated in order to identify their association with thermal discomfort in the office workplace. Our results suggest that males, overweight occupants and those who are more frequently exposed to air-conditioning are more likely to express thermal discomfort due to feeling 'warm', compared to females, non-overweight occupants and those who were exposed to air-conditioning less frequently. In comparison, females, non-overweight occupants, air-conditioning light users, and occupants of centralised HVAC buildings were more likely to declare 'cold' discomfort. We also investigated how those variables were related to the width of thermal comfort zone. The analysis indicates that different groups of occupants require different comfort zones, suggesting that group differences should be considered when designing/operating spaces for diverse groups of occupants.

Keywords: human thermal comfort; gender; obesity; thermal history; mixed-mode buildings.

INTRODUCTION

Since the work of Fanger in 1970 [1], the six most influential variables on human body heat balance were known by means of climate chamber studies: i.e. metabolism and clothing (the human factors), air temperature, mean radiant temperature, air velocity and relative humidity (the environmental factors). However, thermal comfort may not be fully understood just by these six variables in real world situations [2]. Numerous contextual factors can also influence occupants' thermal comfort perception, including behavioural and cultural aspects, individual preferences, demographic and anthropometric characteristics (e.g. age, gender, weight), space layout, architectural features, and adaptive opportunities available [2]. According to the adaptive model of thermal comfort [3, 4], thermal perception can also be influenced by past and current thermal conditions to which people have been exposed (thermal history).

The influence of gender, weight and age on thermal comfort has previously been investigated through: a) climate chamber studies focusing on human physiology and b) statistical comparison of experimental results (either climate chamber or field studies) between different subgroups (for example, male vs. female, overweight vs. lean, young vs. elderly). Climate chamber studies have advantages in the collection of more detailed information about subjects' anthropometric characteristics, such as weight and height. In field settings precise measurements of those characteristics are logistically very difficult, thereby it relies on participants' self-assessment.

In the field of physiology, the concept of thermoneutral zone (TNZ) has been used to explain the differences between gender, age and weight [5]. The TNZ is defined as the range of temperature in which the regulation of body temperature is achieved by means of sensible heat loss, without involving metabolism changes or heat losses by evaporation [5]. Studies have shown that the TNZ: a) is narrower for the elderly[21] in comparison to young adults (elderly would have greater difficulty maintaining the thermal balance and even fail to sense the thermal imbalance), b) shifts down to lower temperatures for overweight people compared to lean people[22] due to their increased tissue insulation (greater adiposity) and c) corresponds to higher temperatures for females than for males [5]. The metabolic rates of a homogeneous group of people (female subjects) were determined through climate chamber experiments in the Netherlands [8]. Females presented differences between -20% and -32% compared to the thermal comfort standards' metabolic rate values (e.g. ASHRAE Standard 55 [9] and ISO Standard 7730 [10]), which were based exclusively on male samples [8].

These discrepancies in metabolic rate were also observed in another climate chamber study in Switzerland and Australia with a heterogeneous population [11]. Metabolic rates presented a difference of 5% between genders and different age groups (females and older adults presented a lower metabolism). However, the greatest difference in the metabolic rate was noted in relation to the weight of subject, as assessed with the Body Mass Index (BMI): overweight subjects had a metabolic rate 30% lower than normal weight people [11].

Climate chamber experiments examining gender differences on thermal comfort were performed in China [12, 13]

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[21] People who are 60 years or over are considered as the elderly according to the United Nations [6].

[22] It appears that in physiology studies the term "lean" refers to subjects with a body mass index less than 25 kg/m^2. This way including the "normal weight" and "underweight" classifications from the World Health Organization [7].

and the Netherlands [14, 15]. All these studies were conducted with young adults (between 20-30 years of age), with equal number of female and male subjects and similar relationship between mass and height. Females tended to feel more uncomfortable and dissatisfied [12] and are also more sensitive to temperature change compared to males [12, 13]. Males preferred a slightly cooler environment, whereas females preferred a slightly warmer condition [12, 13].

Extensive debates of the gender difference can be found in previous review papers [16, 17]. Gender differences in the perception of thermal comfort are not universally consistent across all the studies included in their literature survey, but the weight of evidence suggests that gender differences do exist. In general, females expressed thermal dissatisfaction more frequently than males under the equivalent thermal environments. Females also preferred higher temperatures and were more sensitive to deviations from neutrality than their male counterparts.

Another contextual factor that has received attention of the thermal comfort research community is antecedent thermal exposure or more simply, ‘thermal history’ [18-25]. Climate chambers in Seoul (Korea) and Yokohama (Japan) were set with the same indoor thermal conditions (air temperature equal to 28ºC and relative humidity equal to 50%) to investigate the effects of thermal history [18]. Subjects who were exposed to higher temperatures prior to the experiment answered with cooler thermal sensations than those who were exposed to cooler temperature conditions. Subjects who used air-conditioners at home expressed warmer thermal sensations than those who did not use air-conditioners at home [18]. Another climate chamber study was performed in Beijing (heating is commonly used in winter) and in Shanghai (heating is not commonly used in winter) [21]. Subjects were exposed to a variation of temperature between 12-20ºC during the chamber experiments. Beijing subjects who were accustomed to higher indoor temperatures felt colder thermal sensations than Shanghai subjects who were accustomed to lower indoor temperatures [21].

A field study in Northeastern Brazil (Maceió with a hot and humid climate) was performed in naturally ventilated university classrooms with an aim to examine the effect of thermal history on thermal preferences [19]. Data were organized in two groups:

those users who were exposed to air-conditioning prior to the field studies and those who weren't. Most of the users who were not exposed to air-conditioning preferred no change the thermal conditions of the naturally ventilated classrooms, while those who were exposed to air-conditioning preferred to be cooler [19].

Thermal comfort guidelines prescribed in the international standards (e.g. ASHRAE 55 [9] and ISO 7730 [10]) are generally regarded as universally applicable to all occupants of all building typologies. However, as discussed above, there are a growing number of studies identifying group/individual differences in occupant response to thermal environments. Thus, more research is needed to investigate whether individual or contextual differences can lead to systematic discrepancies in occupant comfort levels, and to delineate the *specific* thermal comfort requirements of different groups of occupants. If different groups of occupants require different indoor thermal environments, we should reconsider the prevalent "one size fits all" approach to engineer indoor climates and change our way of designing spaces to accommodate diverse needs of occupants. Within this broad scope, the overall objective of the current work is to investigate the relationship between various contextual factors and the perception of thermal comfort in workplaces, by examining the gap between the current comfort criteria (i.e. universal comfort zone) and the *actual* comfort requirements of different groups. Specifically, this paper aims (1) to identify demographic and anthropometric variables that are associated with office occupants' perception of thermal comfort, (2) to investigate how thermal history (based on the extent of preceding air-conditioning exposure) can influence thermal comfort in workplace, and (3) to examine the impact of contextual factors on the widths of comfort zone, therefore to propose comfort criteria better suited to specific groups of building occupants.

METHOD

Field studies

The classic "right-here-right-now" type field study, e.g. simultaneous measurements of physical environmental parameters and questionnaire surveys, was conducted by a team of researchers from the Laboratory of Energy Efficiency in Buildings (Federal University of Santa Catarina - Brazil) during 2014-2016. One centrally air-conditioned (HVAC) and three mixed-mode (MM) office buildings located in the city of Florianópolis, Brazil (humid subtropical climate) were investigated. The studied buildings are all public buildings located in the central region of the city. In our sample of MM buildings, occupants were allowed to change the operation mode to suit their preferences – e.g. use of split air-conditioners and opening or closing of the windows. Despite buildings were built in the 1980s (HVAC) and 1990s (MM), the HVAC system was replaced in 2008 and the split air-conditioners are from the 2000s or newer. Background information of the sample buildings are summarised in Table 35. Information that may allow the identification of the sample buildings (e.g. photos and floor plans) was not included in this paper.

Microclimate data loggers recorded the indoor globe temperature, air temperature, relative humidity and air velocity in accordance with ASHRAE 55 [9]. Outdoor environmental conditions were taken from a meteorological station located near the buildings.

Occupant survey questionnaires collected the occupant's anthropometric (weight and height) and demographic (gender and age), as well as their clothing, activity and reliance on air-conditioning system outside of the workspace (frequency and daily usage at home[23]). Participants were asked to answer the questionnaire including the background survey in different seasons with the exception of building H2. Clothing insulation and metabolic rate were estimated according to ASHRAE 55 [9]. Occupants were also asked to report their thermal sensation, preference, acceptability and comfort (Table 36) at the same time and within the same space when the instrumental measurements were performed. We also observed user's adaptive behaviour including the operation of air-conditioners and windows during the

[23] Overall, the residential air-conditioning market in Brazil has been constantly increased on a year to year basis. The use of residential air-conditioners is no longer considered a luxury in Brazil and has become a major concern for the Brazilian electricity sector [26].

monitoring period. More information about the field study methods can be seen in [27-28].

Table 35: Characteristics of the buildings surveyed.

Building identification name	MM1	MM2	MM3	HVAC
Building characteristics and indoor environments				
Construction year	1990s	1990s	1990s	1980s
Total floor plan area (m^2)	6200	8244	3090	27432
Number of blocks	3	1	1	1
Number of floors	1, 1 and 2	12	5	5
Offices	Open plan with lightweight partitions	Open plan with lightweight partitions	Open plan with lightweight partitions	Open plan with lightweight partitions
Ceiling height (m)	2.6	2.6	2.6	2.5
Window operation	Operable windows	Operable windows	Operable windows	Sealed windows
Air-conditioning system	Split	Split	Split	Central
Mixed-mode operation	Changeover controlled by users	Change-over controlled by users	Change-over controlled by users	NA
Occupation and comfort surveys				
Number of occupants	320	350	250	1200
Working hours	8am - 6pm	1pm - 7pm	8am - 6pm	7am - 7pm
Survey period	2014 - 2016	2014	2015 - 2016	2014 - 2016
Survey season	All seasons	Winter	All seasons	All seasons
Number of questionnaires	1567	582	3321	2094

All office workers of the MM buildings were invited to participate in the study. The HVAC building is composed by three floors above-, and two floors below ground level. The research team was allowed to survey only the spaces above ground due to the occupying organisation's security reasons. Thus, office workers of all available spaces were asked to take part in this study. All participants were volunteers, well acclimatised to the studied climate and did not receive any monetary incentive. The participants answered the questionnaire anonymously.

Table 36: Rating scales used in the survey questionnaire.

Scale	-3	-2	-1	0	+1	+2	+3
Thermal sensation (TSV)	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
Thermal preference (TP)	-	-	Cooler	No change	Warmer	-	-
Thermal acceptability (TA)	-	-	-	Accepta-ble	Unaccep-table	-	-
Thermal comfort (TC)	-	-	-	Comfor-table	Uncom-fortable*	-	-

* If users expressed thermal discomfort, they were asked to state if it was caused by warm or cold sensations.

Analysis of the datasets

In order to investigate the link between diverse personal or contextual factors and occupants' perception of thermal comfort, a series of statistical analyses were performed. During our background survey, basic demographic and anthropometric information of the each participant, e.g. gender, age and body mass index (BMI)[24], were collected. In addition, the background questionnaire enquired the respondents' air-conditioning (AC) usage patterns in their everyday life, by asking *when, where* and *how long* they typically operate AC outside their workplaces. The responses on these questions became a basis to broadly determine the degree of the respondent's reliance on AC (see Table 37 for the grouping criteria used for the analysis). The operational type of a building (i.e. HVAC or MM) was also taken

[24] The body mass index was calculated by dividing the weight by the square of the body height. The normal weight classification was assumed as the range between 18.5 and 25.0 kg/m^2.

into account in the analysis as we have learned from our previous analysis that the mode of operation can affect occupants' reaction towards the thermal environment [29]. A relative temperature scale, defined as the temperature offset from neutrality (T_{diff}) was used in our analyses. Given our research design (two years of monitoring), each of the collected survey responses would have carried different thermal experience. Thus T_{diff} was used to adjust the differences in the participants' recent thermal experiences (thermal history) prior to the survey. This concept has been used in other studies [30-32]. The temperature offset from neutrality was calculated for each vote using Eq. 11.

$$\boldsymbol{T_{diff} = T_o - T_{comf}} \quad \textbf{Eq. 11}$$

where: T_{diff} is the temperature offset from neutrality (ºC); T_o is the indoor operative temperature (ºC); T_{comf} is the indoor neutral (comfort) temperature determined by ASHRAE 55's adaptive model of thermal comfort [9].

Table 37: Criteria used to classify user's dependence on air-conditioning outside of the workspace.

Dependence on AC	Grouping criteria
None	Those who do not use air-conditioning outside of the workspace
Light	Those who use air-conditioning outside of the workspace only in hot days, less than 4h per day
Moderate	Those who use air-conditioning outside of the workspace only in hot days, between 4-8h per day
Heavy	Those who use air-conditioning outside of the workspace only in hot days, more than 8h per day and those who use air-conditioning almost always (not climate dependent).

Comfort temperature was estimated for each occupant group by using Griffiths' method [33] (Eq. 12). We used Griffith's method because the linear regression method (TSV vs. To) failed to estimate the comfort temperature within our survey database [29].

$$T_{comf} = T_o - TSV/G \qquad \textbf{Eq. 12}$$

where T_{comf} is the comfort temperature (ºC); T_o is the indoor operative temperature (ºC); TSV is the Thermal Sensation Vote (non-dimensional); G is the Griffiths constant (ºC^{-1}) adopted as 0.5 [29].

Two sets of multiple logistic analyses were performed with the variables mentioned above (T_{diff}, gender, age, BMI, dependence on AC, and ventilation type – Table 38) as the independent variables, and the occurrence of 'warm discomfort' or 'cold discomfort' responses as the dependent variables. Occupant groups coded as 0 in Table 38 were set as the reference group in the logistic analysis (i.e. Odds Ratio of 0). The temperature offset from neutrality (T_{diff}) was included in the logistic models in order to account for the physical thermal conditions that the respondent experienced at the time of the survey. The purpose of the multiple logistic analyses was to identify contextual variables that are associated with occupant's perception of thermal comfort (i.e. expression of discomfort). Simple logistic regression analyses were also performed using gender, age and BMI as independent variable and 'warm discomfort' or 'cold discomfort' occurrence as the dependent variable.

Table 38: Grouping criteria and code for gender, age, BMI, dependence on AC and building ventilation type.

Variable	Grouping criteria and code
Gender	0 = Female 1 = Male
Age	0 = 50 years or under 1 = over 50 years
BMI	0 = Underweight or Normal (BMI ≤ 25.0 kg/m^2) 1 = Overweight (BMI > 25.0 kg/m^2)
Dependence on AC	0 = None 1 = Light 2 = Moderate 3 = Heavy
Building ventilation type	0 = MM 1 = HVAC

To further understand the occupants' reaction towards thermal environment in relation to different contextual factors, a set of logistic regression models were developed for each group of the occupants (categorised by gender, age and BMI). Then the logistic model was fitted between T_{diff} and the occurrences of thermal discomfort (warm or cold) votes. Therefore, the probability of people dissatisfied due to warm- or cold-discomfort, as a function of temperature variation, can be estimated through Eq. 13. The logic behind this analysis is directly comparable to the derivation of PMV-PPD curve [1], which would allow us to estimate the width of comfort zone for each of the occupant groups. R statistical software [34] was used to perform all analysis.

$$\boldsymbol{P(discomfort)} = \frac{\mathbf{1}}{\mathbf{1} + \boldsymbol{e}^{-(\boldsymbol{b0}+\boldsymbol{b1.X1}+\boldsymbol{b2.X2}+\ldots+\boldsymbol{b6.X6})}} \qquad \textbf{Eq. 13}$$

where P(discomfort) is the probability of cold/warm thermal discomfort occurring; e is the base of natural logarithms; b0 is the constant of logistic regression model; b1 is the regression coefficient of the variable X1; b2 is the regression coefficient of the variable X2; and so on. For the simple logistic regressions, a single predictor was adopted (T_{diff}) and, for the multiple logistic regressions, six predictors were used (T_{diff}, gender, age, body mass index, dependence on air-conditioning and building ventilation type).

Wald statistic was used to assess the statistical significance of each *b* coefficient for a predictor in the logistic regression models. If the coefficient of an independent variable in the model is significantly different from zero, that predictor is contributing significantly to the prediction of the outcome. The odds ratio (OR) – the exponential of *b* coefficient, estimates the change in odds resulting from a unit change in the predictor (e.g. T_{diif}, gender, age, BMI, etc.). For example, if the OR is greater than 1 the odds of the outcome occurring increase as the predictor increases; if the OR is less than 1 the odds of the outcome occurring decrease as the predictor increases [35].

RESULTS AND DISCUSSION

A total of 7,564 questionnaire responses were collected from the four sample buildings throughout the two-year field study period. The collected responses were then matched with corresponding background information and physical observations of environmental parameters.

Overview of the data

An overview of the data collected for each building type (HVAC or MM) can be seen in Tables 39 and 40. A total of 2,094 responses were from the HVAC building, while the occupants of MM buildings returned 5,470 responses. Overall, PMV values indicated cooler conditions in the HVAC building (PMV of -0.4~-0.3) compared to the MM buildings (PMV of -0.1~0.0), despite the calculated Griffith's comfort temperature was comparable between the two building types (both 23~24ºC). The sample was also broken down by the respondent's gender, BMI and age to roughly characterise the study population. Except for that females returned a slightly cooler thermal sensation and slightly warmer comfort temperature than males, there were no noticeable differences in average values of thermal comfort variables (e.g. thermal sensation, preference, acceptability, comfort, Griffith's comfort temperature and PMV) between the three occupant groups.

Table 40 shows a statistical summary of personal variables, cross-tabulated by building ventilation type. A heterogeneous population may be observed through anthropometric and demographic data. Clothing insulation varied between 0.41 and 1.40 (1.73 for MM) across different seasons in both building ventilation types. The metabolic rate of the participants was that of typical office activities, including reading, writing, typing and filling.

Table 39: Statistical summary of indoor climate and thermal comfort indices at survey times, cross-tabulated by building ventilation type and personal variables (gender, BMI and age).

Building ventilation type	Variable (mean)	Gender		BMI		Age (years)	
		Female	Male	Normal/ Underweight	Overweight	≤ 50	>50
HVAC	Number of observations	796	1298	1006	1088	1705	389
	Thermal sensation vote	-0.4	-0.1	-0.3	-0.1	-0.2	-0.3
	Thermal preference vote	-0.2	0.1	-0.1	0.1	0.0	-0.1
	Thermal acceptability vote	0.1	0.0	0.1	0.0	0.1	0.0
	Thermal comfort vote	0.2	0.1	0.1	0.1	0.1	0.1
	Griffiths' comfort temperature (ºC)	24.2	23.4	23.9	23.5	23.7	23.9
	PMV	-0.3	-0.4	-0.3	-0.4	-0.3	-0.4
Mixed-mode	Number of observations	2610	2860	2668	2802	4409	1061
	Thermal sensation vote	-0.1	0.1	-0.1	0.1	0.0	0.0
	Thermal preference vote	0.0	0.1	0.0	0.1	0.0	0.1
	Thermal acceptability vote	0.1	0.1	0.1	0.0	0.1	0.1
	Thermal comfort vote	0.1	0.1	0.1	0.1	0.1	0.1
	Griffiths' comfort temperature (ºC)	24.1	23.5	24.0	23.6	23.8	23.8
	PMV	0.0	-0.1	0.0	-0.1	0.0	-0.1

Table 40: Statistical summary of personal variables, cross-tabulated by building ventilation type.

Building ventilation type	Variable	Age (years)	Weight (kg)	Height (m)	BMI (kg/m^2)	Clo	Met	Dependence on AC
HVAC (n=2094)	Mean	39.0	75.3	1.72	25.3	0.66	1.1	1.4
	S.D.	11.1	15.1	0.10	3.7	0.14	0.1	1.1
	Maximum	74.0	135	1.97	41.7	1.40	1.4	3.0
	Minimum	16.0	40	1.50	16.9	0.41	1.0	0.0
MM (n=5470)	Mean	38.3	73.9	1.70	25.5	0.69	1.1	1.3
	S.D.	11.0	15.6	0.10	4.2	0.19	0.1	1.1
	Maximum	81.0	170	1.97	64	1.73	1.4	3.0
	Minimum	15.0	43	1.48	16.9	0.41	1.0	0.0

The histogram of prevailing mean outdoor air temperature[25] and indoor operative temperature at survey times categorised by building ventilation type is illustrated in Fig. 39. Over 92% of recorded operative temperatures ranged between 22 and 25ºC in the HVAC building, indicating that the building provided a narrowly-controlled thermal environment for its occupants regardless of the outdoor climate. On the other hand, a wider range of indoor operative temperature was observed in our sample of MM buildings.

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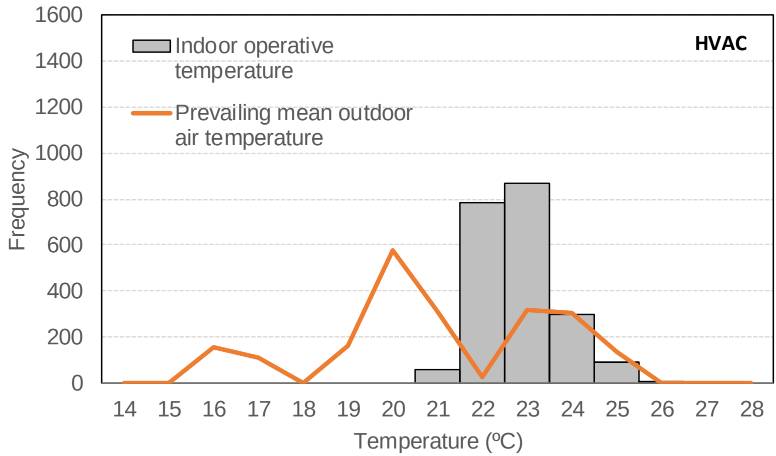
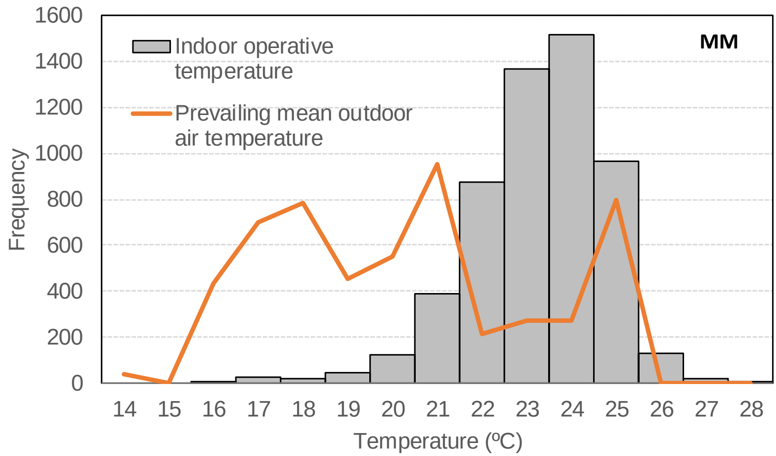
[25] The prevailing mean outdoor air temperature, an exponentially weighted, running mean of daily temperature, was estimated in accordance with ASHRAE 55 [9].



(a) HVAC



(b) Mixed-mode

Fig. 39: Histogram of prevailing mean outdoor air temperature and indoor operative temperature at survey times grouped by building ventilation type. Temperature data was binned at 1ºC intervals.

Identifying personal and contextual factors associated with comfort perception

The link between personal or contextual factors and occupants' perception of thermal comfort was investigated via the logistic regression analysis. The results of multiple logistic analyses are reported in Tables 41 and 42. Odds Ratios (ORs) reported in Tables 41 and 42 estimate the likelihood of the respondents declaring ‘warm discomfort’ and ‘cold discomfort’ respectively. See Table 38 for how reference group was defined in this analysis.

As expected, indoor temperature variation (T_{diff}) was found to be the strongest predictor of occupant discomfort (Wald χ^2 = 177.14 for warm discomfort and 89.57 for cold discomfort). Apart from T_{diff}, our logistic analyses revealed gender, BMI and dependence on AC as variables that are significantly (p<0.001) associated with workplace discomfort.

As reported in Table 41, age and building ventilation type were insignificant with respect to occurrences of ‘warm discomfort’. On the other hand, gender, BMI and dependence on AC were significantly and positively associated with ‘warm discomfort’ in the workplace. For instance, (1) male occupants are 2.31 times (OR = 2.31) more likely to express ‘warm discomfort’ than female occupants; (2) overweight occupants are 1.46 times more likely to express ‘warm discomfort’ than normal or underweight occupants; and (3) those who uses AC more heavily are 1.24 times more likely to express ‘warm discomfort’ than light users of AC.

With respect to ‘cold discomfort’, significantly associated factors were found to be gender, BMI, dependence on AC and building ventilation type (Table 42). The results indicate that (1) females are 2.33 times (OR = 0.43 for males, i.e., OR = 1.00/0.43 for females) more likely to declare ‘cold discomfort’ than males; (2) under- or normal weight people are 2.08 times (OR = 0.48 for overweight group) more likely to experience ‘cold discomfort’ than their counterpart; (3) those who use AC less frequently are 1.45 times more likely to be dissatisfied with cold conditions than those who use AC more heavily; (4) occupants of HVAC buildings are 1.36 times more likely to register ‘cold discomfort’ responses than those in MM buildings.

Table 41: Results of logistic regression model quantifying impact of contextual variables on 'warm discomfort' at workplace.

Predictors	*b*	Wald	Sig.	Odds Ratio (OR)	95% CI of OR
T_{diff}	0.62	177.14	$p<0.001$	1.85	1.69-2.03
Gender	0.84	56.15	$p<0.001$	2.31	1.85-2.87
Age			*NS*		
BMI	0.38	12.45	$p<0.001$	1.46	1.18-1.79
Dependence on AC	0.22	21.79	$p<0.001$	1.24	1.13-1.36
Building ventilation type			*NS*		

Note: N=7,564. R^2=0.12(Nagelkerke). Model $\chi^2(6)=361.82$, p<0.001. Reference group: female, 50 or under, non-overweight, none, MM

Table 42: Results of logistic regression model quantifying impact of contextual variables on 'cold discomfort' at workplace.

Predictors	*b*	Wald	Sig.	Odds Ratio (OR)	95% CI of OR
T_{diff}	-0.40	89.57	$p<0.001$	0.67	0.62-0.73
Gender	-0.84	57.56	$p<0.001$	0.43	0.35-0.54
Age			*NS*		
BMI	-0.74	41.13	$p<0.001$	0.48	0.38-0.59
Dependence on AC	-0.37	50.46	$p<0.001$	0.69	0.62-0.77
Building ventilation type	0.31	8.23	$p<0.01$	1.36	1.10-1.67

Note: N=7,564. R^2=0.12(Nagelkerke). Model $\chi^2(6)=319.33$, p<0.001. Reference group: female, 50 or under, non-overweight, none, MM

Defining thermal comfort zone

In the preceding section, key variables that are related with workplace thermal discomfort were identified through multiple logistic analyses. The next step of our analysis was to look into how those personal/contextual factors affect the range of comfort zone. As an attempt to answer this question, and to estimate the width of comfort zone for different occupant groups, two logistic regression models (i.e. warm discomfort and cold discomfort) was developed for each subgroup (categorised by gender, BMI and age) using T_{diff} as the predictor. Based on the results of logistic regression analysis, the relationship between the indoor temperature variations and the percentage of people dissatisfied due to cold or warm discomfort is illustrated in Fig. 40. The participants' actual responses were grouped into 20 bins of equal size and presented as dot points in this figure for illustration purposes. The logistic regression models (based on unbinned data) are illustrated as curves in Fig. 40. The two model curves (each representing cool- and warm dissatisfied) were added into one curve representing the total percentage of dissatisfied.

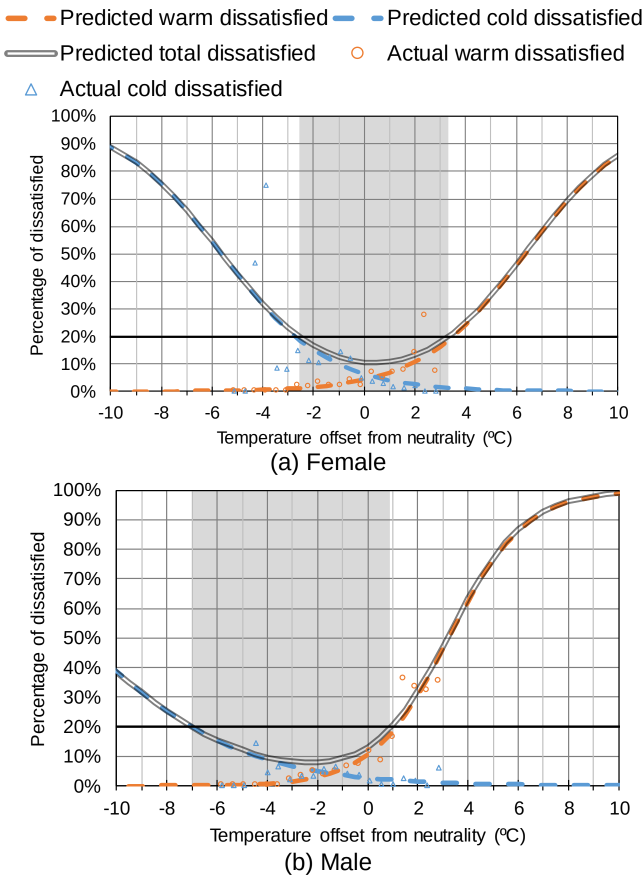
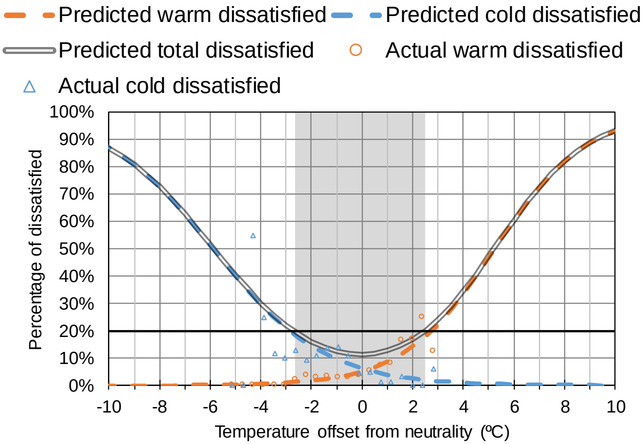
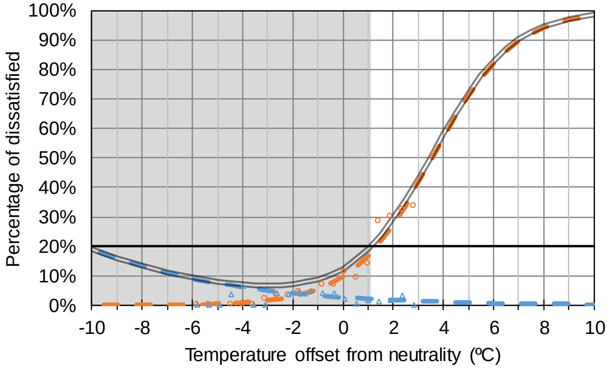


Fig. 40: Percentage of actual and predicted (logistic regression) discomfort as a function of the temperature offset from neutrality for different gender, BMI and age subgroups. Included all data from office buildings in Florianópolis. Actual data points presented are grouped into 20 bins of equal size. The comfort range (80% acceptability) is illustrated as the grey band.

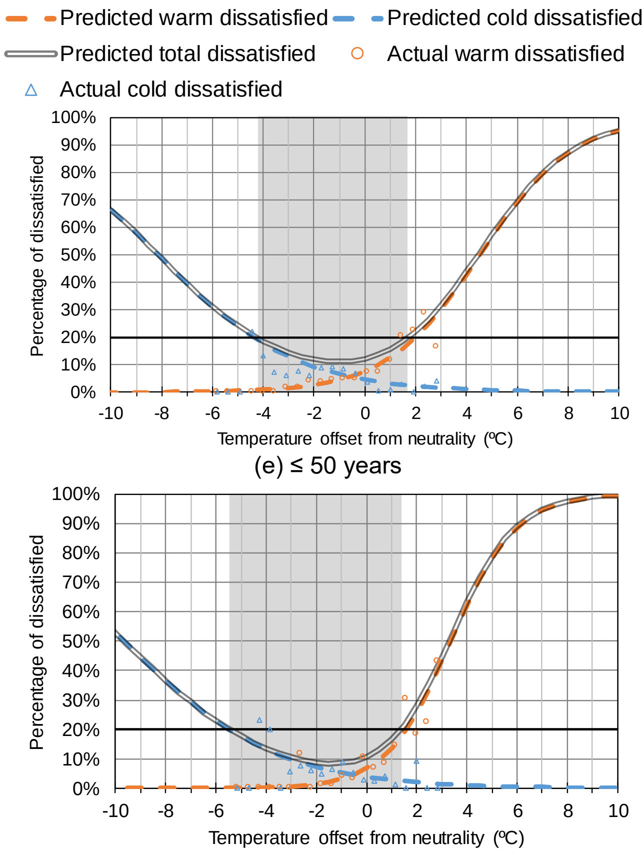


(c) Normal weight



(d) Overweight

Fig. 40: Percentage of actual and predicted (logistic regression) discomfort as a function of the temperature offset from neutrality for different gender, BMI and age subgroups. Included all data from office buildings in Florianópolis. Actual data points presented are grouped into 20 bins of equal size. The comfort range (80% acceptability) is illustrated as the grey band (continuation).



(f) > 50 years

Fig. 40: Percentage of actual and predicted (logistic regression) discomfort as a function of the temperature offset from neutrality for different gender, BMI and age subgroups. Included all data from office buildings in Florianópolis. Actual data points presented are grouped into 20 bins of equal size. The comfort range (80% acceptability) is illustrated as the grey band (continuation).

The model curves indicate that the minimum predicted percentage of dissatisfied (PPD) equals to 10% for females occurring at which the indoor temperature is 0.5ºC warmer than the predicted neutrality (T_{diff} = 0.5ºC), and 8% for males occurring at T_{diff} of -2.5ºC. The minimum PPDs were 11% for the normal/underweight occupants group (at T_{diff} = 0.0ºC) and 7% for the overweight occupants (at T_{diff} = -3.5ºC). Regarding the different age groups, the lowest PPD values were estimated as 11% for ‘50 years old or less’ group (at T_{diff} = -1.0ºC) and 9% for people older than 50 (at T_{diff} = -1.5ºC). The point at which the minimum percentages of dissatisfied occurs was consistently shifted toward the cooler side on the temperature (T_{diff}) scale, except for ‘female’ and ‘normal weight’ groups. The results suggest that the minimum PPD occurs when the indoor operative temperature was between 1 to 2ºC cooler than that recommended by the ASHRAE 55 adaptive model for males or overweight occupants.

The range of indoor comfort temperatures at which more than 80% of the occupants are satisfied (comfortable) can be established by defining the point of intersections between the PPD curve and 20% dissatisfied (grey area in Fig. 40). 80% comfort zone for males, overweight and people older than 50 years tended to further shift down to the cooler side of the scale and are wider than their counterparts - females, underweight/normal weight and people younger than 50 years, respectively.

Table 43 summarises 80% acceptability limits estimated by the logistic regression analysis separately fitted to gender, BMI and age subgroups. In this analysis the entire sample was split by building ventilation type, in order to examine whether the type of ventilation plays a role in shaping the comfort zone of occupants. The results were similar considering just the MM buildings dataset and all data. Logistic regression analyses performed on the HVAC sample did not achieve statistical significance.

According to ASHRAE 55’s adaptive thermal comfort model [9], the range of indoor comfort temperatures corresponding to the 80% acceptability is 7.0ºC. The upper- and lower limits in the adaptive model have equal distances from neutrality (± 3.5ºC from the middle point). Such range is assumed to be valid for all groups of occupants (i.e. universal comfort zone). However, in the context of Brazilian office buildings the results of our analyses suggest that the comfort range can vary depending on the characteristics of the occupants (gender, BMI and age subgroups). Moreover, the results also showed differences within each subgroup category (male vs. female, overweight vs. under/normal weight, older than 50 years vs. younger than 50 years).

Table 43: 80% acceptability ranges predicted by logistic regression analysis for gender, BMI and age subgroups.

Building type	Variable	Gender		BMI		Age (years)	
		Female	Male	Normal/ Underweight	Overweight	≤ 50	>50
All data	Predicted lower range of temperature offset from neutrality (ºC)	-2.6	-7.0	-2.7	-10.3	-4.3	-5.5
	Predicted upper range of temperature offset from neutrality (ºC)	3.3	0.9	2.5	1.1	1.7	1.4
	Minimum predicted percentage of dissatisfied (%)	10	8	11	7	11	9
Mixed-mode	Predicted lower range of temperature offset from neutrality (ºC)	-2.6	-7.3	-2.7	-13.0	-4.3	-5.7
	Predicted upper range of temperature offset from neutrality (ºC)	3.8	0.9	2.4	1.1	1.6	1.3
	Minimum predicted percentage of dissatisfied (%)	10	7	11	6	10	9
HVAC	Predicted lower range of temperature offset from neutrality (ºC)	Not significant					
	Predicted upper range of temperature offset from neutrality (ºC)						
	Minimum predicted percentage of dissatisfied (%)						

It has been discussed in the literature that: 1) Gender differences in thermoregulation are caused due to physiological factors, such as endocrine system and body composition [5]. Females have a lower metabolic rate [8] and a lower skin temperature than males [12, 14], thus, females prefer warmer conditions than males. Differences in thermal discomfort responses can also be attributed to clothing behaviour of the two occupant groups. It is often observed that females have greater variability in *clo*-value, leading to a higher prevalence of local discomfort (e.g. cold draft on ankles) among female occupants; 2) Higher body fat on overweight people, increasing tissue insulation, is the main cause of differences in thermoregulation between obese and lean people (obese prefer cooler conditions) [5]. It is important to note that in this work, as we conducted field studies in actual office buildings with people performing their daily work activities (not in climate chambers), our analysis was carried out using BMI as classification parameter between overweight and non-overweight people. Since BMI does not measure body fat neither the proportion between muscle and fat, it is possible that some of the participants were misclassified into our 'obese' category [36]; 3) Thermoregulation is also affected by age [5, 37]: the elderly (67–73 years) had more distal vasoconstriction and preferred a higher temperature than young adults (20–25 years) [38]. The elderly is suspected to have an impaired ability to keep thermal balance [5, 37], and their thermoneutral zone may be narrower than young adults (this was not yet confirmed by experiments) [5].

Our results on gender and BMI subgroups are well in line with the literature (males and overweight people prefer cooler conditions). In contrast to what's reported in the literature, we found that people older than 50 years accepted even lower temperatures and a wider range of indoor temperatures than people younger than 50 years (Table 43). One possible explanation is the difference between the way our questionnaire was structured when categorising the participants' age (i.e. "older than 50 years") and the elderly group (equal to or older than 60 years) as defined by the United Nations [6]. In this work, we adopted a threshold of 50 years old in our grouping of the occupant sample. This was because we didn't have a significant number of participants older than 60 years. In effect, 51 years is roughly the mean age of the onset of menopause[26] in South Brazil [39]. Another aspect that may enlighten the differences between our work and the literature [5, 38] is the change of body composition with age (lean mass is decreased and fat mass is increased in elderly [5]). However, as stated before, we used BMI, which is not the most precise estimation of body composition. Thus, future studies should be carried out considering *actual* measurements of body fat and muscle mass.

In the literature, individual differences in thermal comfort are often explained by thermoregulatory process [5, 37]. However, thermoregulation based on demographic and anthropometric differences does not fully explain the thermal perception in real-life settings. Behavioural and psychosocial aspects can also influence occupants' thermal perception and their reactions towards the surrounding environment (i.e. environmental control behaviours) [40-42], therefore should be further explored in future research works.

CONCLUSIONS

Large-scale thermal comfort field studies were performed in four office buildings located in a humid subtropical climate zone of Brazil (Florianópolis city). Three buildings were operated under mixed-mode strategy and the other building on the centralised HVAC system. More than 7,500 datasets collected during our longitudinal field study were analysed, with an aim to investigate how personal or contextual variables can affect the office occupants' perception of thermal comfort.

The statistical analysis indicated that demographic (gender), anthropometric (BMI) and extent of previous exposure to AC variables were associated with workplace thermal discomfort:

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[26] Menopause was a topic we were also interested to investigate. However, we did not find significant differences in thermal comfort responses between males and females who are older than 50 years.

- Male occupants are more likely to express thermal discomfort caused by warm sensations than female occupants, whereas females more frequently declared discomfort due to feeling ‘cold’.
- Overweight occupants are more likely to register ‘warm’ discomfort than normal or underweight occupants, whereas normal or underweight occupants are more likely to experience ‘cold’ discomfort.
- Those who use AC more frequently are more likely to express ‘warm’ discomfort than those who use AC less frequently, and *vice versa* for those who use AC less frequently.

We also found that under the equivalent thermal conditions there was a higher prevalence of ‘cold’ discomfort responses among the occupants of centralised HVAC buildings compared to those in MM buildings.

The impact of contextual factors on the perception of thermal comfort in workplaces was investigated separately for the MM building sample and the all-building sample (logistic regression analysis on the HVAC building sample did not return statistically significant results). The range of thermal comfort zone was wider and shifted toward the cooler side on the relative temperature scale, showing a slightly cooler-than-neutral environment preference, for males, overweight occupants and those older than 50 years, compared to females, underweight- or normal weight occupants and those younger than 50 years, respectively.

Thermal comfort models (both PMV-PPD model and adaptive model) prescribed in the international standards present a universal comfort zone. Those models suggest that the distribution of thermal dissatisfaction is symmetrical around neutrality at which the minimum dissatisfaction occurs. However, our findings suggest that ‘neutral’ does not necessarily represent the optimal thermal condition for all the occupants in a building. The current study provides empirical evidences that different groups of people require different comfort zones. Despite this work was exclusively based on office building samples, such diverse comfort zones should be considered when designing or operating spaces for specific groups of occupants. Perhaps, the use of personalized conditioning systems (PCS) [43, 44] can be an effective solution to address individual differences in shared indoor spaces. Providing the occupant with the means to fine-tune the surrounding environment to suit their specific needs has the potential of improving comfort and satisfaction of office occupants. More studies seem necessary in other building typologies and also in buildings with PCS to address this subject of personal differences.

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5. CONCLUSÕES

Estudos de campo sobre conforto térmico, envolvendo a aplicação de questionários ao mesmo tempo em que as condições térmicas eram monitoradas, foram realizados durante dois anos em quatro edificações de escritórios localizadas em Florianópolis/SC (clima subtropical úmido). Uma das edificações opera com sistema central de ar-condicionado, enquanto as outras três edificações operam com a estratégia de ventilação híbrida. Os estudos de campo resultaram em mais de 7500 respostas aos questionários, as quais foram associadas a variáveis ambientais e humanas. Este banco de dados foi analisado no contexto dos objetivos desta tese.

Uma das principais conclusões deste trabalho é que o modo de operação atuante em edificações de escritórios com ventilação híbrida e com sistema central de condicionamento artificial influencia na percepção de conforto térmico dos ocupantes. Em condições térmicas similares, os usuários da edificação com sistema central de ar-condicionado são mais propensos a reportarem desconforto térmico causado por sensações de frio do que usuários das edificações com ventilação híbrida. Em edificações com ventilação híbrida, a percepção térmica dos usuários foi diferente dependendo do modo de operação atuante e uma faixa mais ampla de temperaturas internas foi considerada aceitável pelos usuários durante a operação da ventilação natural. Além disso, este trabalho não encontrou evidências para justificar o desenvolvimento de um modelo adaptativo de conforto térmico específico para as edificações com ventilação híbrida, conforme realizado por alguns pesquisadores (MANU et al., 2016; BARBADILLA-MARTÍN et al., 2017).

Outro estudo analisou os dados coletados durante o ano de 2014 em edificações com ventilação híbrida (DE VECCHI, 2015) - os mesmos analisados nesta tese. Por meio de comparações entre os votos de sensação térmica separados por modo de operação (ventilação natural e ar-condicionado) e a temperatura efetiva padrão, a autora concluiu que, durante a operação da ventilação natural os usuários reportaram maior porcentagem de desconforto por calor e durante o uso do sistema de ar-condicionado, uma maior porcentagem de desconforto por frio. Porém, cabe ressaltar que poucos dados foram obtidos durante a primavera e o verão no período de análise (2014) e no modo de ar-condicionado. Este fato pode ajudar a explicar tais diferenças na percepção térmica dependendo do modo de operação. Nesta tese, considerou-se um banco de dados cerca de três vezes maior, englobando também as estações de primavera e verão, e o modo de operação foi estudado por meio de regressões lineares e logísticas considerando condições térmicas similares. Deste modo, a variável “modo de operação” pode ser avaliada de maneira mais aprofundada com relação à influência na percepção térmica dos usuários.

Por meio de comparações entre as respostas subjetivas dos ocupantes das edificações estudadas e os modelos analítico e adaptativo de conforto térmico presentes na ASHRAE 55 (2013; 2017) pode-se concluir que:

• O modelo analítico não estimou adequadamente a porcentagem de insatisfeitos e superestimou as sensações de frio dos usuários tanto na edificação com sistema central de ar-condicionado, quanto nas edificações com ventilação híbrida. As maiores diferenças foram observadas durante a operação da ventilação natural. Portanto, o modelo analítico não deve ser utilizado para avaliar o conforto térmico em edificações com ventilação híbrida operando com ventilação natural. Durante a operação do sistema de ar-condicionado, o modelo analítico pode ser utilizado, porém, com maiores faixas de variação das condições internas do que as prescritas na ASHRAE 55 (2013; 2017).

• Os usuários em Florianópolis toleraram temperaturas mais baixas do que as preditas pelo modelo adaptativo da ASHRAE 55 (2013; 2017). Além disso, os usuários das edificações com ventilação híbrida, operando no modo de ventilação natural, adaptaram-se às flutuações de temperatura interna, principalmente devido a ajustes de vestimenta, conforme previsto pela teoria de conforto térmico adaptativo. Assim, o modelo adaptativo de conforto térmico pode ser utilizado para avaliar as edificações com ventilação híbrida, durante a operação da ventilação natural.

Primeiramente, estas constatações sobre os modelos da ASHRAE 55 (2013; 2017) foram reforçadas quando do desenvolvimento do modelo adaptativo de conforto térmico para edificações de escritórios com ventilação híbrida em

Florianópolis. Foi encontrada uma forte correlação entre a temperatura interna de conforto e a temperatura predominante média do ar externo durante o uso da ventilação natural; e uma fraca correlação entre as temperaturas internas e externas durante a operação do sistema de ar-condicionado, indicando que os usuários estavam desconectados do clima externo. Apesar disso, o modelo adaptativo desenvolvido para edificações com ventilação híbrida, durante a operação do sistema de ar-condicionado, pode ser utilizado para avaliar o conforto térmico durante este modo de operação. Tal modelo resultou em uma faixa de aceitabilidade aproximadamente entre 22ºC e 26ºC, o que se assemelha às condições térmicas aceitáveis do método gráfico da ASHRAE 55 - baseado no modelo analítico de Fanger (1970). Desta maneira, o conforto térmico em edificações com ventilação híbrida pode ser avaliado, separadamente, conforme o modo de operação atuante (ventilação natural ou ar-condicionado), por meio de dois modelos adaptativos.

Além disso, as conclusões deste trabalho são contrárias à recomendação da ASHRAE 55 (2013; 2017) que especifica que as edificações com ventilação híbrida devem ser avaliadas pelo modelo analítico de Fanger. O comitê da ASHRAE 55 (2013) provavelmente estabeleceu esta abordagem mais conservadora, pois na época de lançamento da norma poucos trabalhos tratando de conforto térmico em edificações com ventilação híbrida eram encontrados na literatura. À luz de novas evidências científicas sobre o tema (INDRAGANTI; OOKA; RIJAL, 2013; INDRAGANTI et al., 2014; OROPEZA-PEREZ; PETZOLD-RODRIGUEZ; BONILLA-LOPEZ, 2017), incluindo-se aqui os resultados desta tese, a ASHRAE 55 deveria ser revisada[27], indicando a aplicação do modelo adaptativo para avaliação de conforto térmico em edificações com ventilação híbrida, durante a operação da ventilação natural. Isto pode promover o uso da estratégia de ventilação híbrida em edificações a serem construídas ou reformadas, reduzindo o consumo de energia e, consequentemente, as emissões de gases do efeito estufa, minimizando os impactos ambientais e climáticos.

Os modelos de conforto térmico adaptativo desenvolvidos para edificações com ventilação híbrida localizadas em

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[27] Mesmo em sua versão mais recente de 2017, a norma ASHRAE 55 não alterou o procedimento de avaliação dos edifícios com ventilação híbrida (ASHRAE 55, 2013).

Florianópolis são limitados a temperaturas predominantes médias do ar externo entre 17ºC e 25ºC (ventilação natural) e entre 16ºC e 26ºC (ar-condicionado). Mais estudos de campo de conforto térmico são necessários, em outras cidades com clima subtropical no Brasil – onde o uso de aquecimento artificial não é comumente utilizado em edificações de escritórios – para complementar e expandir o escopo de aplicação dos modelos adaptativos desenvolvidos. Este trabalho contribui para a construção de modelos adaptativos de conforto térmico para o clima subtropical brasileiro.

Os modelos adaptativos desenvolvidos neste trabalho, bem como os modelos da ASHRAE 55 (analítico e adaptativo), apresentam uma zona de conforto universal, aplicável a todos os grupos de usuários (homens e mulheres, jovens e idosos, etc.). Tais modelos também sugerem que o desconforto térmico ocorre de maneira simétrica em torno da neutralidade térmica (situação com a menor percentagem de desconforto). Porém, neste trabalho investigou-se a relação entre variáveis contextuais (idade, gênero, peso e altura, histórico térmico e estratégia de ventilação) e a percepção de conforto térmico de usuários em edificações de escritórios e concluiu-se que: 1) a neutralidade térmica não representa a condição térmica ótima para todos os ocupantes de uma edificação; 2) diferentes grupos de pessoas requerem diferentes zonas de conforto térmico – usuários do gênero masculino, pessoas acima do peso e ocupantes com idade superior a 50 anos preferem ambiente mais resfriado que a neutralidade térmica do que ocupantes do gênero feminino, pessoas com peso normal ou abaixo do peso e usuários com 50 anos ou menos, respectivamente. Além disso, as zonas de conforto térmico de cada grupo de usuários não são simétricas em torno da neutralidade térmica; 3) usuários do gênero masculino, pessoas acima do peso e ocupantes que utilizam o sistema de ar-condicionado fora do ambiente de trabalho com maior frequência possuem maior probabilidade de expressar desconforto térmico causado por sensações de calor do que pessoas do gênero feminino, usuários com peso normal ou abaixo do peso e ocupantes que utilizam o sistema de ar-condicionado fora do ambiente de trabalho menos frequentemente; estes últimos, possuem maior probabilidade de expressar desconforto térmico causado por sensações de frio. As diferenças nas zonas de conforto térmico deveriam ser consideradas durante a etapa de projeto ou durante a operação de ambientes destinados a algum grupo específico de ocupantes. O uso de sistemas de condicionamento personalizado pode ser uma possível solução para diminuir as diferenças subjetivas em espaços interiores compartilhados por várias pessoas (VESELÝ; ZEILER, 2014; ZHANG; ARENS; ZHAI, 2015). Novos estudos, explorando os limites das zonas de conforto térmico, podem ser realizados em outras tipologias construtivas, em espaços que utilizam sistemas de condicionamento personalizado e em climas distintos para ajudar na compreensão dos diferentes requerimentos térmicos dependendo do grupo de pessoas.

Outra área de pesquisa para futuros trabalhos, pouco explorada nos estudos com adultos, está relacionada à semântica das perguntas do questionário e as escalas de respostas. Neste trabalho foi adotada uma escala binária para as respostas às perguntas sobre conforto térmico (“Confortável” ou “Desconfortável”) e aceitabilidade térmica (“Aceitável” ou “Inaceitável”). De modo geral, os ocupantes das edificações estudadas reportaram sentirem-se em conforto térmico e aceitaram as condições térmicas ambientais na maior parte do tempo (aproximadamente 90% das respostas apontaram para conforto/aceitabilidade). Talvez a escala binária adotada possa ter influenciado nas respostas dos usuários. Por exemplo, em um determinado momento, um usuário podia estar sentindo algum desconforto leve, mas não possuindo essa opção no questionário, acabou optando pela resposta “Confortável”.

O conforto térmico em edificações tem recebido crescente interesse por parte de pesquisadores de diferentes campos do conhecimento ao redor do mundo, mas principalmente em países desenvolvidos e alguns emergentes (China e Índia). Relativamente a estes países, os estudos de campo realizados no Brasil ainda são escassos, talvez devido aos custos envolvidos na aquisição e manutenção dos equipamentos de medição ambiental e na dificuldade no processo de autorização dos estudos de campo em edificações. Novos conceitos e explicações surgiram para ajudar na compreensão dos variados aspectos (comportamentais, fisiológicos, psicológicos, por exemplo) que influenciam na percepção de conforto térmico. Esta área de estudo interdisciplinar demanda novos estudos e tende a continuar despertando o interesse da comunidade acadêmica frente às mudanças climáticas.

5.1 LIMITAÇÕES DO TRABALHO

Este trabalho limita-se a edificações de escritório, a ambientes de escritório com planta livre, a edificações operando com sistema de ar-condicionado central ou com ventilação híbrida (controle realizado pelos usuários) sem a utilização de aquecimento artificial e ao clima subtropical úmido.

Cabe ressaltar também algumas limitações decorrentes do método de coleta de dados empregado (estudos de campo sobre conforto térmico realizados com usuários em edificações):

• Metabolismo e vestimenta: os valores de taxa metabólica e de isolamento da vestimenta foram estimados de acordo com a ASHRAE 55, considerando-se as respostas dos usuários e as observações realizadas pelos pesquisadores. Dessa maneira, podem existir diferenças entre os valores estimados e os valores reais (obtidos por medição) de taxa metabólica (KINGMA; VAN MARKEN LICHTENBELT, 2015; HASAN; ALSALEEM; RAFAIE, 2016; LUO et al., 2016) e isolamento da vestimenta (LU et al., 2015; SUN; FAN, 2017).

• Massa corporal e altura: a massa corporal e a altura foram obtidas neste trabalho por meio das respostas (autoavaliação) dos usuários (não foram medidos). Além disso, neste trabalho foi considerado o índice de massa corpórea (relação entre a massa corporal e a altura) como parâmetro de classificação de pessoas acima do peso, pessoas com peso normal e pessoas abaixo do peso. Este índice não mede a gordura corporal e pode não refletir adequadamente a proporção entre músculo e gordura, o que pode levar a classificações errôneas (AHIMA; LAZAR, 2013).

5.2 SUGESTÕES PARA TRABALHOS FUTUROS

Além das recomendações apresentadas nas conclusões (explorar outros climas e tipologias construtivas e investigar a semântica das questões sobre conforto térmico e aceitabilidade térmica) sugere-se:

• Estudar edificações com ventilação híbrida operando com sistema central de ar-condicionado ou com controle automatizado da alternância entre a ventilação natural e o ar-condicionado;

• Examinar ambientes de escritórios individuais operando com ventilação híbrida;

• Pesquisar o impacto do uso de sistemas de condicionamento personalizado (ventiladores portáteis, por exemplo) em ambientes de escritórios na faixa de aceitabilidade térmica;

• Avaliar o comportamento do usuário perante o uso de controles (sistema de ar-condicionado e operação de aberturas);

• Analisar o conceito de disposição térmica e da percepção da umidade do ar pelos usuários;

• Realizar uma análise sistêmica do ambiente construído considerando, além do conforto térmico, o conforto visual, acústico e olfativo.

5.3 REFERÊNCIAS DO CAPÍTULO 5

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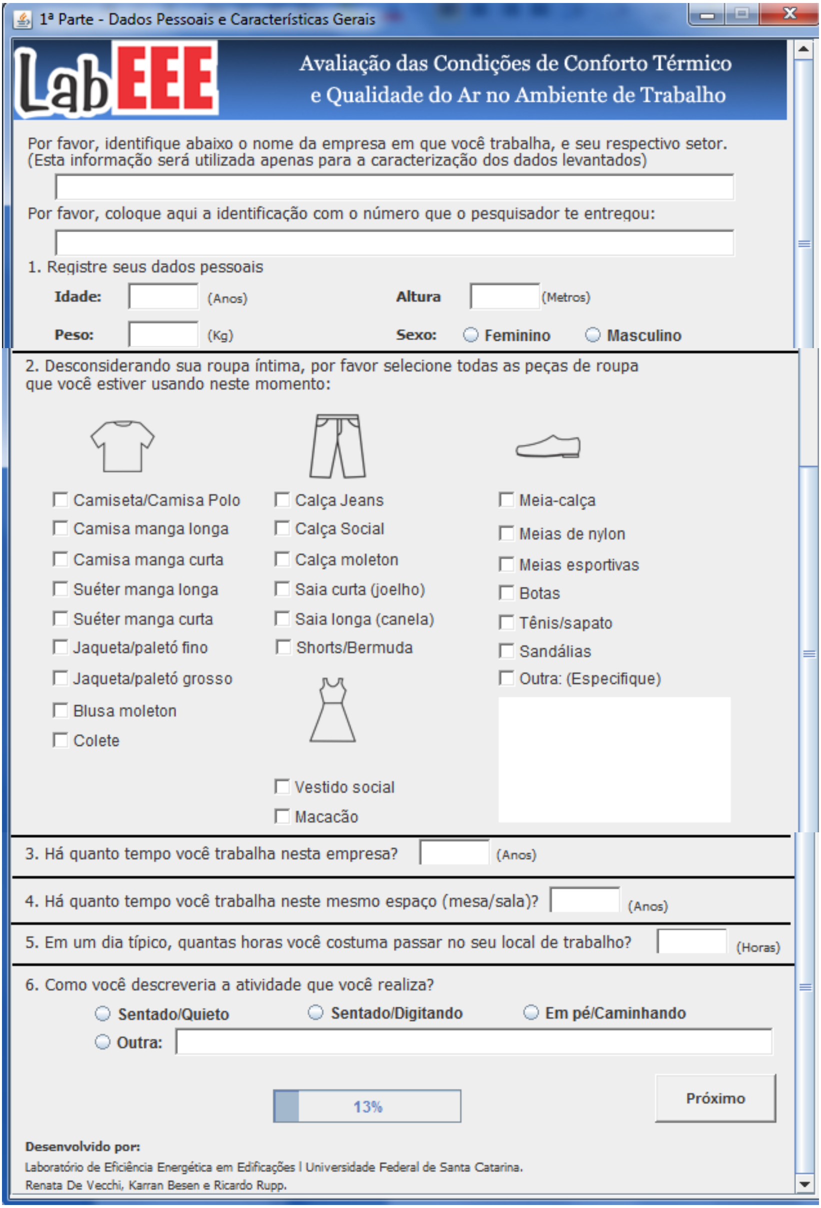
APÊNDICES

APÊNDICE A – Questionário eletrônico de conforto térmico

Figura A.1: Primeira parte (primeira rodada de perguntas).



1ª Parte - Dados Pessoais e Características Gerais

LabEEE

Avaliação das Condições de Conforto Térmico
e Qualidade do Ar no Ambiente de Trabalho

Por favor, identifique abaixo o nome da empresa em que você trabalha, e seu respectivo setor.
(Esta informação será utilizada apenas para a caracterização dos dados levantados)

Por favor, coloque aqui a identificação com o número que o pesquisador te entregou:

1. Registre seus dados pessoais

Idade: (Anos) **Altura** (Metros)

Peso: (Kg) **Sexo:** ○ Feminino ○ Masculino

2. Desconsiderando sua roupa íntima, por favor selecione todas as peças de roupa
que você estiver usando neste momento:

- ☐ Camiseta/Camisa Polo
- ☐ Camisa manga longa
- ☐ Camisa manga curta
- ☐ Suéter manga longa
- ☐ Suéter manga curta
- ☐ Jaqueta/paletó fino
- ☐ Jaqueta/paletó grosso
- ☐ Blusa moleton
- ☐ Colete
- ☐ Calça Jeans
- ☐ Calça Social
- ☐ Calça moleton
- ☐ Saia curta (joelho)
- ☐ Saia longa (canela)
- ☐ Shorts/Bermuda
- ☐ Vestido social
- ☐ Macacão
- ☐ Meia-calça
- ☐ Meias de nylon
- ☐ Meias esportivas
- ☐ Botas
- ☐ Tênis/sapato
- ☐ Sandálias
- ☐ Outra: (Especifique)

3. Há quanto tempo você trabalha nesta empresa? (Anos)

4. Há quanto tempo você trabalha neste mesmo espaço (mesa/sala)? (Anos)

5. Em um dia típico, quantas horas você costuma passar no seu local de trabalho? (Horas)

6. Como você descreveria a atividade que você realiza?

○ Sentado/Quieto ○ Sentado/Digitando ○ Em pé/Caminhando

○ Outra:

13%

Próximo

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Figura A.2: Segunda parte (primeira rodada de perguntas).

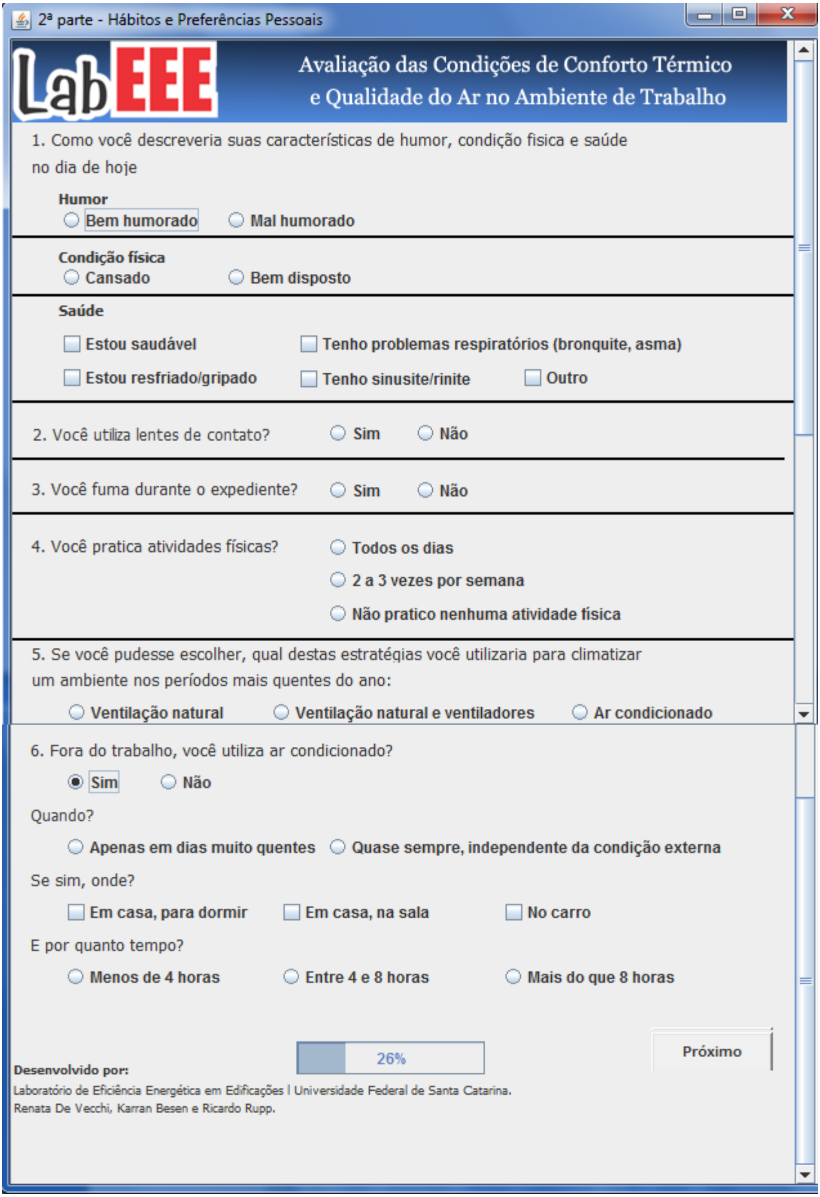
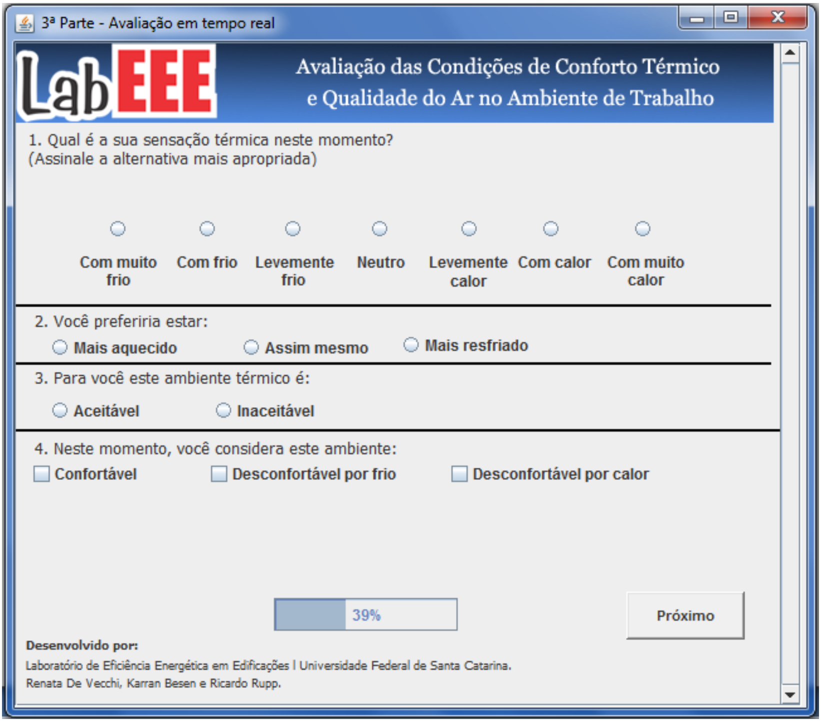
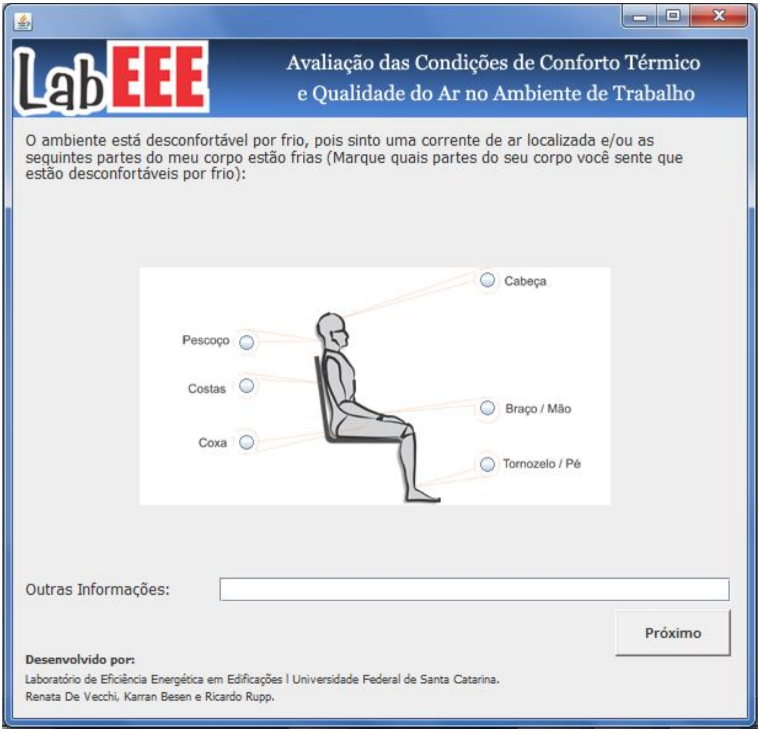


Figura A.3: Terceira parte (segunda à sexta rodada de perguntas), (a) questões relativas a sensação, preferência e aceitabilidade térmica e conforto térmico, (b) questões sobre desconforto por frio, (c) questões sobre desconforto por calor. As questões "b" e "c" somente são realizadas caso o usuário marque a opção "desconfortável por frio" e/ou "desconfortável por calor" na questão de número 4 em "a".



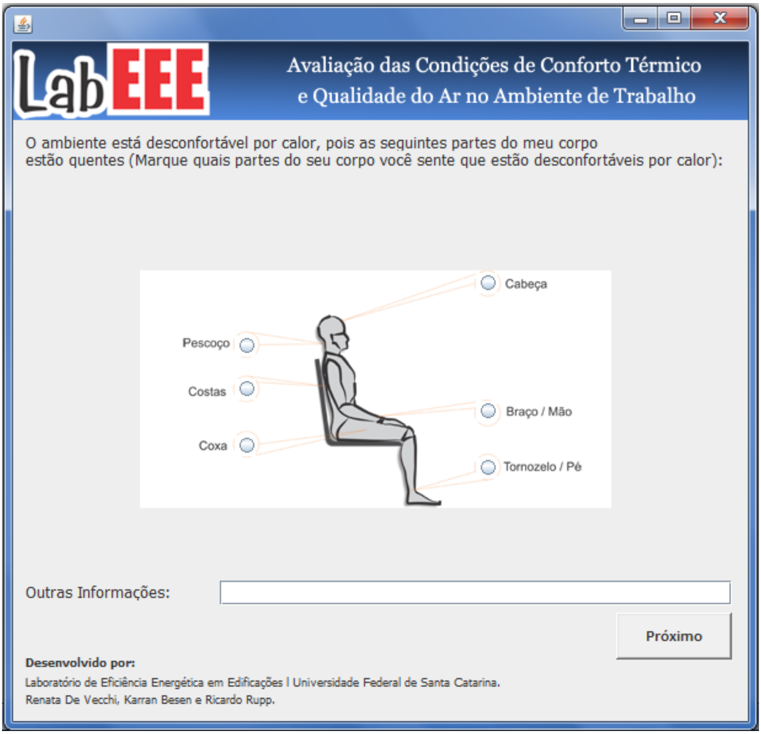
(a) Questões relativas a sensação, preferência e aceitabilidade térmica e conforto térmico.

Figura A.3: Terceira parte (segunda à sexta rodada de perguntas), (a) questões relativas a sensação, preferência e aceitabilidade térmica e conforto térmico, (b) questões sobre desconforto por frio, (c) questões sobre desconforto por calor. As questões "b" e "c" somente são realizadas caso o usuário marque a opção "desconfortável por frio" e/ou "desconfortável por calor" na questão de número 4 em "a" (continuação).



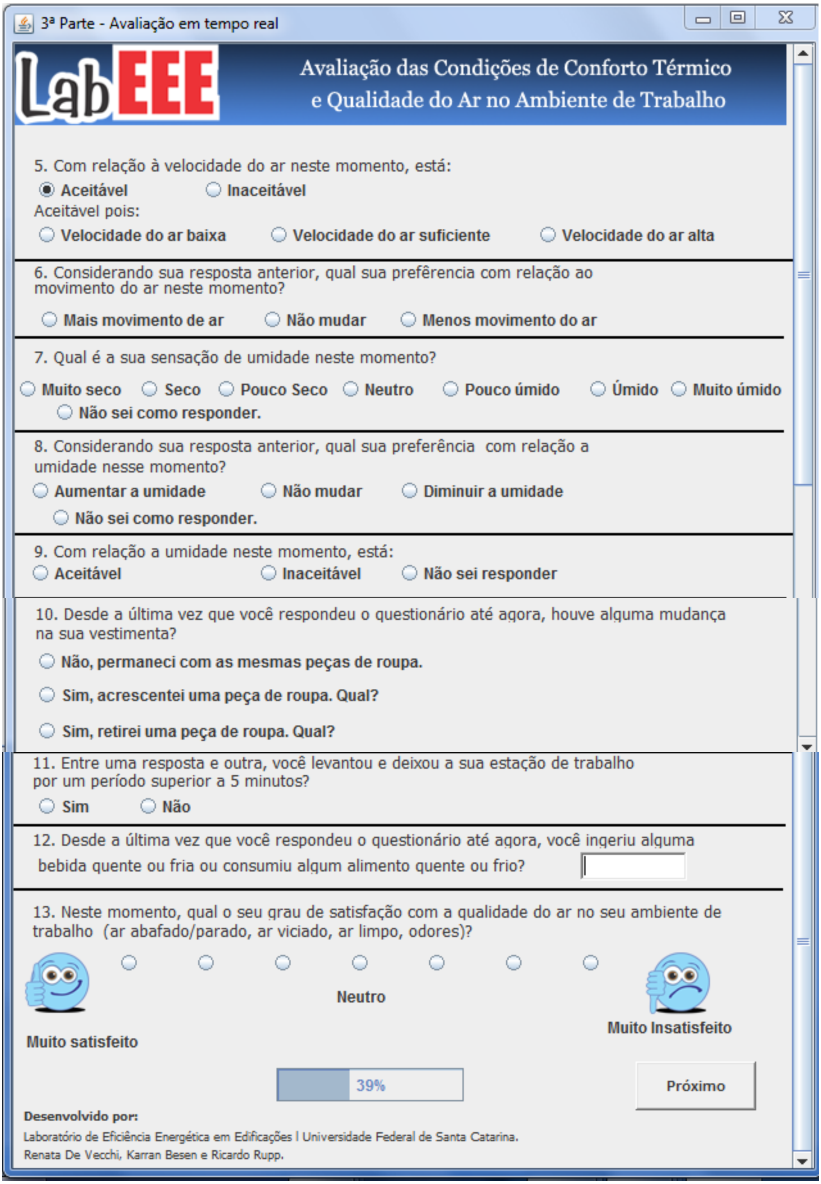
(b) Questão sobre desconforto por frio.

Figura A.3: Terceira parte (segunda à sexta rodada de perguntas), (a) questões relativas a sensação, preferência e aceitabilidade térmica e conforto térmico, (b) questões sobre desconforto por frio, (c) questões sobre desconforto por calor. As questões "b" e "c" somente são realizadas caso o usuário marque a opção "desconfortável por frio" e/ou "desconfortável por calor" na questão de número 4 em "a" (continuação).



(c) Questão sobre desconforto por calor.

Figura A.4: Continuação da terceira parte do questionário (segunda à sexta rodada de perguntas).



3ª Parte - Avaliação em tempo real

LabEEE

Avaliação das Condições de Conforto Térmico e Qualidade do Ar no Ambiente de Trabalho

5. Com relação à velocidade do ar neste momento, está:

(•) Aceitável ( ) Inaceitável

Aceitável pois:

( ) Velocidade do ar baixa ( ) Velocidade do ar suficiente ( ) Velocidade do ar alta

6. Considerando sua resposta anterior, qual sua prefêrencia com relação ao movimento do ar neste momento?

( ) Mais movimento de ar ( ) Não mudar ( ) Menos movimento do ar

7. Qual é a sua sensação de umidade neste momento?

( ) Muito seco ( ) Seco ( ) Pouco Seco ( ) Neutro ( ) Pouco úmido ( ) Úmido ( ) Muito úmido

( ) Não sei como responder.

8. Considerando sua resposta anterior, qual sua preferência com relação a umidade nesse momento?

( ) Aumentar a umidade ( ) Não mudar ( ) Diminuir a umidade

( ) Não sei como responder.

9. Com relação a umidade neste momento, está:

( ) Aceitável ( ) Inaceitável ( ) Não sei responder

10. Desde a última vez que você respondeu o questionário até agora, houve alguma mudança na sua vestimenta?

( ) Não, permaneci com as mesmas peças de roupa.

( ) Sim, acrescentei uma peça de roupa. Qual?

( ) Sim, retirei uma peça de roupa. Qual?

11. Entre uma resposta e outra, você levantou e deixou a sua estação de trabalho por um período superior a 5 minutos?

( ) Sim ( ) Não

12. Desde a última vez que você respondeu o questionário até agora, você ingeriu alguma bebida quente ou fria ou consumiu algum alimento quente ou frio?

13. Neste momento, qual o seu grau de satisfação com a qualidade do ar no seu ambiente de trabalho (ar abafado/parado, ar viciado, ar limpo, odores)?

Muito satisfeito ( ) ( ) ( ) ( ) Neutro ( ) ( ) ( ) Muito Insatisfeito

39%

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Figura A.5: Continuação da terceira parte do questionário (segunda à sexta rodada de perguntas). Estas questões somente são realizadas caso o usuário marque na questão 13 (Figura A.4), uma das três opções que expressam insatisfação na escala sétima.

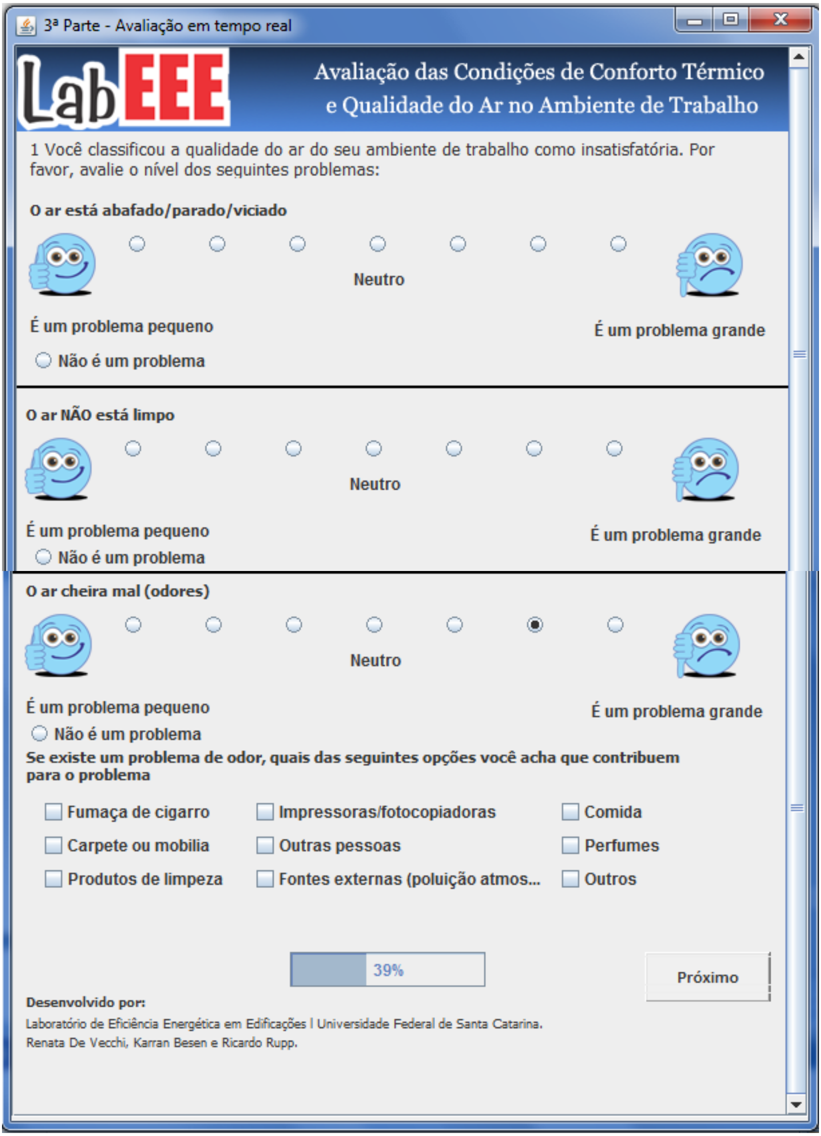
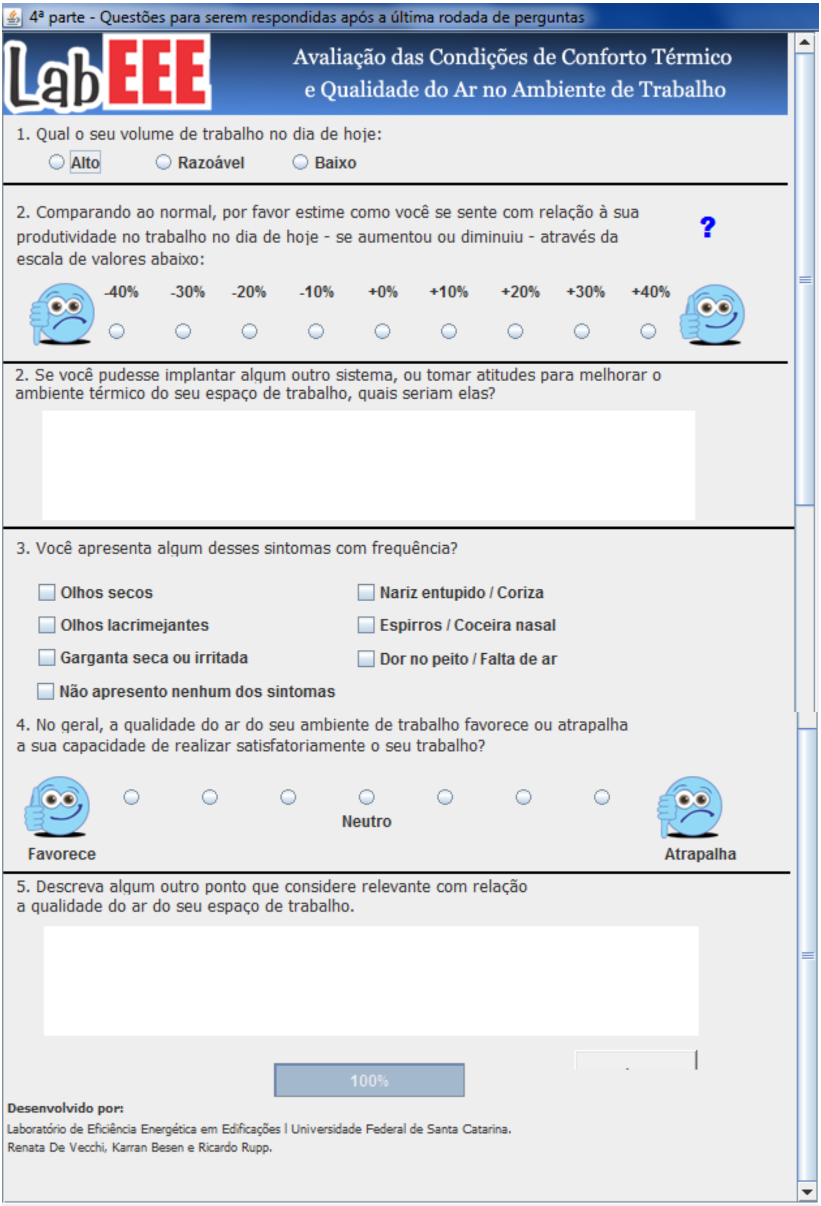


Figura A.6: Quarta parte do questionário (sexta rodada de perguntas).



4ª parte - Questões para serem respondidas após a última rodada de perguntas

LabEEE

Avaliação das Condições de Conforto Térmico
e Qualidade do Ar no Ambiente de Trabalho

1. Qual o seu volume de trabalho no dia de hoje:

◯ Alto ◯ Razoável ◯ Baixo

2. Comparando ao normal, por favor estime como você se sente com relação à sua produtividade no trabalho no dia de hoje - se aumentou ou diminuiu - através da escala de valores abaixo:

?

-40% -30% -20% -10% +0% +10% +20% +30% +40%

2. Se você pudesse implantar algum outro sistema, ou tomar atitudes para melhorar o ambiente térmico do seu espaço de trabalho, quais seriam elas?

3. Você apresenta algum desses sintomas com frequência?

☐ Olhos secos
☐ Olhos lacrimejantes
☐ Garganta seca ou irritada
☐ Não apresento nenhum dos sintomas
☐ Nariz entupido / Coriza
☐ Espirros / Coceira nasal
☐ Dor no peito / Falta de ar

4. No geral, a qualidade do ar do seu ambiente de trabalho favorece ou atrapalha a sua capacidade de realizar satisfatoriamente o seu trabalho?

Favorece — Neutro — Atrapalha

5. Descreva algum outro ponto que considere relevante com relação a qualidade do ar do seu espaço de trabalho.

100%

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