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Translating thermal performance into thermal resilience: A simulation framework to assess buildings and communities

[**Traduzindo o desempenho térmico em resiliência térmica:** Um *framework* de simulação para avaliar edifícios e comunidades]

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

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ABSTRACT

Building design and operation is undergoing a mentality shift driven by the increasing materialization of long-known threats from climate change. In this context, optimization of performance and cost gives space to also consider resilience. This work aims to propose a simulation framework to quantify and improve the thermal resilience of buildings and communities against overheating threats. Such an analysis is based on resilience profiles that combine a set of six integrated key performance indicators that allow a multidimensional understanding of whether buildings are able to provide comfortable and healthy indoor thermal environments for occupants. An aggregation approach is also proposed to better evaluate resilience at the community scale, leveraging the identification of thermally vulnerable populations. The application of the framework is demonstrated through two case studies, one adopting representative single-family residential buildings exposed to three different Brazilian climates, and another composed of 92 real buildings in the city of Florianopolis, Brazil. The latter also explores the effect of nine weather scenarios on thermal resilience, considering historical (2010s), mid-term future (2050s), and long-term future (2090s) typical meteorological years, as well as years with heat waves within each period. A combination of strategies is considered to improve resilience, such as cool walls and roofs, and solar shading. These analyses were structured within the scope of three journal articles that define the main steps necessary to develop this thesis: (1) quantifying thermal resilience; (2) proposing an evaluation framework; and (3) applying the framework. Results reflect the necessity of planning for resilience. This is because, often, strategies and technologies recommended under current weather conditions might not be ideal in the future. Therefore, a flexible design should be prioritized. Energy consumption for cooling could increase by 48% by the 2050s if not improved current building practices, while excessive overheating issues could reach 37% of the investigated 92 buildings. Simple passive strategies are able to significantly suppress part of this heat stress, especially improving thermal autonomy and energy use. The impact of weather scenarios might be perceived differently depending on the indicator. Thus, a comprehensive thermal resilience analysis should ultimately be accompanied by a thorough reflection on the objectives of quantifying resilience, available resources, planning horizon, and risks assumed for not being resilient.

Keywords: thermal resilience; buildings; communities; building performance simulation.

RESUMO

O processo de projeto e operação de edifícios passa por um ajuste de mentalidade impulsionado pela crescente materialização dos efeitos das mudanças climáticas. Neste contexto, a otimização do desempenho e dos custos dá espaço para considerar também a resiliência. Este trabalho tem como objetivo propor um *framework* de simulação para quantificar e melhorar a resiliência térmica de edifícios e comunidades contra riscos de sobreaquecimento. Tal análise baseia-se em perfis de resiliência que combinam um conjunto de seis indicadores integrados que permitem uma compreensão multidimensional sobre a capacidade dos edifícios de proporcionar ambientes térmicos confortáveis e saudáveis para os ocupantes. É também proposta uma abordagem de agregação para melhor avaliar a resiliência à escala comunitária, alavancando a identificação de populações termicamente vulneráveis. A aplicação do *framework* é demonstrada através de dois estudos de caso, um adotando edifícios residenciais unifamiliares representativos expostos a três climas brasileiros diferentes, e outro composto por 92 edifícios reais na cidade de Florianópolis, Brasil. Este último também explora o efeito de nove cenários climáticos na resiliência térmica, considerando anos meteorológicos típicos históricos (anos 2010), futuros de médio prazo (anos 2050) e futuros de longo prazo (anos 2090), bem como anos com ondas de calor dentro de cada período. Ademais, considera-se uma combinação de estratégias para melhorar a resiliência, tais como paredes e telhados frios e proteções solares. Estas análises foram estruturadas no âmbito de três artigos científicos que delimitam os principais passos necessários ao desenvolvimento desta tese: (1) quantificar a resiliência térmica; (2) propor um *framework* de avaliação; e (3) aplicar o *framework*. Os resultados obtidos reflectem a necessidade de planejar a resiliência. Isto porque, muitas vezes, as estratégias e tecnologias recomendadas nas condições climáticas atuais podem não ser ideais no futuro. Portanto, um projeto flexível deve ser priorizado. O consumo de energia para resfriamento por ar condicionado poderá aumentar 48% até 2050 se não forem melhoradas as atuais práticas construtivas, enquanto os problemas de sobreaquecimento poderão atingir 37% dos 92 edifícios investigados. Estratégias passivas simples são capazes de suprimir significativamente parte desse estresse térmico, melhorando principalmente a autonomia térmica e o uso de energia. O impacto dos cenários climáticos pode ser percebido de forma diferente dependendo do indicador. Assim, uma análise abrangente da resiliência térmica deve, em última análise, ser acompanhada por uma reflexão aprofundada sobre os objetivos de quantificação da resiliência, dos recursos disponíveis, do horizonte de planejamento e dos riscos assumidos por não ser resiliente.

Palavras-chave: resiliência térmica; edifícios; comunidades; simulação computacional.

RESUMO EXPANDIDO

Introdução

A incerteza climática tem pressionado por uma mudança de mentalidade na forma como projetamos os edifícios. Os eventos extremos comuns em determinado local podem, agora ou no futuro, ocorrer onde nunca ocorreram antes (OECD - ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2021). Um exemplo é o calor sem precedentes que marcou o verão de 2022 na Europa (BALLESTER et al., 2023; SERRANO-NOTIVOLI et al., 2023), seguido por um padrão semelhante em julho de 2023 na América do Norte, Europa e China (ZACHARIAH et al., 2023). Em São Paulo, Brasil, os atendimentos ambulatoriais e as internações por exposição ao calor aumentaram 102,5% nos primeiros sete meses de 2023, em comparação com 2022 (SECRETARIA DE ESTADO DA SAÚDE DE SÃO PAULO, 2023). A tendência de elevação dos riscos de sobreaquecimento em edificações parece inexorável (ZHANG et al., 2022), uma vez que o consumo de ar condicionado já é o uso de energia que mais cresce no mundo (IEA - INTERNATIONAL ENERGY AGENCY, 2018a) e prevê-se que eventos de calor extremo ocorram com mais frequência e severamente no futuro (WEDLER; PINTO; HOCHMAN, 2023). A prática convencional de projeto focada na otimização de desempenho e custo precisa ser atualizada para incluir um projeto resiliente, que busque minimizar riscos e aumentar a adaptabilidade (HOLZER et al., 2022).

A resiliência térmica de edificações representa a capacidade de manter ou retornar rapidamente às condições térmicas internas desejadas diante de uma perturbação, de se adaptar às mudanças, e transformar rapidamente sistemas que limitam a capacidade adaptativa atual ou futura (adaptado de Meerow, Newell e Stults (2016)). A avaliação da resiliência térmica dos edifícios é realizada principalmente através da simulação computacional de edifícios, pois permite não só aprender com experiências passadas, mas sobretudo explorar e projetar diferentes condições olhando para o futuro. No entando, um procedimento padrão e abrangende de análise de resiliência térmica ainda não foi definido (KESIK; O'BRIEN; OZKAN, 2022).

Objetivos

Este trabalho tem como objetivo desenvolver um *framework* de simulação para diagnosticar a resiliência térmica de edifícios e de comunidades contra o sobreaquecimento. Para tanto, esta tese baseia-se no desenvolvimento de três artigos que abordam diferentes objetivos específicos: (1 - Artigo 1) identificar indicadores capazes de fornecer um diagnóstico abrangente da resiliência térmica de edifícios; (2 – Artigo 2) desenvolver um procedimento para avaliar a resiliência térmica e um método de agregação para traduzir os diagnósticos individuais dos edifícios em uma avaliação relevante para a escala urbana; (3 – Artigo 3) avaliar a eficácia do *framework* através de um estudo de caso considerando um conjunto de edifícios expostos ao sobreaquecimento; (4 – Artigo 3) identificar os cenários climáticos recomendados para testar de forma abrangente a resiliência térmica em um estudo de caso.

Método

Todos os artigos foram desenvolvidos por meio da simulação computacional de edifícios usando o *software* EnergyPlus. O Artigo 1 utiliza a norma de desempenho brasileira, NBR 15575-1:2021, como pano de fundo para explorar os indicadores necessários para expandir uma análise de desempenho para a resiliência térmica. Para tanto, multiplos indicadores são calculados e comparados a partir de um estudo de caso. O Artigo 2 utiliza os indicadores mais promissores identificados anteriormente e propõe um *framework* de análise a partir de perfis de resiliência. Estes perfis caracterizam os edifícios a partir de estágios de resiliência identificados na literatura e que representam a resistência, a robustez e a capacidade de recuperação das edificações quando expostas a condições térmicas adversas. Esses perfis de resiliência permitem também a análise de multiplas edificações, de modo a mapear grupos de edificações mais vulneráveis dentro de uma comunidade. O Artigo 3 aplica o *framework* em um grupo real de edificações na cidade de Florianópolis, Brasil. Além de verificar a eficácia do *framework*, este artigo também explora o impacto de múltiplos cenários climáticos sobre a resiliência térmica, de modo a trazer recomendações a respeito da forma mais abrangente de simular a resiliência. Foram considerados nove cenários climáticos, dentro de três períodos: histórico (2001-2020), futuro médio (2041-2060) e futuro longo (2081-2100). Cada período contou com três cenários, sendo: um ano meteorológico típico (TMY), um ano com uma onda de calor intensa, e um ano com onda de calor severa e longa.

Resultados e discussão

A partir do Artigo 1, foram identificados seis indicadores relevantes para compreender de forma abrangente a resiliência térmica das edificações. Estes indicadores foram utilizados no Artigo 2, subdivididos em três estágios de resiliência. Para compreender a capacidade das edificações de manterem condições térmicas adequadas (resistência), considerou-se a autonomia térmica (*thermal autonomy*), o consumo de energia para resfriamento ativo (ou seja, com ar condicionado), e o grau de sobreaquecimento interno (*indoor overheating degree [IOD]*). A autonomia térmica descreve a frequência em que a edificação proporciona conforto térmico ao longo das horas ocupadas. O IOD corresponde ao grau médio de sobreaquecimento da edificação ao longo das horas ocupadas. Para analisar as condições extremas que ocorrem dentro da edificação, foram selecionados a temperatura anual máxima (Tmax), e a vulnerabilidade térmica (TV). A vulnerabilidade térmica representa a frequência em que a zona térmica com pior desempenho da edificação proporciona condições térmica consideradas extremas, ou seja, que podem prejudicar a saúde dos seus ocupantes. No estágio de recuperação, foi adotado um indicador que mede o tempo levado pelo ambiente mais crítico para se recuperar da temperatura anual máxima (Tmax) até chegar no conforto térmico novamente. Este indicador é chamado de tempo de recuperação (*recovery time* [t_R]). Todos estes indicadores foram representados por meio de perfis que permitem uma visão multidimensional da resiliência térmica de edificações, tanto individuais como em grupos (comunidades).

Com a aplicação do *framework* no Artigo 3, verificou-se que, se considerarmos que um edifício está sobreaquecido quando a vulnerabilidade térmica ultrapassa 3% das horas ocupadas, 2,2% dos edifícios não cumpririam este critério na condição base (TMY histórico). A manutenção das condições base em um ano típico na década de 2050 poderia resultar em 37% dos edifícios sujeitos ao sobreaquecimento. Além disso, o consumo mediano de energia para resfriamento poderia aumentar 48% em um futuro médio (2041-2060). Este valor pode atingir 116% na década de 2090 e até 148% durante um ano de ondas de calor. Este aumento da demanda pode sobrecarregar fortemente a rede eléctrica e deve ser abordado através de políticas com longos prazos de implementação. No entanto, o consumo poderia ser reduzido em 59% e 48% nas décadas de 2050 e 2090, respetivamente, se forem promovidas estratégias passivas simples.

Apesar de uma expressiva melhora na maioria dos indicadores, aqueles que descrevem condições térmicas extremas em edificações demonstraram ser muito mais difíceis de mitigar somente com estratégias passivas. Este é o caso, por exemplo, da temperatura máxima e do tempo de recuperação (t_R). Tal observação ressalta a importância da análise da resiliência a partir de multiplos indicadores que possam mapear as mais diversas condições dentro de uma edificação. Em diversos casos, inclusive, verificaram-se *trade-offs* entre o aumento da resistência da edificação (por exemplo, a autonomia térmica) e a sua robustez e capacidade de recuperação. Dessa forma, observa-se a necessidade de dispor-se de soluções ativas para mitigar condições térmicas adversas, bem como o estabelecimento de planos emergenciais de evacuação.

Para prever o impacto dos cenários climáticos na rede elétrica, podem ser adotadas ondas de calor severas, uma vez que estão altamente correlacionadas com o aumento do consumo de energia. No entanto, foi verificado que os picos de demanda de resfriamento da comunidade ocorreram durante as ondas de calor mais intensas, e não durante os eventos mais severos e longos. Também foi identificado que a intensidade de uma onda de calor se correlaciona com a temperatura interna máxima (Tmax) e a vulnerabilidade térmica (TV) em edifícios com ventilação natural e híbridos. Assim, estes eventos intensos podem ser adequados para aplicações como o desenvolvimento de planos de evacuação durante eventos extremos.

A resiliência precisa de ser tratada através de planos de manutenção e modernização a longo prazo, porque as estratégias e tecnologias ideais podem mudar ao longo do tempo, à medida que o clima muda. Para a elaboração de políticas, a análise de um futuro a longo prazo (década de 2090) seria útil para definir caminhos para uma mudança regulatória suave.

Ao abordar a resiliência térmica de uma comunidade real, em vez de edifícios prototípicos isolados, é possível mapear vulnerabilidades e desenvolver planos de ação para responder durante eventos extremos. Por exemplo, a assistência a edifícios com temperatura máxima e tempo de recuperação elevados poderia ser priorizada pelas equipes de emergência. Esta informação seria particularmente útil se combinada com outros dados de saúde e comorbilidades da população, por exemplo, para identificar edifícios com elevada vulnerabilidade térmica ocupados por idosos ou pessoas com mobilidade reduzida. No entanto, uma análise detalhada na escala do edifício continua a ser essencial, especialmente quando realizada por equipes de projeto. Estes profissionais poderão analisar detalhadamente quais são as zonas mais afetadas e o que está causando tal vulnerabilidade, fornecendo assim soluções à medida de cada contexto. Em ambos os casos, no entanto, o *framework* proposto continua a ser útil dado o conjunto abrangente de indicadores adotados, que também podem ser calculados e analisados para zonas térmicas individuais no interior de edifícios.

Considerações finais

Este estudo propõe um *framework* de simulação para avaliar e melhorar a resiliência térmica de edifícios utilizando um conjunto integrado de métricas de desempenho. Este trabalho também aborda como agregar perfis de resiliência de edifícios à escala urbana, apoiando a avaliação de comunidades termicamente resilientes. Este representa o primeiro passo para conectar as escalas predial e urbana em uma análise de resiliência, buscando atender às necessidades de diversos *stakeholders*. A aplicação do *framework* é exemplificada através de dois estudos de caso considerando: (1) edifícios residenciais unifamiliares representativos expostos a três climas brasileiros; e (2) 92 edifícios reais na cidade de Florianópolis, Brasil. O segundo estudo de caso também considera múltiplos cenários climáticos no período histórico, futuro de médio prazo, e futuro de longo prazo.

Os resultados reflectem a necessidade de planear a resiliência. Isto porque, muitas vezes, as estratégias e tecnologias recomendadas nas condições climáticas atuais podem não ser ideais no futuro. Portanto, o projeto flexível e o planejamento de manutenção e modernização são

fundamentais. Além disso, objetivos diferentes podem exigir cenários climáticos diversos, resultando por vezes em *trade-offs* entre melhorar a resistência ou a robustez dos edifícios.

De modo geral, os anos com as ondas de calor mais severas e mais longas em cada período (histórico, futuro de médio ou longo prazo) tiveram maior impacto na resiliência térmica no que diz respeito a todos os seis indicadores combinados. No entanto, aplicações específicas podem se beneficiar da adoção de ondas de calor intensas, especialmente para identificar condições térmicas extremas (Tmax) e picos de demanda de energia. Tal decisão deverá, em última análise, ser acompanhada de uma reflexão aprofundada sobre os objectivos de quantificação da resiliência, dos recursos disponíveis, do horizonte de planeamento e dos riscos assumidos por não ser resiliente.

Palavras-chave: resiliência térmica; edificações; comunidades; simulação computacional.

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ABNT	Brazilian National Standards Organization [*Associação Brasileira de Normas Técnicas*]
AC	Air-conditioned (building)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AWD	Ambient Warmness Degree
BEM	Building Energy Modeling
CCOHS	Canadian Centre for Occupational Health and Safety
CEN	European Committee for Standardization
CgTA	Heating loads
CgTR	Cooling loads
CgTT	Total loads (cooling and heating)
CIBSE	Chartered Institution of Building Services Engineers
CORDEX	Coordinated Regional Downscaling Experiment
DBT_m	Mean Dry-Bulb Temperature
EPE	Energy Research Office
GCM	Global Climate Models
GlobalABC	Global Alliance for Buildings and Construction
HI	Heavy and Insulated envelope
HI’	Heat Index
HVAC	Heating, Ventilation, and Air Conditioning
HWY	Heat Wave Year
IBGE	Brazilian Institute of Geography and Statistics [*Instituto Brasileiro de Geografia e Estatistica*]
IEA	International Energy Agency
INI-C	Inmetro's normative instruction for the energy efficiency classification of commercial, service and public buildings [*Instrução Normativa Inmetro para a Classificação de Eficiência Energética de Edificações Comerciais, de Serviços e Públicas*]
INMETRO	National Institute of Metrology Standardization and Industrial Quality [*Instituto Nacional de Metrologia, Qualidade e Tecnologia*]
IOD	Indoor Overheating Degree
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design

MME	Ministry of Mines and Energy
NOAA	National Oceanic and Atmospheric Administration
NV	Naturally ventilated (building)
OECD	Organisation for Economic Co-operation and Development
PHFT	Percentage of occupied Hours within a temperature range [*Percentual de Horas ocupadas dentro de uma Faixa de Temperatura*]
PHHI’	Percentage of occupied hours within a heat index range
PHT_{upp}	Percentage of occupied Hours above the upper limit Temperature
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
Ref	Reference model (from NBR 15575-1:2021)
SET	Standard Effective Temperature
SHGC	Solar Heat Gain Coefficient
TA	Thermal Autonomy
TC	Thermal Capacity
Tmax	Annual maximum temperature
TMY	Typical Meteorological Year
Tomax	Maximum annual operative temperature
Tomin	Minimum annual operative temperature
t_R	Recovery time
TRY	Test Reference Year
T_{upp}	Upper limit temperature
TV	Thermal Vulnerability
U	Thermal transmittance
UBEM	Urban Building Energy Modeling
UNEP	United Nations Environment Programme
WBGT	Wet Bulb Globe Temperature
WHO	World Health Organization
WLU-RLI	Light and Uninsulated Walls and the Light and Insulated Roof
XMY	eXtreme Meteorological Year

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1. INTRODUCTION

Climate uncertainty has been pushing for a mentality shift in how we approach building design. Hazards that are familiar in one place may, now or in the future, occur where they never did before (OECD - ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, 2021). An example is the unprecedented warmth that marked the summer in 2022 in Europe (BALLESTER et al., 2023; SERRANO-NOTIVOLI et al., 2023), followed by a similar pattern in July 2023 in North America, Europe, and China (ZACHARIAH et al., 2023). In São Paulo, Brazil, outpatient care and hospitalizations from heat exposure increased 102.5% in the first seven months of 2023, compared to 2022 (SECRETARIA DE ESTADO DA SAÚDE DE SÃO PAULO, 2023). A trend toward overheating hazards seems nonetheless inexorable (ZHANG et al., 2022) as air conditioning is already the fastest-growing use of energy in buildings (IEA - INTERNATIONAL ENERGY AGENCY, 2018a) and extreme heat events are projected to occur more often and severely in the future (WEDLER; PINTO; HOCHMAN, 2023). The conventional design practice of optimizing performance and cost needs to be updated to include a resilient design, which seeks to minimize risks and increase adaptability (HOLZER et al., 2022).

Thermal resilience is *the ability of the built domain — and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales — to maintain or rapidly return to desired indoor thermal conditions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity* (adapted from Meerow, Newell and Stults (2016)). The assessment of thermal resilience of buildings is mainly performed through building performance simulation as it allows one not only to learn from past experiences but especially to explore and project different conditions looking into the future. However, a standardized modeling framework is still missing (KESIK; O'BRIEN; OZKAN, 2022).

1.1. PROBLEM AND RELEVANCE OF THIS WORK

In the face of prospected climate changes, building design can no longer focus only on typical conditions but rather account for extreme weather events. It is not enough to plan from past experiences, but rather a resilience assessment is required. Adverse conditions increasingly felt in the built environment should be a source of concern of researchers, urban planners, policy makers and all stakeholders who can make buildings and cities prevail. Thus, a framework to diagnose resilience against overheating at the building and urban level is essential to guide adaptation and mitigation strategies to tackle the effects of climate change. Such a framework should allow stakeholders to consider diverse stressors and strategies in a way that can be applied flexibly in variable contexts, especially in developing countries whose reality is often misrepresented.

The framework proposed in this study was developed having the Brazilian context as a background. This is relevant because most resilience studies are currently developed targeting the Global North (e.g., in Attia et al. (2021) and Homaei and Hamdy (2021), which often leads to the proposition of methods and strategies that are either not applicable or ineffective in the Global South.

In Brazil, several cities are expected to experience highly dangerous heat during most of the year in the 2050s (KOMMENDA et al., 2023). Such a projection is likely to coexist with a low possession of air-conditioning systems to cope with extreme heat (ELETROBRAS, 2019a), a significant prevalence of energy poverty (BEZERRA et al., 2022) and informal settlement issues (REN, 2018). Additionally, appropriate codes and standards are either nonexistent or not sufficiently enforced, with minimal incorporation of resilience into local codes (GLOBALABC; IEA; UNEP, 2020), while decarbonization plans primarily focus on deforestation and transportation issues (INSTITUTO TALANOA, 2023). In this context, there is a strong need to quantitatively understand the indoor overheating risk and evaluate effective measures to improve the building stock for occupant health and wellbeing.

1.2. CONTRIBUTION AND INNOVATION

Considering the demand of improving the resilience of buildings in warm developing countries, this study builds upon the recently revised Brazilian building performance standard—NBR 15575-1:2021 (ABNT - BRAZILIAN NATIONAL STANDARDS ORGANIZATION, 2021a)—to explore how *thermal performance* can be translated into *thermal resilience*. For doing so, a framework to assess thermal resilience of buildings and communities was proposed, which provides the following contributions:

- The thermal resilience quantification is based on solid resilience literature, relating consolidated key performance indicators (KPIs) to primary characteristics expected from resilient buildings;

- This comprehensive set of KPIs allows design teams, energy modelers, and researchers to deeply understand and address fragilities in a resilience-oriented design.
- The selected KPIs have objective and easy-to-understand dimensions and meanings, which facilitate future adoption by different stakeholders;
- The proposition of a visualization approach of results through a resilience profile that covers the three stages of resilience;
- The flexibility to consider multiple stressors and strategies in short and long time periods;
- The proposition of an aggregation approach to translate detailed diagnoses at the building scale to the urban scale, facilitating identification and decision-making regarding thermally vulnerable populations.
- The identification of suitable weather scenarios to assess thermal resilience within a case study in the face of climate change.

1.3. OBJECTIVES

This work aims to develop a simulation framework to diagnose thermal resilience of buildings and communities against overheating, considering coping and adaptation strategies, as well as different sources of stress, especially those related to climate change. This general goal can be broken down into four specific objectives:

1) To identify key performance indicators capable of providing a comprehensive diagnosis of thermal resilience of single buildings;
2) To develop a procedure to assess thermal resilience and an aggregation method to translate the individual building diagnoses into a meaningful evaluation of the urban scale (i.e., communities);
3) To evaluate the effectiveness of the simulation framework through a case study considering a group of buildings exposed to overheating;
4) To identify what are the recommended weather scenarios to comprehensively test thermal resilience within the case study.

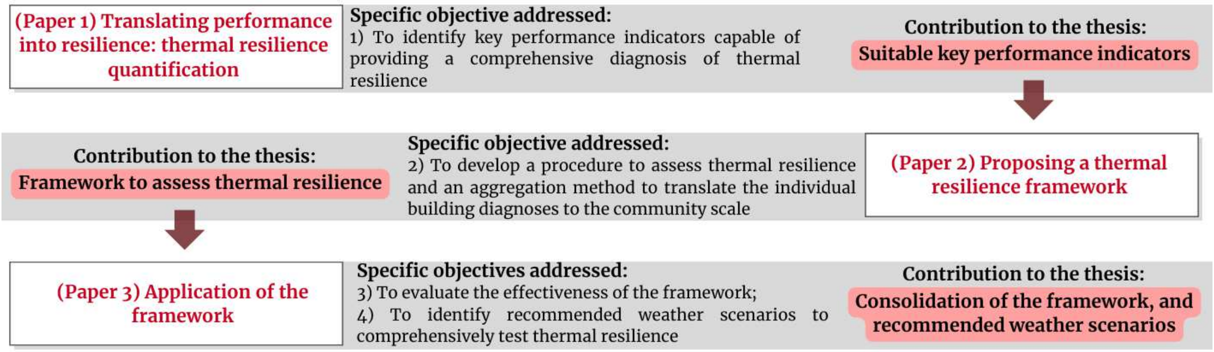
1.4. STRUCTURE OF THE THESIS

The work described herein combines efforts and results published in two journal papers, and a third paper to be submitted by November/December 2023. They are described in Table 1. Papers 1 and 2 were summarized in Sections 3 and 4, and were included as accepted for publication in Appendices A and B, respectively. The method and results of Paper 3 are entirely described in Section 5.

Fig. 1 shows how these articles are connected to specific objectives and how they build the steps necessary for the development of this thesis. All the co-authors provided a shared authorship agreement, as shown in Appendix C. All references are presented at the end of this document for conciseness.

Table 1 - Journal papers composing this thesis

Number and section	Title	Authors	Status
Paper 1 (Section 3)	A thermal performance standard for residential buildings in warm climates: Lessons learned in Brazil	**Krelling, A.F.**, Eli, L.G., Olinger, M.S., Machado, R.M.E.S., Melo, A.P., Lamberts, R.	Published in Energy and Buildings (DOI: 10.1016/j.enbuild.2022.112770)
Paper 2 (Section 4)	A simulation framework for assessing thermally resilient buildings and communities	**Krelling, A.F.**; Lamberts, R.; Malik, J., Hong, T.	Published in Building and Environment (DOI: 10.1016/j.buildenv.2023.110887)
Paper 3 (Section 5)	Defining weather scenarios for simulation-based assessment of thermal resilience of buildings and communities in Brazil under current and future climates: A case study	**Krelling, A.F.**; Lamberts, R.; Malik, J., Zhang, W., Sun, K. Hong, T.	To be submitted by November/December 2023



(Paper 1) Translating performance into resilience: thermal resilience quantification

Specific objective addressed:
1) To identify key performance indicators capable of providing a comprehensive diagnosis of thermal resilience

Contribution to the thesis:
Suitable key performance indicators

(Paper 2) Proposing a thermal resilience framework

Specific objective addressed:
2) To develop a procedure to assess thermal resilience and an aggregation method to translate the individual building diagnoses to the community scale

Contribution to the thesis:
Framework to assess thermal resilience

(Paper 3) Application of the framework

Specific objectives addressed:
3) To evaluate the effectiveness of the framework;
4) To identify recommended weather scenarios to comprehensively test thermal resilience

Contribution to the thesis:
Consolidation of the framework, and recommended weather scenarios

Fig. 1 - Structure of the thesis in journal papers connected to specific objectives

2. LITERATURE REVIEW

This review covers the definition of resilience in the literature, as well as its quantification and assessment procedures. In Section 2.7, the Brazilian context is also presented to provide the background for the framework proposed herein. In the last section of this review, a literature overview summarizes the key messages from this chapter.

2.1. RESILIENCE IN THE LITERATURE

The frequency and intensity of weather extremes have increased in the past decades as a consequence of human-induced climate change (IPCC - INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2021). In this context, the term "resilience" has been flooding academic literature. Nevertheless, this is not a new concept. In fact, it has been discussed since roughly 1973, when C.S. Holling (HOLLING, 1973) published his seminal paper about "*resilience and stability of ecological systems*." Holling (HOLLING, 1973) addresses resilience in terms of the persistence of relationships within a system, despite future unexpected changes. These changes can be understood mainly based on three equilibrium viewpoints (FOLKE, 2006; HOLLING, 1986).

Under the first, the equilibrium-centered viewpoint, resilience describes "*how fast the variables return towards their equilibrium following a perturbation*" (PIMM, 1984, p. 2). The equilibrium-centered viewpoint is thoroughly contested by Holling (HOLLING, 1986, p. 294), who describes it as "*the policy world of a benign nature where trials and mistakes of any scale can be made with recovery assured once the disturbance is removed.*" Notwithstanding, this is the basis for many resilience studies. It is also termed "***engineering resilience***" (HOLLING, 1996).

The second viewpoint describes multiple equilibria states, with the system being able to adapt and change, reaching a stable state that is not necessarily the same. This second viewpoint is also called "***ecological resilience***" and is focused on "*maintaining existence of function,*" while the former engineering approach is focused on "*maintaining efficiency of function*" (HOLLING, 1996, p. 33).

The third viewpoint considers a non-equilibrium dynamic, where the focus is to stay "*in the game*" rather than reaching a stable condition (HOLLING, 1973, p. 18; PICKETT; CADENASSO; GROVE, 2004). According to Holling (HOLLING, 1986, p. 295), "*successful efforts to constrain natural variability lead to self-simplification and so to fragility of the* *ecosystem.*" This viewpoint is called by some authors "***evolutionary resilience.***" For example, Davoudi (DAVOUDI, 2012, p. 302) states that "*faced with adversities, we hardly ever return to where we were.*"

Throughout the years, the concept of resilience has been reshaped to fit many scientific fields. This approach has an upside and a downside: on one hand, divergent conceptions and approaches may convey vagueness and ambiguity to its adoption; on the other hand, its malleability can foster communication between distinct areas and stakeholders (BRAND; JAX, 2007; VALE, 2014).

The urban environment is a fruitful field to study resilience, given the concentration of people and economic activities that make risks and damages less acceptable. Also, this very urbanity often enhances hazards, especially those related to climate change (TROMEUR et al., 2012). The built domain determines where functions essential to human life are carried out (ISO, 2019a) within an urban system. It is a source of protection against weather conditions, enhancing human health and risk reduction (UNEP, 2021). Among several disruptive events that may affect the built environment, the extreme temperature hazard (MILLER et al., 2021) stands out for affecting occupants' health and well-being, while also depleting natural resources through an increasing need for air conditioning (IEA, 2018a).

Studies that tackle the resilience of buildings regarding indoor thermal quality can be found in literature, mainly through terms such as thermal resilience (HOMAEI; HAMDY, 2021; KESIK; O'BRIEN; OZKAN, 2022; MIRZABEIGI et al., 2022), robustness (HOMAEI; HAMDY, 2020; KOTIREDDY; HOES; HENSEN, 2018; MOAZAMI; CARLUCCI; GEVING, 2019), and resilient cooling (ATTIA et al., 2021; MILLER et al., 2021). The latter comes from the work of the International Energy Agency's Annex 80: Resilient Cooling of Buildings, whose objective is to support low energy and low carbon solutions for addressing cooling and overheating issues in buildings (IEA, 2019). As a product of Annex 80, the work of Attia et al., (2021), together with that of Miller et al. (2021), provide a thorough definition of resilience in the built environment. To sum it up, Attia et al. (2021) describe resilience against overheating and power outages through stages of vulnerability, resistance, robustness, and recovery. A vulnerability assessment that considers foreseeable risk factors is conducted during the design stage. The resistance stage encompasses the period when the building is exposed to usual and extreme weather conditions, yet its design features and embedded coping strategies are able to prevent critical thermal conditions. The robustness stage is characterized by the failure of these features and strategies. When a robust building reaches critical conditions after failure, it is able to survive and adapt its performance, leading to a recovery stage.

This, or similar definitions, may be applied to numerous buildings, but still, it does not easily translate thermal resilience of the group of buildings (i.e., within the urban scale). An aggregation procedure is already common when analyzing energy consumption or carbon emissions of groups of buildings, e.g., in bottom-up approaches for Urban Building Energy Modeling (UBEM) (FERRANDO et al., 2020; HONG et al., 2020). However, a framework to quantitatively evaluate thermal resilience on an urban scale, covering multiple stressors and strategies, is still missing. This is especially sensitive when considering passive strategies, such as natural ventilation, or when addressing disruptions that affect energy availability (e.g., power outages).

2.2. CHARACTERISTICS AND INDICATORS OF THERMAL RESILIENCE

To better understand a certain phenomenon, the logical first step is to try to measure it; this has already been attempted in resilience analyses in a variety of ways (ATTIA et al., 2021; HOMAEI; HAMDY, 2021; ISO, 2019b). Beyond the challenge of not having a common definition, thermal resilience cannot be directly measured. Such a setting leaves plenty of space for interpretation, choices of metrics, time frames, and stressors, ultimately leading to all sorts of "*resilient buildings*." To suitably cover the major aspects of resilience against overheating, it is necessary to identify the characteristics expected from a resilient system. Measuring the satisfaction of these characteristics may be a proxy for measuring resilience itself (DA SILVA; KERNAGHAN; LUQUE, 2012).

Table 2 summarizes the definitions of characteristics related to resilience in the literature. Most of these characteristics can be perceived as qualities that should be observed to enhance resilience (e.g., adaptability and learning capacity) whereas aspects of resilience related to resistance, robustness, and recoverability can be evaluated through performance metrics directly measuring responses to predefined hazards towards indoor thermal conditions. Building performance simulation can be used to quantify such characteristics (highlighted in bold in Table 2), thus being the focus of the framework proposed in this study.

Building performance metrics are calculated through long-term comfort evaluation methods (CEN - EUROPEAN COMMITTEE FOR STANDARDIZATION, 2007; ISO, 2005a), which have been thoroughly reviewed by Carlucci et al. (CARLUCCI; PAGLIANO, 2012) and, more recently, by Rahif et al. (RAHIF; AMARIPADATH; ATTIA, 2021). However, performance indicators have not yet been directly associated with characteristics of resilience.

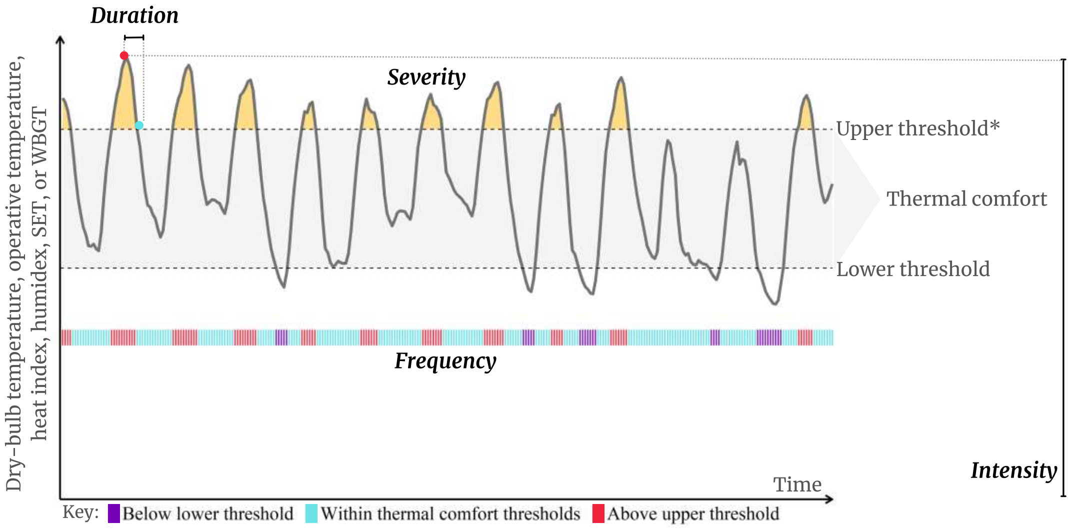
Table 2 - Characteristics of resilience

Characteristic	Definition
Vulnerability	The intrinsic properties of something, resulting in a propensity to be adversely affected. In buildings, it may involve the sensitivity of indoor comfort conditions to disruptions (ATTIA et al., 2021; IPCC, 2021; ISO, 2009, 2019b; MILLER et al., 2021).
Adaptability	The ability to adjust to potential damage and to take advantage of opportunities while focused on anticipated future change. It reflects the capacity of actors to influence resilience with proactive strategies aiming to protect the system (CLARKE; KUIPERS; ROOS, 2019; FOLKE et al., 2010; GRAFAKOS et al., 2020; IPCC, 2012, 2021; MILLER et al., 2021; PASIMENI et al., 2019; WALKER et al., 2004).
Transformability	The capacity to correct vulnerabilities when the existing system is untenable, even by changing fundamental attributes (CLARKE; KUIPERS; ROOS, 2019; DA SILVA; KERNAGHAN; LUQUE, 2012; FOLKE et al., 2005, 2010; IPCC, 2012; PRIVITERA et al., 2018; WALKER et al., 2004).
Learning capacity	The capacity to learn from past experiences and failures in order to adjust, reorganize, and prepare for future decisions, uncertainties, and surprises (DA SILVA; KERNAGHAN; LUQUE, 2012; FOLKE et al., 2005; IPCC, 2012).
Dependency (on local ecosystems)	“*Resilient urban systems exercise a greater degree of control over the essential assets required to support well-being, securing access to and quality of such resources. This involves recognising the value of the services provided by local and surrounding ecosystems (often described as the city’s green and blue infrastructure) and taking steps to increase their health and stability*” (DA SILVA; KERNAGHAN; LUQUE, 2012).
Mitigation (to climate change)	“*A human intervention to reduce emissions or enhance the sinks of greenhouse gases*” (IPCC, 2021).
Resistance	**The ability to maintain initial conditions and prevent disturbances from translating into impact** (ADGER, 2000; ATTIA et al., 2021; WALKER et al., 2004)**.**
Safe failure / Robustness*	**The “*ability to absorb shocks and the cumulative effects of slow-onset challenges in ways that avoid catastrophic failure if thresholds are exceeded*”** (DA SILVA; KERNAGHAN; LUQUE, 2012)**.** ***Authors diverge about the definition of “*robustness*.” For instance, in** (MOAZAMI; CARLUCCI; GEVING, 2019) **“*robustness*” is described similarly to “*resistance*.” On the other hand, in** (ATTIA et al., 2021) **the presence of failure is essential to represent “*robustness*,” thus it can be related to “*safe failure.*” The latter interpretation is considered throughout this work.**
Responsiveness / Recovery	**“*The ability to re-organise, to re-establish function and sense of order following a failure*”** (DA SILVA; KERNAGHAN; LUQUE, 2012)**.**
Flexibility	“*The ability to change, evolve and adopt alternative strategies (either in the short or longer term) in response to changing conditions*” (DA SILVA; KERNAGHAN; LUQUE, 2012).
Smartness	“*Quality of contributing to sustainable development and resilience, through soundly based decision making and the adoption of a long- and short-term perspective [...] It implies a holistic approach, including good governance and adequate organization, processes and behaviours, and appropriate innovative use of techniques, technologies and natural resources* [...] *Smartness is addressed in terms of performance, relevant to technologically implementable solutions*” (ISO, 2016).
Diversity	The ability to respond to a disturbance in a diversity of ways (ANDERIES, 2014; BIGGS et al., 2012).
Redundancy	The presence of components, strategies, or actors that can compensate for each other (e.g., in case of disruptions). Redundancy comes with investment and performance costs that require thorough evaluation (ANDERIES, 2014; BIGGS et al., 2012; DA SILVA; KERNAGHAN; LUQUE, 2012; STEVENSON; BABORSKA-NAROZNY; CHATTERTON, 2016).
Modularity	Modularity provides a system with different functional modules that can evolve somewhat independently. Modules may be loosely linked by design so that failure of one module does not severely affect the others (ANDERIES, 2014).

Indoor thermal conditions can be described through many parameters, usually chosen based on what is being assessed (i.e., minimum or critical conditions) and data availability. The Dry-Bulb Temperature (DBT) is an easy and common parameter to evaluate the thermal environment, but its translation to thermal comfort or thermal distress lacks additional information. Operative temperature incorporates the DBT and the mean radiant temperature, more frequently used as a simplified approximation to evaluate thermal comfort. The Standard Effective Temperature (SET) (ASHRAE, 2020a) is another alternative, but it is relatively complex to obtain from field measurements as it requires six parameters for calculation, including indoor air velocity, humidity, occupant metabolic rate, and clothing insulation (JI et al., 2022). Nonetheless, if solely using building performance simulation, the SET would be a comprehensive alternative, and simulation tools such as EnergyPlus calculate and directly output SET. The heat index (NOAA, 2022), humidex (CCOHS, 2019; MASTERTON; RICHARDSON, 1979), and the Wet Bulb Globe Temperature (WBGT) (ISO, 2017) are often measures of thermal stress. These parameters provide measures of indoor thermal conditions in a certain moment, while a screening analysis throughout time is conducted mainly by indicators describing intensity, frequency, duration, or severity of events (see Fig. 2). This procedure may depend on comfort models (i.e., static or adaptive) and comfort categories to set appropriate thresholds to calculate key performance indicators (KPIs). Table 3 describes types of KPIs, their application, limitation, and examples in the literature.

A major challenge regarding characteristics of resilience measured by indoor thermal conditions is that they are calculated for a thermal zone. Methods of calculating these results for the whole building (i.e., multiple thermal zones) are already broadly applied (e.g., in (ABNT, 2021a; HAMDY et al., 2017; HOMAEI; HAMDY, 2021)) but translating them to a group of buildings is not common. An appropriate summary of results needs to be developed in such a way that it still holds meaning regarding the overall performance of urban buildings, as well as indicating best practices and points of caution.

It is important to highlight that more than one indicator may be necessary to describe each characteristic of resilience, as well as to cover the effectiveness of different strategies. An appropriate set of indicators should be chosen based on their capacity to communicate additional information that helps to portray the whole picture of resilience in buildings and groups of buildings.



*Limit to provide minimum thermal conditions to prevent overheating.
Thresholds to represent critical thermal conditions can be drawn above this line

Fig. 2 - Key performance indicators for indoor thermal conditions

Table 3 - Types, limitations, and examples of key performance indicators for indoor thermal conditions

Application	Limitations	Examples in the literature
Indicators that describe intensity		
Describe the worst thermal conditions	Do not communicate whether this is a frequent event or an isolated occurrence	Maximum and minimum air temperatures or operative temperatures when an air conditioning system is unavailable (ABNT, 2021a; KESIK; O'BRIEN, 2019; SAMUELSON; BANIASSADI; GONZALEZ, 2020).
Indicators that describe frequency		
Describe how often (i.e., the proportion of time) a certain condition happens (e.g., thermal comfort or thermal stress)	Do not communicate how far indoor thermal conditions are from thresholds. For example, they may consider crossing the threshold by 0.5 ºC or by 4 ºC the same way)	Thermal autonomy (KO et al., 2018)
Indicators that describe duration		
Describe the length of time in a certain condition. They are especially meaningful to assess the risk of thermal conditions affecting human health, sometimes indicating whether a building should be evacuated (KESIK; O'BRIEN, 2019)	Insufficient to characterize alone thermal resilience, especially when considering whole-year analyses	Hours of safety (AYYAGARI; GARTMAN; CORVIDAE, 2020) and Heating Passive Habitability (HPH) (KESIK; O'BRIEN, 2019), both accounting for the length of time before a building becomes uninhabitable
Indicators that describe severity		
Aggregate information from both intensity and frequency	The magnitude of results may be hard to grasp, often lacking a definition of what range of results is acceptable for an indoor thermal environment	Degree hours (CEN, 2007, 2019), SET-hours (HONG et al., 2021), Indoor Overheating Degree (IOD) (HAMDY et al., 2017)

2.3. SOURCES OF STRESS IN BUILDING PERFORMANCE MODELS

At the core of any resilience study is the response of the system to stressors through available coping strategies. In this study, the term “*stressor*” is used to describe a source of disturbance to the building thermal dynamics that can lead to overheating. Table 4 lists examples of stressors, only considering those that can be directly represented through building performance simulation.

Even the building occupant can be considered a source of stress. This is because occupants’ presence and activities will influence the building’s thermal balance (CARLUCCI et al., 2020) through actions like operating windows and solar shadings, light switching, adjusting thermostats, and using appliances (CARLUCCI et al., 2020; IEA, 2018b). Rouleau, Gosselin and Blanchet (2019) found that the hours of discomfort varied by 74% on average when changing occupant profiles, prompting the authors to conclude that offering a range of possible energy consumption values may be more realistic than unitary values. O’Brien et al. (2016) also argued that providing alternative validated occupant models could be an opportunity for stressing the model and better evaluating building performance under uncertain scenarios.

Table 4 - Sources of stress and modeling approaches for building performance simulation

Stressors	Modeling approach
Variation in occupant behavior and occupation density/ patterns (e.g., during a pandemic)	Modeling of multiple occupation patterns (CARLUCCI et al., 2021; ELI et al., 2021; HOBSON et al., 2021)
Extreme weather events (e.g., heat waves)	Adoption of weather files encompassing the event (historical or projected future) (CRAWLEY; LAWRIE, 2015, 2019; FLORES-LARSEN; BRE; HONGN, 2022)
Urban heat island	Adoption of weather files with variables measured onsite or adapted through tools that simulate the urban heat island effect (HONG et al., 2021; SALVATI et al., 2020)
Power outages	Modeling of power availability constraints (BANIASSADI; HEUSINGER; SAILOR, 2018a; SAMUELSON; BANIASSADI; GONZALEZ, 2020)
Occupants’ physical limitations	Modeling of building operation constraints
Wildfires, air pollution, technical failure of building systems, or other events that affect building operation, especially those related to AC operation or the ability of opening windows	Modeling of building operation constraints

Another source of stress to urban buildings is the occurrence of power outages, which prevent the use of technical building systems, with a special impact on air conditioning. The absence of power may jeopardize the safety and health of building occupants, especially those of vulnerable populations, and particularly when outages occur simultaneously with extreme cold (AYYAGARI; GARTMAN; CORVIDAE, 2020) or hot (KESIK; O'BRIEN, 2019; MILLER et al., 2021) weather events. For example, Samuelson, Baniassadi and Gonzalez, (2020) reported the possibility of occupants facing high nighttime temperatures inside insulated buildings during longer power outages.

The climatic response of buildings would be better understood if evaluated under a varied range of weather conditions, instead of only focusing on an average year (CRAWLEY; LAWRIE, 2019). Also, openly available weather files (e.g., Test Reference Year [TRY] and Typical Meteorological Year [TMY] files) are already known for commonly not representing the urban microclimate of cities, given that many weather stations are in a distant and rural location. Thus, building performance simulation for resilience assessment would benefit from considering weather files encompassing: urban microclimate, extreme weather conditions, heat waves, cold spells, and projections for future weather conditions based on various climate change scenarios.

2.4. THERMAL RESILIENCE ASSESSMENT THROUGH BUILDING ENERGY MODELING

Building Energy Modeling (BEM) is an important tool to assess thermal resilience. However, a standardized modeling framework is still missing (KESIK; O'BRIEN; OZKAN, 2022). Homaei and Hamdy (2021) described a resilience test procedure that encapsulates the building performance during the disruptive event and a few days after it. They proposed the overall Weighted Unmet Thermal Performance ($WUMTP_{Overall}$) to quantify resilience, which is based on degree-hours (CEN, 2007, 2019), but different penalties are applied depending on the phase when the temperature differential is calculated (during or after disruption), the hazard level (i.e., how far the operative temperature is from the acceptable level), and the exposure time in a given hazard level. This is a novel approach that takes into account the intensity and frequency of events, while also encapsulating how buildings respond to failure and how they recover from it. However, its applicability is restricted to a short time frame analysis centered on a disruptive event about which a few parameters need to be defined to build specific boundary conditions (e.g., the duration of phases during and after the event, and the initiation time of the disruptive event). This framework (HOMAEI; HAMDY, 2021) is also subjected to the definition of suitable penalty values applicable to 12 segments in a resilience curve which would heavily depend on inputs from physiological research. Such dependency on penalty values may hinder its broad application, especially when considering multiple sources of stress and compound events.

Among efforts from IEA Annex 80 researchers, Rahif et al. (2022) described a method to evaluate and compare the overheating resistivity of cooling strategies. They propose the Climate Change Overheating Resistivity (CCOR) as the rate of change in the Indoor Overheating Degree (IOD) (related to the indoor environment) with an increasing Ambient Warmness Degree (AWD) (related to the outdoor environment). This is a synthetic metric that provides an overall understanding of how buildings are suppressing outdoor thermal stress under multiple future climate scenarios. However, being a rate of change in resistivity, it does not directly describe the thermal resilience of buildings in a way that allows identifying what is causing a vulnerability to overheating (e.g., describing the indoor thermal conditions in a specific scenario). Thus, such an approach is highly valuable for the intended comparative analysis of climate scenarios and cooling strategies, but less suitable to understand resiliency.

Flores-Larsen, Filippín and Bre (2023) used building performance simulation and field measurements to understand the correlation between overheating metrics and the outdoor thermal stress in a bioclimatic office in Argentina. The authors argue that the previous thermal history and the solar irradiance level highly influence the thermal resilience of free-running buildings.

In a similar approach to that of Rahif et al. (2022), the dynamic simulation guideline proposed by Annex 80 researchers (ZHANG et al., 2023) adopts the CCOR and additional thermal comfort, energy, and emission metrics, aiming at evaluating and comparing resilient cooling solutions across multiple climate scenarios worldwide. Nevertheless, the metrics included are broadly described, still lacking a consistent structure behind their selection and application. That is, describing the reasons why the specific metrics quantify resilience and how they work together for a robust resilience diagnosis. Additionally, a method to visualize results and compare the different selected metrics is still absent in the second version of the guidelines, requiring further development.

Within the urban context, Sun et al. (2021) modeled two vulnerable communities in the U.S. through the web-based platform CityBES (HONG et al., 2016), seeking to evaluate the effect of passive cooling strategies towards heat resilience. In the most severe scenario, buildings were exposed to a heat wave during a power outage while aided by several strategies, including natural ventilation. Katal, Mortezazadeh and Wang (2019) used CityFFD and CityBEM to evaluate the resilience of a group of buildings exposed to an extreme snowstorm coupled with a three-day power outage. Nevertheless, a structured resilience assessment of urban buildings has not matured yet, with very different procedures adopted in the literature: e.g., an individual building sampled to be analyzed within a certain urban context and microclimate (CANTATORE; FATIGUSO, 2021; CHIESA; PALME, 2018), and multiple buildings only represented by demand profiles (MOHSENI; BRENT; BURMESTER, 2020; PATEL et al., 2021).

2.5. CURRENT STATE OF BUILDING ENERGY MODELING FOR THERMAL RESILIENCE

Physics-based models can replicate a building thermal dynamic to investigate the effect of different events and disruptions to the indoor thermal environment, which is especially useful in a thermal resilience analysis. For instance, BEM has been used to assess buildings exposed to multiple events, especially heat (BANIASSADI; HEUSINGER; SAILOR, 2018b; BORGHERO et al., 2023) and cold (HOMAEI; HAMDY, 2021) waves, and future climate scenarios (RAHIF et al., 2022).

Scaling from individual buildings to communities has formed a prominent field of study that can feed many stakeholders, from design and operation to policy making, with quantitative insights about neighborhoods, districts, and cities (HONG et al., 2020; REINHART; CEREZO DAVILA, 2016). Urban Building Energy Models (UBEM) simulate the performance of a group of buildings exposed to the urban environment and its dynamics (HONG et al., 2020).

Bottom-up physics-based UBEM considers detailed end-use information from which building models are constructed and simulated according to thermodynamic principles (LI et al., 2017). This approach should be suitable to evaluate thermal resilience, already counting with consolidated and freely available tools. However, Ferrando et al. (2020) thoroughly reviewed bottom-up physics-based UBEM tools and, among described features, one characteristic stands out: restricted opportunities to evaluate thermal performance apart from energy use. This may compromise an appropriate modeling and evaluation of communities where passive strategies are prioritized. For instance, natural ventilation is the preferred strategy to improve indoor air quality in Brazilian households (RAMOS et al., 2020a), while only 17% of them are equipped with an air conditioning system (ELETROBRAS, 2019a). Thus, to appropriately represent such a context, a UBEM tool would need to consider the effect of multi-zone airflows, as well as incorporate inputs describing building operation concerning ventilative cooling or other passive strategies. Considering that many of these tools—e.g., UMI, CityBES, and URBANopt (EL KONTAR et al., 2020; HONG et al., 2016; HOUSSAINY et al., 2020; REINHART et al., 2013)—rely on EnergyPlus (which already offers this functionality) as the simulation engine, adaptations are theoretically possible. However, it is uncertain whether an adequate simulation of airflows would be obtained in overly simplified building zones—e.g., UMI's Shoeboxer (DOGAN; REINHART, 2017). Moreover, there's a potential overestimation of benefits from natural ventilation since EnergyPlus, as well as other similar engines, do not consider the wind sheltering effect from surrounding objects (COSTANZO et al., 2019).

For evaluating the thermal resilience of buildings and groups of buildings, it would be necessary:

- To allow modeling of diverse hazards and disruptions (e.g., power outages, heat waves, and the heat island effect);
- To allow modeling of multiple strategies to respond to hazards and disruptions, including passive strategies such as ventilative cooling;
- To provide suitable indicators to assess thermal resilience; or to provide the means for calculating these indicators, for example, by reporting (at least) hourly outputs regarding indoor thermal quality and energy use.

The addition of all these features could overburden an already cost-intensive computer simulation (CHEN; HONG; PIETTE, 2017; HUBER; NYTSCH-GEUSEN, 2011), and would require certain trade-offs (FERRANDO et al., 2020). For instance, increased model detailing may require an expressive reduction in the sample size and/or long periods to run the simulation.

There is a growing interest in the resilience of buildings and communities; thus, it seems opportune to consider a resilience assessment as an additional challenge that can be covered by urban building energy modeling. Despite the challenges, with the prospects of rapid development of system resources, big data, and the internet of things, it is expected that UBEM will be able to increasingly provide value to communities regarding energy efficiency, sustainability, and resilience (HONG et al., 2020). By scaling the resilience diagnosis from individual buildings to the urban level through UBEM, many other stakeholders, such as urban planners, insurance companies, and first responders can benefit in the future.

2.6. WEATHER SCENARIOS FOR RESILIENCE ASSESSMENT

Historical weather data have been largely used for building performance simulation to assess thermal performance and energy efficiency in buildings, especially in the form of Typical Meteorological Years (TMY). That is, considering median weather conditions (ISO, 2005b).

Other types of weather files have been adopted to reflect extreme conditions, such as an eXtreme Meteorological Year (XMY) (CRAWLEY; LAWRIE, 2015, 2019) and historical heat wave data (SUN; SPECIAN; HONG, 2020). Sengupta et al. (2023a) analyzed the impact of heat waves and system shocks on a nearly zero energy educational building. They have found that heat waves had 20 to 93 times more critical impact than the worst system failure, with future climate scenarios being the most extreme shock.

Climate projections based on Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023) scenarios have been leveraging the assessment of buildings looking into the future (RAHIF et al., 2022; SENGUPTA et al., 2023b). Future weather data are generated by downscaling general circulation models through techniques such as morphing, interpolation, and dynamic downscaling (BELCHER; HACKER; POWELL, 2005). The adoption of Regional Climate Models (RCMs), obtained through dynamic downscaling, allows a better simulation of mesoscale weather processes, and improved reliability. However, the generation of future weather files can be computer intensive and require expertise in the field, thus not yet being accessible to several stakeholders of thermal resilience. Additionally, the creation of weather scenarios may involve a large amount of measured weather data from the selected location across several years. Measured data are used not only for identifying typical meteorological years in the historical period, but also for bias-correction of future climate projections from RCMs. Initiatives like that of the Weather Data Task Force of IEA EBC Annex 80 can help to bridge this gap by providing future weather files for cities in most climate zones across the world. In Brazil, a similar initiative is on the way to provide data to all 26 state capitals in the country. Still, a user-friendly tool to curate these weather files is missing, often limiting its use within the scientific domain.

Alternatively, the morphing method (BELCHER; HACKER; POWELL, 2005) is one of the most straightforward techniques for developing future weather files, with the CCWorldWeatherGen (JENTSCH et al., 2013) being a useful tool that applies such a method. The open-source, cross-platform developed by Rodrigues, Fernandes and Carvalho (2023) is another alternative to generate future weather files for building performance simulation. However, a number of limitations are associated with morphing, including neglecting the growing severity and frequency of extreme weather events, and not ensuring consistency among climate variables (EAMES; KERSHAW; COLEY, 2012; JENTSCH et al., 2013).

Weather data can be used not only to curate typical future years, but also to identify extreme weather events such as future heat waves. Still, there’s no standard definition of how to detect heat waves (HONG et al., 2023). Flores-Larsen, Bre and Hongn (2022) compared three existing popular detection methods and found Ouzeau's (OUZEAU et al., 2016) to be the most suitable for building applications. This method is further described in Section 5.1.2.2.

To analyze thermal resilience, it is also conceivable that synthetic extreme weather data could be generated, but there is not a universal recipe to curate these data since building's vulnerabilities are dependent on design (KESIK; O'BRIEN; OZKAN, 2022). Thus, even though one can intuitively select extreme weather data to test resilience, specific impacts of different weather scenarios still lack further study. Also, often practitioners do not want to focus on resilience to extreme events at the expense of other annual metrics such as energy and emissions (BUCKING et al., 2022), which requires a comprehensive evaluation through multiple weather scenarios and metrics.

2.7. BRAZILIAN CONTEXT AND CURRENT STAGE IN BUILDING PERFORMANCE ANALYSES

In the Brazilian housing sector, building envelopes are usually non-insulated, with the most common building components in low-income residential projects comprising the following: walls made of concrete, concrete blocks, or clay bricks; concrete slabs or PVC (polyvinyl chloride) ceiling; fiber cement corrugated sheets or clay roof tiles; and glazing composed of single clear glass and aluminum or steel frames (TRIANA; LAMBERTS; SASSI, 2015). In the residential building stock, around 33% of the buildings are categorized as economic class D or E (low-income) (ELETROBRAS, 2019b). These types of housing projects are commonly developed under a Brazilian habitational program to subsidize social housing, and similar design strategies are adopted all around the country. They are, however, known for not performing adequately everywhere, particularly in hotter climate zones (TRIANA; LAMBERTS; SASSI, 2015).

The Brazilian performance standard, referred to hereinafter as NBR 15575, provides two procedures for the analysis of the thermal performance of residential buildings: a simplified procedure and a computer simulation procedure. This study addresses only the computer simulation procedure, which is the most comprehensive option to evaluate thermal performance.

NBR 15575 is a national standard with widespread implementation by big construction companies, but still limited compliance in the case of small companies. Nonetheless, it is enforced by the Consumer Protection Code, which makes its application mandatory for new residential buildings across the country. A similar national standard for commercial buildings is still nonexistent.

Brazil’s territory is of continental proportions, being the only country in the world crossed by both the Equator and the Tropic of Capricorn. Climates vary from 0A (extremely hot) to 3A (warm), according to the ASHRAE 169 classification system (ASHRAE, 2020b). Thus, mild climate conditions are abundantly present, allowing the uptake of passive strategies to enhance the thermal performance of buildings. In fact, Ramos et al. (RAMOS et al., 2020b) identified a huge preference for naturally ventilated spaces in Brazilian homes (89% of all interviewed occupants). This preference prompts more occupants to open the windows instead of turning on the air conditioner whenever possible (RAMOS et al., 2020b). Moreover, as previously mentioned, only 17% of Brazilian households were equipped with an air conditioner until 2019 (ELETROBRAS, 2019b). However, according to the Brazilian Ten-Year Plan for Energy Expansion (EPE; MME, 2022), this situation is expected to change as it predicts an increase of almost 30% in the energy consumption related to air conditioning between 2021 and 2031.

To account for this scenario, it was important to express the culturally recognized preference for natural ventilation in the performance standard without neglecting the increasing use of air conditioners in the residential sector. Thus, in NBR 15575, the building energy model should be simulated under passive and active operation modes. This allows the potential of building design to deliver adequate thermal performance as a free-running building to be assessed, while also accounting for energy demands when this mode of operation is insufficient to meet acceptable performance.

Many thermal performance standards around the world evaluate buildings primarily or exclusively based on their cooling and heating loads, and these would not correctly reflect the Brazilian context and culture. Considering that inappropriate indicators could invalidate the whole process (CASALS, 2006), a set of KPIs were tailored to fulfill the objectives of the regulation. NBR 15575 evaluates thermal performance through three types of KPIs, two calculated from the results of the model under passive operation (free-running) and one from those of the model under active operation. This approach should provide insights regarding performance under current typical passive usage, and also cover expected results when air conditioning is more frequently present in residential buildings. A summary of the computer simulation procedure can be seen in Fig. 3.

The PHFT, calculated using Equation 1, describes the proportion of time a room is occupied and the operative temperature is within an acceptable range (Table 5). Tomax and

Tomin (Equations 2 and 3, respectively) are considered indicators of extreme conditions found inside the building when it is occupied. Cooling and heating loads are calculated by comparing results from the two models, under passive and active operation conditions. Even though the model with AC is mechanically conditioned throughout the year, its thermal load is only considered when the operative temperature of the free-running model is outside the acceptable range in the same time frame. Thus, the annual summation of considered thermal load values, as given by Equations 4, 5, and 6, should translate the amount of energy to be removed from or added to the building when natural ventilation is not sufficient to guarantee acceptable indoor thermal conditions. These KPIs are calculated as follows:

$$\mathrm{PHFT} = \frac{\mathrm{N_{occ;range}}}{\mathrm{N_{occ;tot}}}.100 \qquad (1)$$

$$\mathrm{Tomax} = \max(\mathrm{To_{occ;n}}) \qquad (2)$$

$$\mathrm{Tomin} = \min(\mathrm{To_{occ;n}}) \qquad (3)$$

$$\mathrm{CgTR} = \sum_{n=1}^{\mathrm{N_{occ;tot}}} \mathrm{Q_{cool;n}} \cdot \mathrm{f_{To}(n)} \qquad (4)$$

$$\mathrm{CgTA} = \sum_{n=1}^{\mathrm{N_{occ;tot}}} \mathrm{Q_{heat;n}} \cdot \mathrm{f_{To}(n)} \qquad (5)$$

$$\mathrm{f_{To}(n)} = \begin{cases} 0 \text{ if } \mathrm{To_{occ;n}} \text{ is within the PHFT range} \\ 1 \text{ if } \mathrm{To_{occ;n}} \text{ is outside the PHFT range} \end{cases} \qquad (6)$$

In Equations 1-6, $\mathrm{N_{occ;tot}}$ is the total number of hours a room is occupied throughout the year; $\mathrm{N_{occ;range}}$ is the total number of hours a room is occupied throughout the year with operative temperatures within a predefined range in the passively operated model; $\mathrm{To_{occ;n}}$ is the hourly operative temperature when the room is occupied at hour "*n*" in the passive operation mode; $\mathrm{Q_{cool;n}}$ and $\mathrm{Q_{heat;n}}$ are the hourly cooling and heating loads in the actively operated model at hour "*n*", respectively; n is an hourly time frame considering only occupied hours; $\mathrm{f_{To}(n)}$ is a function that states whether the cooling or heating load at hour "*n*" should be summed in Equations 4 and 5, respectively. The PHFT is given as a percentage, Tomax and Tomin are measured in ºC, and CgTR and CgTA are given in kWh/year or $\mathrm{kWh/m^2}$.year. These indicators only take into account rooms of prolonged stay, such as bedrooms and living rooms. Results for the whole building are calculated as: the average PHFT; the maximum Tomax; the minimum Tomin; and the sum of all values of CgTR and CgTA, separately. The summation of hourly cooling and heating loads (CgTR and CgTA) is equal to the total thermal load (CgTT).

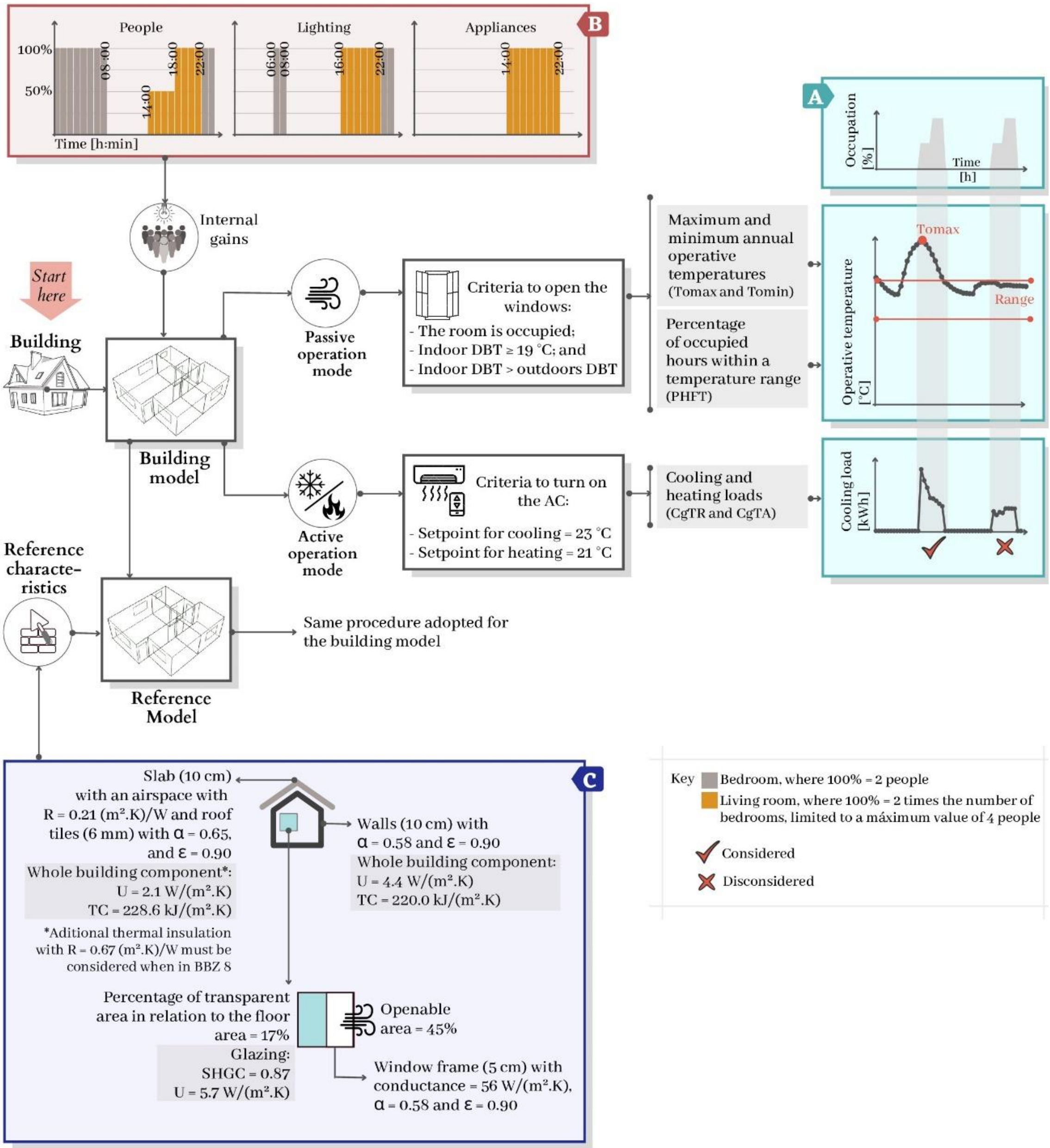


Fig. 3 - NBR 15575 workflow to evaluate the thermal performance of residential buildings

In light of the propensity of houses to be naturally conditioned during the entire year, and the occupants' willingness to take various adaptive actions, NBR 15575 considers different tolerances to indoor thermal conditions. NBR 15575 established three intervals of annual mean dry bulb temperature (DBT_m) on which the calculation of key performance indicators should be based (Table 5). Therefore, as an example, if the DBT_m of a specific climate is lower than 25 ºC, the range of operative temperatures used to calculate the PHFT is between 18 ºC and 26 ºC. Outside these limits, the assistance of mechanical systems would be necessary, leading to cooling or heating loads being actively removed or supplied. When the DBT_m is equal to or higher than 25 ºC, it is assumed that heating is not required. These operative temperature ranges are supported by field surveys regarding the thermal preferences of residential building occupants (DE DEAR; KIM; PARKINSON, 2018; RAMOS et al., 2020b).

Table 5 - Acceptable operative temperature ranges (ABNT, 2021a)

Outdoor temperature interval	**Annual mean dry bulb temperature (DBT_m) interval**	**Operative temperature (To) range**	**Operative temperature (To) to account for cooling loads**	**Operative temperature (To) to account for heating loads**
Interval 1	$DBT_m < 25$ ºC	18 ºC < To < 26 ºC	To ≥ 26 ºC	To ≤ 18 ºC
Interval 2	25 ºC ≤ $DBT_m < 27$ ºC	To < 28 ºC	To ≥ 28 ºC	Not considered
Interval 3	$DBT_m \geq 27$ºC	To < 30 ºC	To ≥ 30 ºC	Not considered

2.8. LITERATURE OVERVIEW

Despite many approaches adopted throughout the literature on thermal resilience, a standard assessment procedure is still not defined. Such a problem is aggravated when looking at warm developing countries, whose context is often misrepresented or impossible to address with current practices. A flexible framework is necessary to bridge this gap, which would involve establishing appropriate indicators quantifiable within multiple contexts. For example, capturing the performance of buildings under passive, hybrid, or active operation (i.e., air-conditioned) modes, and comprehensively explaining both the indoor thermal environment and consequent energy demands. Additionally, such a procedure should be viable to apply within short- (e.g., days or weeks) and long-time frames (e.g., whole year), including variable sources of stress. Ideally, indicators of thermal resilience should be simple to apply and have straightforward physical meanings, facilitating adoption by multiple stakeholders.

However, thermal resilience cannot be directly measured, so appropriate indicators should be able to capture whether buildings hold characteristics expected from resilient buildings. Among many characteristics, resistance, robustness, and recoverability can be quantified through building performance simulation. They describe how well buildings provide thermal comfort, suppress thermal stress, and recover from extreme indoor thermal conditions.

The assessment of thermal resilience through building performance simulation involves exposing the building models to multiple scenarios. These scenarios usually involve typical and extreme weather events, such as heat waves. Power outages and other operation constraints should also be considered to test resilience comprehensively, which allows one to identify what are the required adaptation and coping strategies and capabilities necessary to foster better buildings against future threats.

Multiple tools already exist to model buildings individually (BEM) and at the urban level (UBEM), but special attention is necessary when modeling thermal resilience. The indoor thermal environment needs to be appropriately represented, including passive strategies based on natural ventilation. Also, the tool should allow representation of different sources of stress, such as the occurrence of power outages. This is because the building's thermal dynamics need to be represented as realistically as possible in order to reflect how buildings would respond in real life to different scenarios.

Within countries in the Global South, Brazil is expected to face severe overheating impacts from climate change, which should be amplified by energy poverty and informal settlement issues. Also, the population exhibits a distinguishable trait of exploring natural ventilation the most to passively operate their buildings. Such a context might provide valuable insights when investigating thermal resilience, especially on how to explore resilient low-carbon affordable cooling strategies. The Brazilian national performance standard, NBR 15575, already evaluates buildings under this perspective, which might serve as a background to develop a novel thermal resilience assessment framework.

There are still multiple questions to address when studying the thermal resilience of buildings. We explored ten of these questions in Hong et al. (2023), a few of them discussing the need to define a robust assessment procedure through BEM. The work described in this thesis pursues this challenge aiming to shed light on best practices to evaluate thermal resilience comprehensively, while remaining representative of populations most in need in warm developing countries.

3. TRANSLATING PERFORMANCE INTO RESILIENCE: THERMAL RESILIENCE QUANTIFICATION (PAPER 1)

This section summarizes the study reported in the article "*A thermal performance standard for residential buildings in warm climates: Lessons learned in Brazil*," published in Energy and Buildings with DOI 10.1016/j.enbuild.2022.112770.

3.1. METHOD

Considering the importance of selecting the best KPIs to ensure a comprehensive thermal resilience analysis, this section compares the results of KPIs defined by NBR 15575 with others described in the literature. This step of the analysis seeks to investigate if alternative indicators could add important information that the NBR 15575 procedure is not able to map. Table 6 lists the KPIs analyzed, detailing the equation, unit, and information they aggregate.

To allow comparison, the same thresholds will be considered for all indicators that require an acceptable range of operative temperatures that resemble those of thermal comfort. These are given in Table 5, from NBR 15575, varying according to the annual average dry bulb temperature (DBT_m).

Table 6 - Alternative key performance indicators for assessing thermal resilience

KPI	Equation or calculation procedure	Unit	Aggregated information
Indoor overheating degree (HAMDY et al., 2017)	**For single zone or multi-zones:** $IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z}-TL_{comf,i,z}\right)^{+}.t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}}$ *where z: building zone counter; Z: total number of zones in a building; i: occupied hours counter; t: time step (1 h);* $N_{occ(z)}$*: total occupied hours in a given calculation period;* T_{fr}*: free-running indoor operative temperature at time step i in zone z;* TL_{comf}*: comfort temperature limits at time step i in zone z.*	°C	Quantifies the overheating risk, taking into account both the intensity and the frequency of indoor overheating
Overheating escalation factor (HAMDY et al., 2017)	**For single zone or multi-zones:** $\alpha_{IOD} = \frac{IOD}{AWD_{18°C}}$ Calculated from IOD (above) and $AWD_{18°C}$: $AWD_{18°C} \equiv \frac{\sum_{i=1}^{N}\left[\left(T_{a,i}-T_{b}\right)^{+}.t_{i}\right]}{\sum_{i=1}^{N} t_{i}}$ *where* T_a*: outdoor dry-bulb air temperature;* T_b*: base temperature set at 18 °C; N: number of occupied hours such that* $T_{a,i} \geq T_b$	-	Encompasses the intensity and frequency of acceptable indoor thermal conditions. When $\alpha_{IOD} > 1$, the indoor thermal conditions are worse when compared to outdoor thermal stress. When $\alpha_{IOD} < 1$, the building can suppress some of the outdoor thermal stress

KPI	Equation or calculation procedure	Unit	Aggregated information
Degree hours criteria (CEN, 2019)	**For a single zone:** When $\theta_o < \theta_{o,limit,lower}$ or $\theta_{o,limit,upper} < \theta_o$, $wf = \theta_o - \theta_{o,limit}$ Warm period: $\Sigma wf.time$, for $\theta_o > \theta_{o,limit,upper}$ Cold period: $\Sigma wf.time$, for $\theta_o < \theta_{o,limit,lower}$ *where* θ_o*: indoor operative temperature (ºC);* $\theta_{o,limit}$*: lower or upper limit of the comfort range specified; wf: weighting factor.* **For multi-zones*:** average value considering all zones	ºC. hours	Encompasses the intensity and frequency of acceptable indoor thermal conditions
Percentage of occupied hours above the upper limit temperature (PHT_{upp}) (adapted from CIBSE 2013))	**For a single zone:** Proportion of occupied hours with operative temperature above the upper limit temperature (T_{upp}) (CIBSE, 2013), which is 4 K above the threshold **For multi-zones*:** higher value among all zones	% of hours	Measures the frequency of extreme indoor thermal conditions
Percentage of occupied hours within a heat index range (PHHI') (adapted from (NOAA, 2022))	**For a single zone:** Proportion of occupied hours that a space is occupied and its heat index (HI') (NOAA, 2022) is within each of the different ranges (NATIONAL WEATHER SERVICE, 2022): ▪ Safe (HI' < 26.7 °C); ▪ Caution (26.7 °C ≤ HI' < 32.2 °C); ▪ Extreme caution (32.2 °C ≤ HI' < 39.4 °C); ▪ Danger (39.4 °C ≤ HI' < 51.7 °C); ▪ Extreme danger (HI' ≥ 51.7 ºC). **For multi-zones*:** average values for each range considering all zones	% of hours	Measures the frequency of indoor thermal conditions at different levels of danger towards human health
Recovery time (t_R) (adapted from Homaei and Hamdy (2021))	**For a single zone:** Amount of time between the moment of maximum annual operative temperature (Tomax) and the time when the space reaches an acceptable operative temperature threshold **For multi-zones*:** amount of time the zone with highest Tomax takes to recover	hours	Measures the time required to recover from an extreme indoor thermal condition

*Authors did not describe a procedure to aggregate the indicator from single-zone to multi-zones (i.e., whole housing unit), thus, a procedure is established herein.

3.1.1. Case study for thermal resilience quantification

The case study considered throughout this section is a detached house identified by Triana, Lamberts and Sassi (2015) as representative of low-income buildings in Brazil. These buildings represent approximately 33% of all residential buildings, while 86% of the national building stock in the residential sector is composed of detached houses (IBGE, 2020). It has two bedrooms and a living room with an open kitchen, which will be referred to throughout this document solely as "bedroom" and "living room", respectively. These spaces are considered rooms of prolonged stay and are targeted when evaluating the thermal performance of a building in NBR 15575. More details of the case study are shown in Fig. 4. Characteristics of the reference model were considered for the detached house (see Fig. 3C). All models were developed using the software EnergyPlus, version 9.5.0.

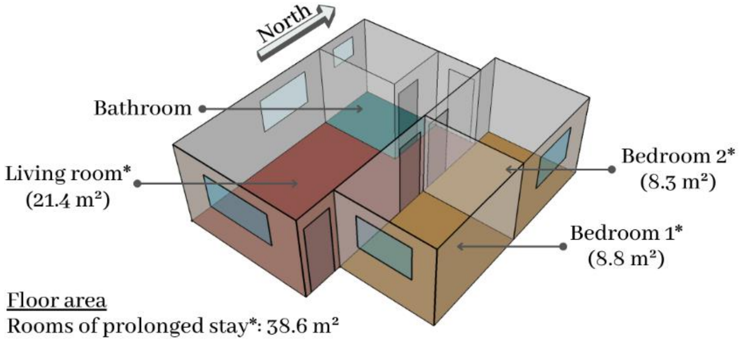


Fig. 4 - Details of the case study for thermal resilience quantification

The climates of Curitiba, Florianópolis, and São Luís were considered in this work, which are cities located in the South and Northeast regions of Brazil. Table 7 shows how they are described according to different climate classification systems. Fig. 5 shows their location within the Brazilian territory while juxtaposing with the ASHRAE 169 climate zones (ASHRAE, 2020b). On the right side, hourly values of dry bulb temperature and relative humidity throughout the year are plotted for each city. The climate data originate from ABNT TR 15575-1-1 (ABNT, 2021b). The DBT_{annual} of Curitiba, Florianópolis, and São Luís fall into intervals 1, 1, and 2 of Table 5, respectively.

Table 7 - Climate classification for Curitiba, Florianopolis, and São Luís

Climate classification	**Curitiba**	**Florianópolis**	**São Luís**
Brazilian bioclimatic zones (ABNT, 2005)	1	3	8
ASHRAE 169 (ASHRAE, 2020b)	3A	2A	0A
Köppen-Geiger climate classification	Temperate oceanic climate (Cfb)	Humid subtropical climate (Cfa)	Bordering dry-summer tropical savanna climate (As) and tropical monsoon climate (Am)

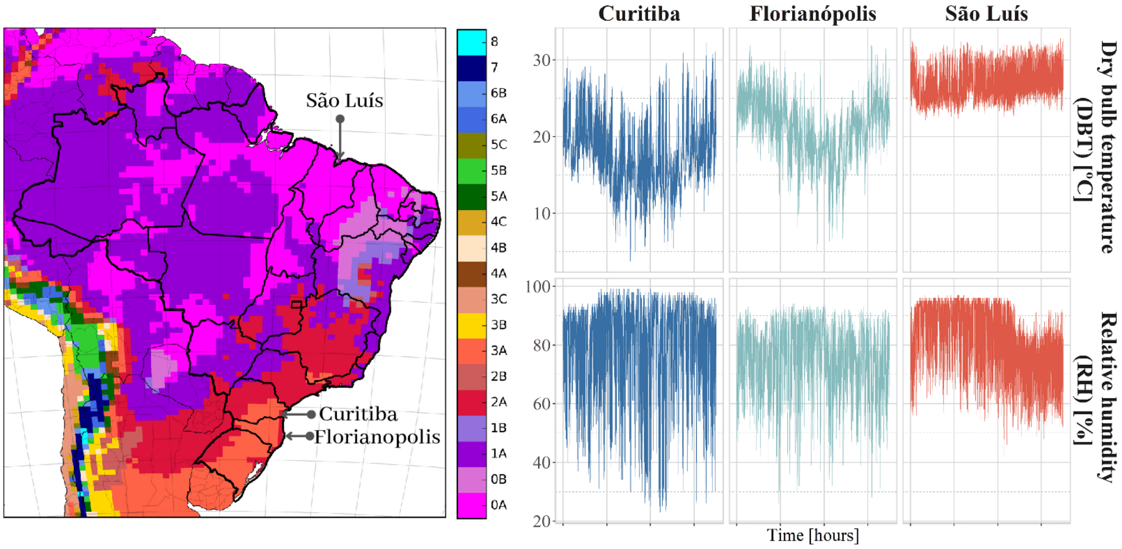


Fig. 5 - Location of Curitiba, Florianópolis and São Luís within the Brazilian territory and annual variation in dry bulb temperature and relative humidity

Three different building envelopes were considered: Ref (reference model established by NBR 15575), HI (Heavy and Insulated envelope), and WLU-RLI (Light and Uninsulated Walls and the Light and Insulated Roof). They are described in Table 8.

Table 8 - Description of building envelopes

Building component	**Envelope: Ref**	**Envelope: HI**	**Envelope: WLU-RLI**
Exterior walls	100 mm wall	EIFS composed of a concrete wall (100 mm), EPS (100 mm) and stucco	Light steel framing composed of a cement board, an air layer (90 mm) and a gypsum board
	U: 4.4 W/(m².K)	U: 0.4 W/(m².K)	U: 2.5 W/(m².K)
	TC: 220.0 kJ/(m².K)	TC: 221.8 kJ/(m².K)	TC: 27.7 kJ/(m².K)
	α: 0.58	α: 0.58	α: 0.58
Roof	Slab (100 mm) with a hip roof composed of 6 mm roof tiles. In São Luís an insulation layer with 0.67 (m².K)/W of thermal resistance is also added	Concrete slab (100 mm) with a hip roof composed of clay roof tiles (15 mm) and insulated with glass wool (50 mm)	Hip roof composed of fiber cement roof tiles (cement reinforced with synthetic fiber sheets), glass wool (100 mm), a single sided radiant barrier foil and a ceiling made of gypsum boards
	U: 2.1 (Curitiba and Florianópolis) / 0.9 W/(m².K) (São Luís)	U: 0.6 W/(m².K)	U: 0.3 W/(m².K)
	TC: 228.6 kJ/(m².K)	TC: 248.0 kJ/(m².K)	TC: 24.6 kJ/(m².K)
	α: 0.65	α: 0.65	α: 0.37

U: thermal transmittance; TC: thermal capacity; α: solar absorptance; EPS: expanded polystyrene; EIFS: exterior insulation and finish system.

3.2. RESULTS

Fig. 6 shows a large mosaic where all indicators can be compared by city, envelope configuration, and room (i.e., living room, bedrooms 1 and 2, and for the overall housing unit). The main objective of this comparison is to explain the thermal performance of each case in a way that addresses, for instance, whether the building is able to maintain the design indoor thermal conditions, how often and with what intensity disruptions occur and how the building recovers from a disruption. All of these KPIs are available to build such a narrative, but only some of them will effectively add information about resilience.

A heavy and insulated (HI) envelope provided optimal results for Curitiba, a city with a temperate oceanic climate (Köppen-Geiger's Cfb), at both the individual room and building levels, which is verified by all KPIs. It can be expected that this building, when exposed to typical meteorological conditions and with a standardized occupant behavior, could survive passively throughout the year. The maximum and minimum operative temperature ranges are close to the acceptable thresholds for the PHFT (18 ºC – 26 ºC), indicating that no extreme conditions are reported for this case. However, when moving to a light envelope (WLU-RLI), some indicators show that the building is often cold. This can be seen through the increased number of degree hours below 18 ºC, followed by the quantification of heating loads to meet desirable conditions. This effect can be noted especially in the bedrooms, which are occupied during the night, possibly because the light and mostly uninsulated envelope cannot store enough heat and loses it to the colder outdoor environment. Thus, operative temperature in the bedroom can drop as low as 12.1 ºC (Tomin). One aspect to highlight is that, even though some KPIs have a component to address thermal discomfort associated with cold, the main focus herein is overheating because it tends to be the primary concern in the context being analyzed. For instance, the PHHI' cannot capture the occurrence of cold since anything below 26.7 °C is considered "*safe*," according to the heat index ranges. Nevertheless, a similar evaluation would be possible in cold climates with the adaptation of some of the KPIs.

In the mild climate of Florianopolis, all three selected envelopes obtained relatively good thermal performance, with some key differences. On comparing the average PHFT calculated for each envelope, WLU-RLI obtained the highest value with 81% of occupied hours with operative temperatures between 18 ºC and 26 ºC. Ref and HI obtained corresponding values of 73% and 79%, respectively. However, when looking at extreme conditions, Ref and WLU-RLI obtained considerably higher annual maximum and lower annual minimum operative temperatures (Tomax and Tomin, respectively). This can also be observed for the percentage of occupied hours above the upper limit temperature (PHT_{upp}), with these envelopes presenting between 4 and 5% of occupied hours with operative temperatures 4 K above the superior threshold of 26 ºC, considering the worst condition of the indoor spaces. PHT_{upp} for HI was negligible, that is, even when outside acceptable thresholds, the operative temperatures are rarely higher than 30 ºC. On the other hand, once an annual maximum operative temperature of 30 ºC was reached in the living room of HI, it took 269 hours (11.2 days) (t_R) to recover and reach 26 ºC again. In contrast, Ref and WLU-RLI recovered much faster from even higher temperatures. Ref recovered from 32.7 ºC in 2.4 days and WLU-RLI from 34.2 ºC in 1.3 days.

The climate in São Luís is classified as 0A by ASHRAE 169 (ASHRAE, 2020b), being considerably more severe with respect to heat than Curitiba and Florianopolis. Heavy envelopes (e.g., Ref and HI) in this climate do not usually perform well because the outdoor temperature is constantly high and heat tends to be stored in the envelope with few opportunities to dissipate. On the other hand, a light and almost uninsulated envelope (WLU-RLI) may not provide enough resistance against the severity of outdoor thermal conditions. In all cases, the thermal performance of the living room was low in São Luís, with none to very few moments (maximum PHFT equal to 10%) with operative temperatures within the threshold for São Luís (below 28 ºC). Even though some KPIs indicated very similar performance results for the living room in Ref and HI (PHFT equal to zero and similar PHHI'), it can be observed that the intensity of thermal discomfort was not the same. For instance, Ref was worse than HI by 1,597 ºC.hours, which is also reflected by a considerably higher proportion of time during which the room is exposed to operative temperatures above 32 ºC (39% of the time for Ref versus 12% for HI). If these overheating periods were to be distributed in occupied hours throughout the year (IOD), the living room would always be around 2.23 ºC to 3.19 ºC above the threshold. However, considering that the Ambient Warmness Degree (AWD) for São Luís is equal to 7.97 ºC for a base temperature of 18 ºC, which indicates the severity of outdoor warmness (HAMDY et al., 2017), it can be considered that all envelopes are capable of suppressing some of the outdoor thermal stress ($\alpha_{IOD} < 1$). Additionally, considering all three envelope alternatives, the living room would require at least 121 kWh/m² of thermal load to be removed annually if an air conditioning system were installed.

*CgTA and heating degree hours are given as negative values to improve visibility

Fig. 6 - Comparison between key performance indicators calculated for the reference model and two envelope alternatives

Results obtained for WLU-RLI in São Luís could be misleading depending on the indicators adopted and the calculation procedure used to aggregate results at the building level. The bedrooms are only occupied after 22:00, allowing a light envelope to dissipate heat. This is reflected by a high PHFT value (66% - 77%) for this room. The living room, which is occupied during the day, does not follow this pattern and has a PHFT of only 10%. At the building level, however, the average performance is generally of interest, for which a high value of 51% was obtained. In this context, the observation of multiple indicators can be of value to fill in the gaps and provide a comprehensive evaluation. Even with a high average PHFT value, indicating good resistance to hazardous temperatures, stress conditions should also be verified. In this regard, a PHT_{upp} value of 28% would be obtained, indicating that more than a quarter of the hours occupied in the worst-performing room would be extremely uncomfortable. In fact, if the heat index was adopted to describe the indoor thermal conditions, 7% of occupied hours in the living room would be considered dangerous to the occupants' health. On the other hand, even when the operative temperature in the living room reaches 36.4 ºC (maximum value for all spaces), the light envelope only takes 10 hours to recover and reach the threshold again. This contrasts with the minimum of 265 hours (11 days) required by heavy envelopes in the same climate. However, it can be observed that the bedroom takes longer to recover from a lower maximum temperature (84 hours).

3.3. MAIN FINDINGS

Some KPIs can be selected to enhance the thermal performance analysis, translating into thermal resilience. The following indicators were considered suitable:

- **PHFT:** to describe the frequency in which buildings are able to sustain indoor thermal conditions within minimum thresholds without the assistance of active cooling systems (i.e., air-conditioning). For the following sections of this document, this indicator will be addressed as "**thermal autonomy**" (TA) to align its use with the international literature.
- **Indoor overheating degree (IOD)** (HAMDY et al., 2017): to measure the severity that thermal conditions surpass minimum thresholds. Alternatively, degree-hours could be selected as a measure of intensity, but the significance of the magnitude of the values (i.e., which values are good and which are not) may be unclear to those unfamiliar with this indicator.

- **Cooling load:** to provide a measure of depletion of energy resources related to overheating. Alternatively, energy consumption for cooling can be adopted to capture the efficiency of building technical systems.
- **Percentage of occupied hours above the upper limit temperature (PHT_{upp}):** to account for the frequency of extreme indoor thermal conditions. For the following sections of this document, this indicator will be addressed as "**thermal vulnerability**" (TV).
- **Annual maximum operative temperature (Tomax):** to account for the intensity of uncomfortable conditions. For the following sections of this document, this indicator will be addressed as "**maximum temperature**" (Tmax) to allow flexibility for using other parameters to describe the indoor thermal environment besides operative temperature (e.g., SET).
- **Recovery time (t_R):** to estimate how long it takes to recover from the maximum temperature.

The PHFT could also be calculated using the "safe" range of the heat index. In fact, even though most of the indicators analyzed herein consider the operative temperature as the main input, the same procedure could be applied to indicators based on other parameters that describe indoor conditions, such as the heat index (NOAA, 2022), humidex (CCOHS, 2019; MASTERTON; RICHARDSON, 1979) and SET (ASHRAE, 2020a). Also, the adaptive thermal comfort model could be adopted, with a variable thermal comfort range based on outdoor air temperature (ASHRAE, 2020a; CIBSE, 2013).

4. PROPOSING A THERMAL RESILIENCE FRAMEWORK (PAPER 2)

This section summarizes the study reported in the article "*A simulation framework for assessing thermally resilient buildings and communities*," published in Building and Environment with DOI 10.1016/j.buildenv.2023.110887.

4.1. METHOD

4.1.1. Description of the framework

Fig. 7 and Fig. 8 illustrate the proposed thermal resilience simulation framework, starting from the building diagnosis (Fig. 7) and aggregating it to the urban buildings' diagnosis (Fig. 8). The building diagnosis is divided into the stages of resilience defined by Attia et al. (2021), namely: resistance, robustness, and recovery (see Section 2.1). The building' performance should be assessed based on KPIs suitable for each stage. In the resistance stage, KPIs will be based on maintaining minimum thermal conditions, while the robustness stage requires KPIs based on surpassing critical thermal conditions. In turn, the recovery stage is based on moving from critical conditions and reaching minimum thermal conditions again. Considering the capacity of occupants to adapt themselves and their buildings in multiple forms—not necessarily the same (non-equilibrium states)— that will allow them to endure adversities, we consider this approach to fit within the third viewpoint on resilience, evolutionary resilience (see Section 2.1).

Considering the results described in Section 3, the resistance stage could be measured through three indicators: (1) **thermal autonomy**; (2) **indoor overheating degree (IOD)** (HAMDY et al., 2017); and (3) **cooling load**. For the robustness stage, two indicators are suggested: (1) **thermal vulnerability (TV)**; and the (2) **maximum temperature (Tmax)**. To account for the recovery stage, the **recovery time (t_R)** could be adopted to estimate the time taken to recover from a maximum temperature (i.e., Tmax) until reaching minimum thresholds again. In this way, the recovery time (t_R)—which is an indicator of duration—would complement the maximum temperature. Such combination provides a better understanding of continuous exposure to extreme thermal conditions. Table 9 describes each KPI in detail, which represents the selected indicators among those first introduced in Table 6.

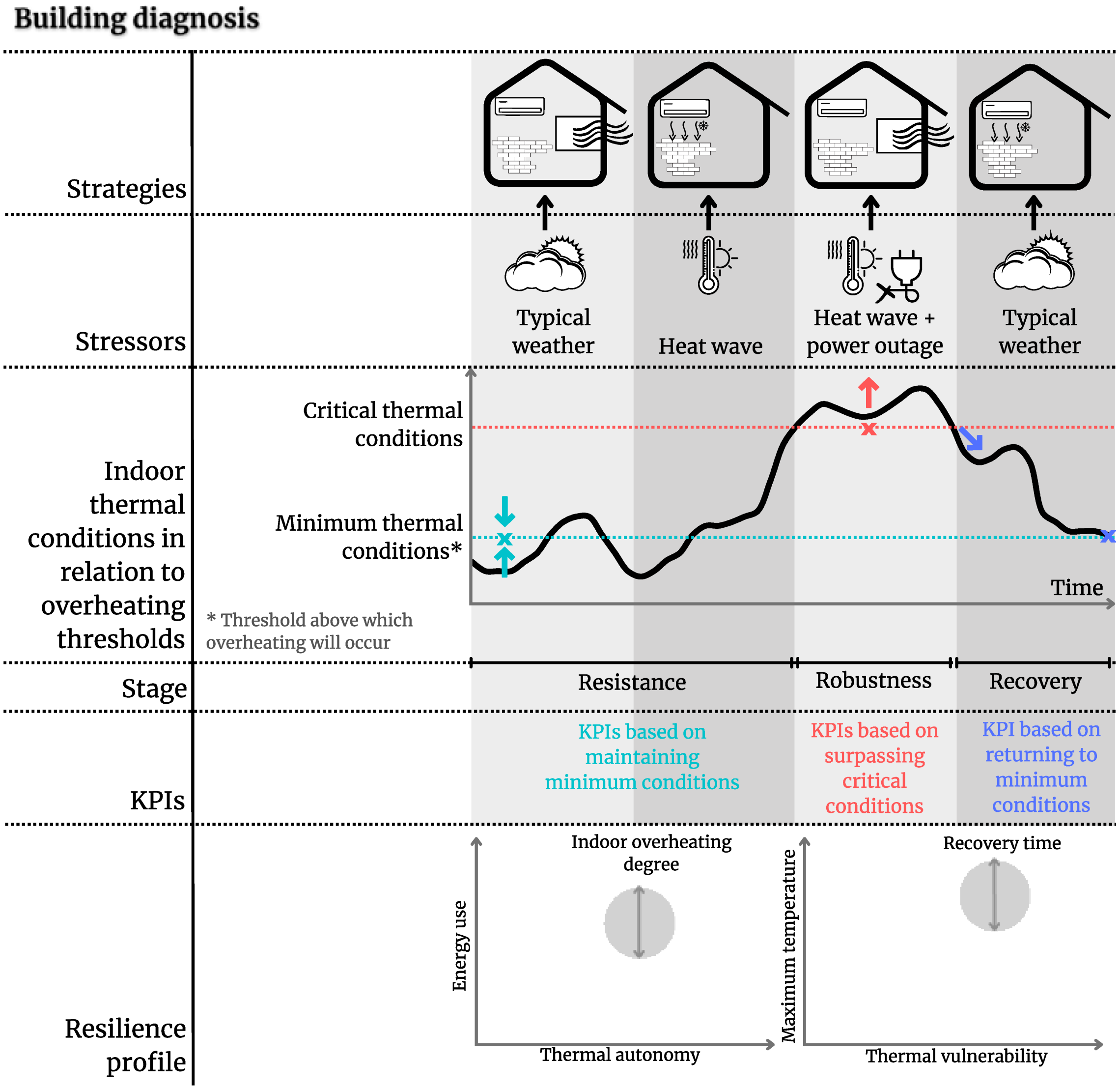


Fig. 7 - Thermal resilience simulation framework for single buildings

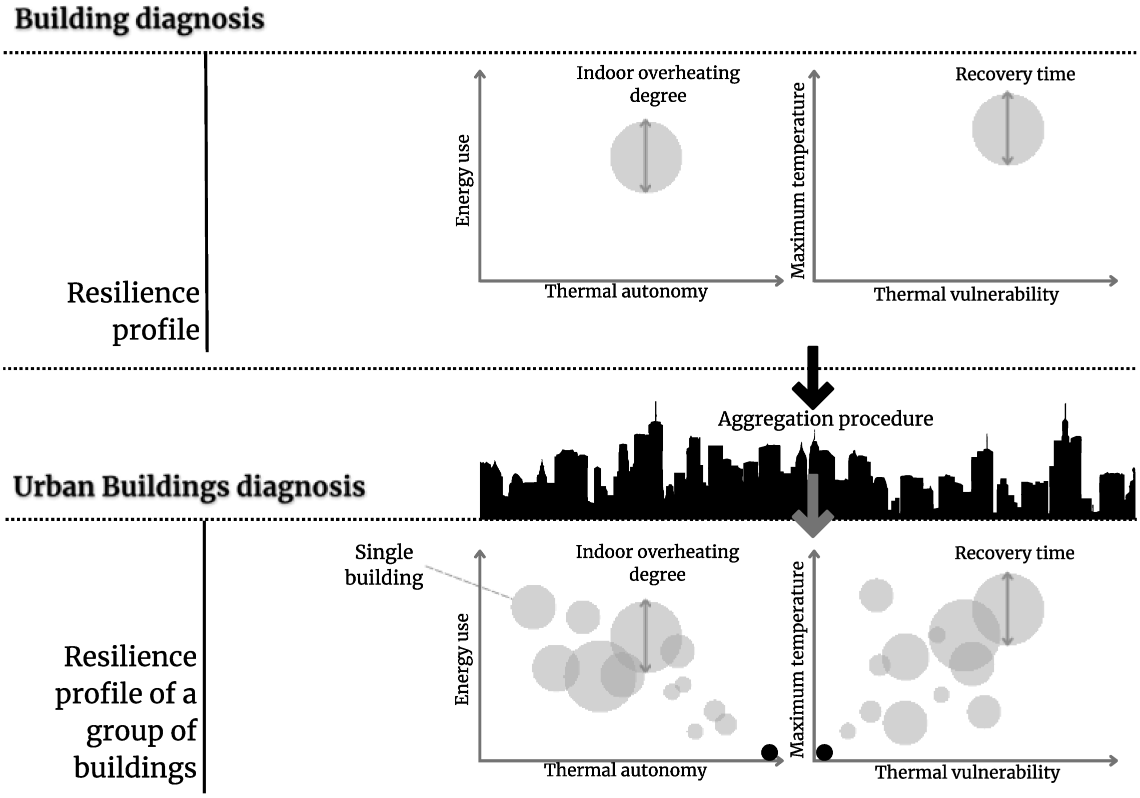


Fig. 8 - Thermal resilience simulation framework for groups of buildings

The urban buildings' diagnosis is based on translating the data collected during several individual building diagnoses into meaningful information regarding whether a certain group of buildings is bound to resist or face disruption. This final diagnosis should be detailed enough to portray aspects of strength and frailty within the group in a way that enhances learning capacity and preparedness.

A resilience profile is proposed to gather all the information from every single building, predefined KPI, and resilience stage. Fig. 7 (building scale) and Fig. 8 (urban scale) exemplify this profile, which is designed as two bubble plots separated between the resistance stage (left) and the robustness and recovery stages (right). These plots are derived from a scatter plot where the relationship between two of the indicators on axis *x* and *y* is shown, while a third dimension is considered by scaling the size of each point according to another indicator. In the resistance stage, better performing cases would have the smallest bubble located in the lower-right corner. In the robustness and recoverability stages, it would be better to be in the lower-left corner, with a smaller bubble size. Examples of ideal results are marked with black bubbles in Fig. 8. This type of profile should allow a quick comparison between multiple buildings, comprising up to six indicators.

Table 9 - Key performance indicators suggested to assess thermal resilience in each stage

KPI	Equation or calculation procedure	Stage of resilience
Thermal autonomy (TA) [%]	**For a single zone:** $\mathrm{TA} = \frac{N_{occ;range}}{N_{occ;tot}}.100$ *Where: $N_{occ;tot}$ is the total number of hours a room is occupied throughout the year; $N_{occ;range}$ is the total number of hours a room is occupied throughout the year with operative temperature within a minimum range of thermal conditions without the assistance of active cooling systems* **For multi-zones:** average value between all zones	Resistance
Indoor overheating degree (IOD) [ºC] (HAMDY et al., 2017)	**For single zone or multi-zones:** $\mathrm{IOD} \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z}-TL_{comf,i,z}\right)^{+}\times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}}$ *Where: z: building zone counter; Z: total number of zones in a building; i: occupied hour counter; t: time step (1 h); $N_{occ(z)}$: total occupied hours in a given calculation period; T_{fr}: free-running indoor operative temperature at the time step i in zone z; TL_{comf}: comfort temperature limits at the time step i in zone z*	Resistance
Cooling load* [kWh/m²]	**For a single zone:** Quantity of heat that must be removed from a space to maintain setpoint. Measured in thermal energy. *Can be replaced by energy use, considering the summation of the zone's annual HVAC electricity consumption. **For multi-zones:** summation of values of all zones divided by the building floor area or by the conditioned floor area	Resistance
Thermal vulnerability (TV) [%]	**For a single zone:** Proportion of occupied hours with operative temperature above the upper limit temperature (T_{upp}) (CIBSE, 2013) (i.e., critical threshold), which is 4 ºC above the minimum threshold **For multi-zones:** highest value between all zones	Robustness
Maximum temperature (Tmax) [ºC]	**For a single zone:** $\mathrm{Tmax} = \max(T_{occ;n})$ *Where: $T_{occ;n}$ is the hourly operative temperature when the room is occupied at hour "n"* **For multi-zones:** highest value between all zones	Robustness
Recovery time (t_R) [h]	**For a single zone:** Amount of time between the moment of maximum annual operative temperature (Tmax) and the time when the space reaches an acceptable operative temperature threshold **For multi-zones:** amount of time the zone with highest Tmax takes to recover	Recovery

It is recommended to use this framework considering whole-year scenarios; that is, running simulations through the course of a year to account for seasonal variability. Stressors can be applied in different periods of the year and with increasing intensities, creating scenarios that test resilience. The framework nonetheless is flexible to be applied in shorter time frames during specific events. For instance, it could be applied in the time frame of the most severe, longest, or most intense heat wave (OUZEAU et al., 2016), based on historical or future weather scenarios, possibly coupled with a power outage.

4.1.2. Mapping populations based on thermal resilience profiles

After gaining an overall understanding of how buildings perform, a mapping procedure is proposed to identify populations with similar resilience profiles as well as building samples that represent these populations. Such an approach is conducted through a cluster analysis based on the key performance indicators previously selected. Evaluating the performances of tens or hundreds of buildings, each one of them with multiple key performance indicators, would be unpractical. Thus, this procedure aims to display some actual buildings that are representative of a group of buildings as a way to materialize the tendencies and distributions explored through the resilience profiles.

The cluster analysis is a multivariable analysis technique with the objective of grouping objects in the same class or cluster, so that the same cluster displays very similar characteristics (high internal homogeneity), while objects from different clusters display low similarity (high external heterogeneity) (ARAMBULA LARA et al., 2015; HAIR et al., 2013). A non-hierarchical method was applied in this study, considering the k-medoids clustering method to select representative cases. The Euclidean distance was adopted as the similarity measure, which is a well-known and common measure for clustering (JAIN; MURTY; FLYNN, 1999; SHIRKHORSHIDI; AGHABOZORGI; WAH, 2015). The representative building, also known as medoid, is the most centrally located case in the cluster. Considering that indicators have different measurement units, they were rescaled before clustering. The standardization method was applied; it rescales data to have a mean equal to 0 and a standard deviation equal to 1. This analysis was developed using the R software (R CORE TEAM, 2020) with R-Studio interface (RSTUDIO TEAM, 2021) and the package “cluster” (MAECHLER et al., 2022).

4.1.3. Illustrative case study

The framework was applied to a group of detached single-family residential buildings, considering the same representative design for low-income houses (TRIANA; LAMBERTS; SASSI, 2015) adopted in Paper 1 (see Section 3.1.1). The group of buildings was created through the variation of building components of the envelope to create 448 unique cases. These cases are the result of a parametric combination of 14 different compositions of exterior walls, 2 interior walls, and 16 different roofs. The thermal properties of each component are shown in Fig. 9. There are two reasons to take this approach. The first is to provide the same boundary conditions, to allow comparisons of the effect of the envelope over thermal resilience and to verify if the building diagnosis is reasonably describing resilience and its different stages within a controlled experiment. Second, even with fixed boundary conditions, the variability of results obtained from changing building components was considered sufficient to conduct the illustrative example intended herein.

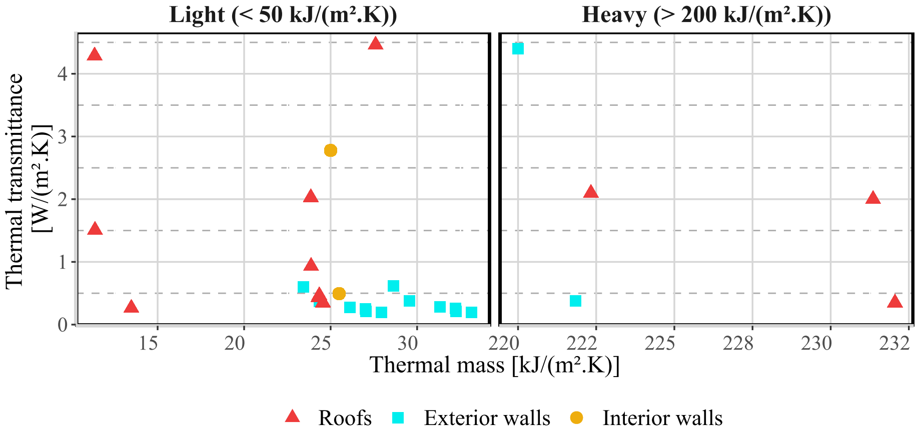


Fig. 9 - Thermal properties of the building components

Again, Curitiba, Florianópolis, and São Luís are the cities considered in this study. Calculation of indicators followed the same procedure adopted in Section 3 (Paper 1), including the acceptable thresholds for indoor thermal conditions, and also adopting the same modeling approach based on NBR 15575.

Whole-year simulations were run for each case, considering TMYs obtained through NBR 15575-1-1 (ABNT, 2021b). The results obtained herein should verify the thermal resilience of buildings under typical conditions, thus providing a baseline to compare results if included other stressors. Nevertheless, if one adopts an XMY (CRAWLEY; LAWRIE, 2015, 2019), a weather file with a heat wave or with prospected future climate conditions, the same procedure would be followed.

4.2. RESULTS

In this analysis, indicators described in Table 9 were calculated for every single building in three different climates. However, for conciseness, results for São Luís were included in this section as an example of how the resilience profiles are analyzed. The procedure of mapping different populations was also included to demonstrate how to identify vulnerabilities and facilitate decision-making in the context of communities. The reader is referred to the Appendix B for the results of the other cities, Florianópolis and Curitiba. Nonetheless, the application of the framework is further discussed in Section 5 through a case study with real buildings in Florianópolis, Brazil.

Fig. 10 shows the thermal resilience profile for São Luís, highlighting the results of the representative buildings of each cluster. Buildings within the same population have the same color adopted for their representative case. Different numbers of clusters were tested until finding the minimum quantity that would appropriately describe the results. Five clusters were considered suitable. A low number of cases is preferred to facilitate the analysis and decision-making. However, the ideal number of clusters may differ depending on the intended application and community analyzed.

Marked in purple, Fig. 10 shows the cluster of buildings with the best performances in the resistance stage, being closer to the lower right corner of the graph. By looking at its representative, it can be said that it is common for a building within this population to have a thermal autonomy of about 50% and require to remove 145 kWh/m^2.year of cooling loads when natural ventilation cannot provide minimum thermal conditions. However, this group faces disruptive conditions over 25% of the occupied hours of the worst performing room, which happens when operative temperatures surpass the threshold for critical thermal conditions (i.e., 32 ºC in São Luís). Regardless of the intensity of extreme indoor conditions, the buildings are able to recover in a short period of time, requiring about nine hours to reach the minimum threshold.

The cluster colored in yellow stands out for reaching the most extreme indoor thermal conditions, with its representative having a Tmax equal to 42.4 ºC, while temperatures above 32 ºC happen 38% of the time (TV) in at least one room. Even though buildings from the cluster colored in red most commonly have lower Tmax than those from the yellow cluster, extreme thermal conditions happen more often and last longer. Considering that their thermal autonomy is close to zero, buildings rely heavily on air conditioning and may face disruptive conditions for entire weeks or months when it is not available. Thus, it is valuable for researchers, utilities, and policy makers to be aware of this low performance within an urban context as they consider suitable solutions tailored to a disadvantaged population.

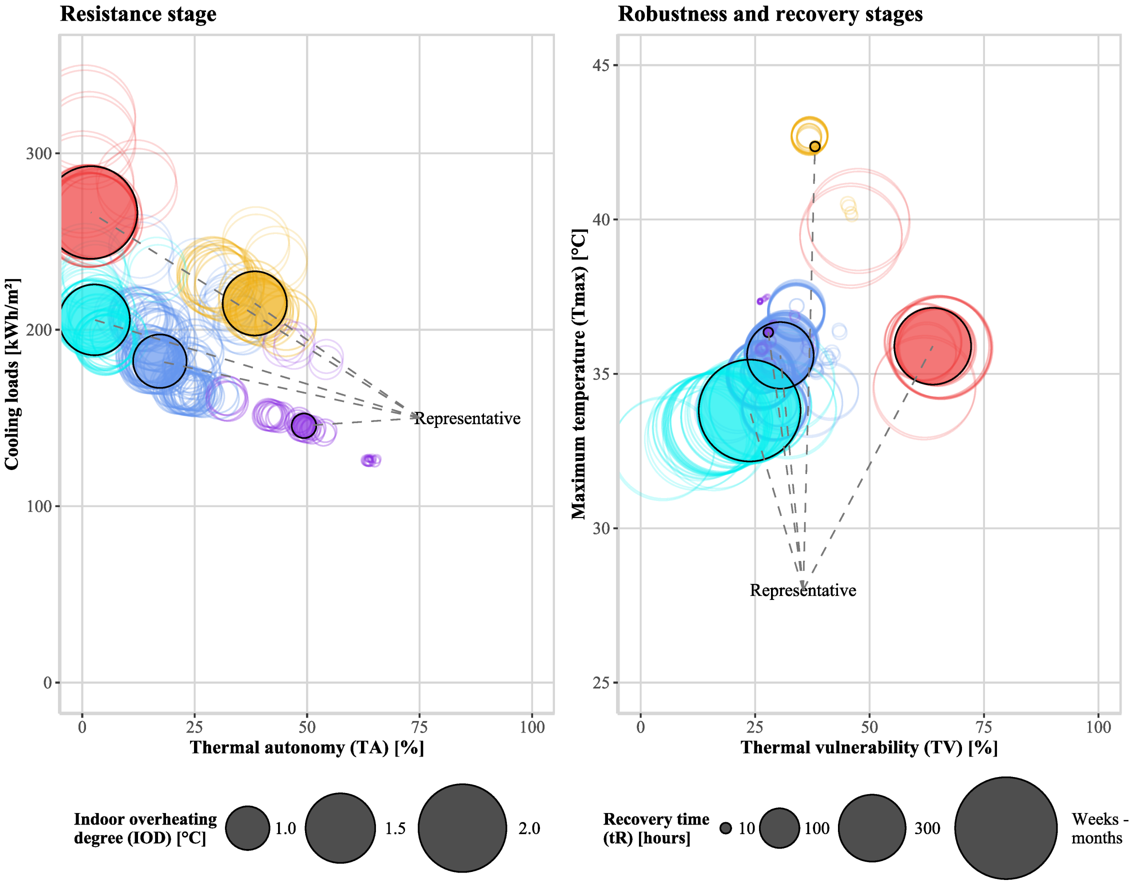


Fig. 10 - Thermal resilience profile with representative cases for São Luís

4.3. MAIN FINDINGS

Even though this analysis has been applied with a focus on free-running residential buildings, the same procedure could be applied to other building types and operation strategies, and be only impacted by the distribution of bubbles in the resilience profile. For example, an office building could be fully air-conditioned, therefore having no thermal autonomy.

Several stakeholders could benefit from adopting the proposed framework. During the design phase, the framework can be applied by design teams and building technology experts to prescribe adequate design features and strategies to endure all possible foreseeable stressors, beginning with average weather conditions, and also encompassing extreme and future weather and energy availability constraints. The resilience profile could also be used to better visualize the performance of different design strategies to find an optimal solution.

Translating the results obtained by the application of this framework to other audiences would involve adapting the key performance indicators depending on the stakeholder. Thresholds could be adjusted considering vulnerable populations; for instance, the elderly, children, and people with psychiatric, cardiovascular, and pulmonary illnesses (WHO, 2018), as well as those with reduced mobility. Insurance companies could use metrics such as heat-related mortality (ALAM et al., 2016), which could be determined through correlations with the indicators adopted in this study (e.g., using the intensity, duration, and frequency of exposure to high temperatures, that is, Tmax, t_R, and TV). Other existing public data such as building age, energy label, census data, and socioeconomic indicators could be used to support these correlations (TERÉS-ZUBIAGA et al., 2023). Commissioning providers and building owners could be better informed to provide training plans, system manuals, and maintenance programs to help occupants prepare and respond to disruptive events.

At the urban level, the framework should enable users to diagnose resilience at the current state and project the effect of policies and regulations on the performance of urban buildings when exposed to present and future threats, covering all stages of resilience. By contrast, first responders would be less interested in buildings during a resistance stage, but more so when a failure occurs, which characterizes the robustness and recovery stages. Vulnerability maps and emergency protocols could be developed through the application of the framework, indicating populations likely to require assistance when exposed to certain scenarios (e.g., heat waves with power outages). In this context, researchers should bridge the gap between the simulation-based method described in this study and other formats suitable for different stakeholders' needs.

Considering the effectiveness of the framework verified in this simplified case study, the next step of the analysis was to test it in a real group of buildings with larger variability and more complex operations. Also, it was important to evaluate the results using multiple scenarios to comprehensively assess resilience. This was addressed in Section 5 (Paper 3).

5. APPLICATION OF THE FRAMEWORK (PAPER 3)

This section summarizes the study to be reported in the article "*Defining weather scenarios for simulation-based assessment of thermal resilience of buildings and communities in Brazil under current and future climates: A case study*," This article will be submitted to a high-impact journal by November/December 2023.

5.1. METHOD

The thermal resiliency of buildings was investigated through a case study composed of real buildings located in Florianopolis, Brazil. In the context of this document, this group of buildings is addressed as a community.

The community was analyzed under two conditions: the baseline condition and the optimized condition. The latter was developed through the application of multiple strategies to improve its thermal resiliency. Both community conditions were then evaluated under multiple weather scenarios. Fig. 11 summarizes the method, which is further described from Section 5.1.1 to 5.1.4.

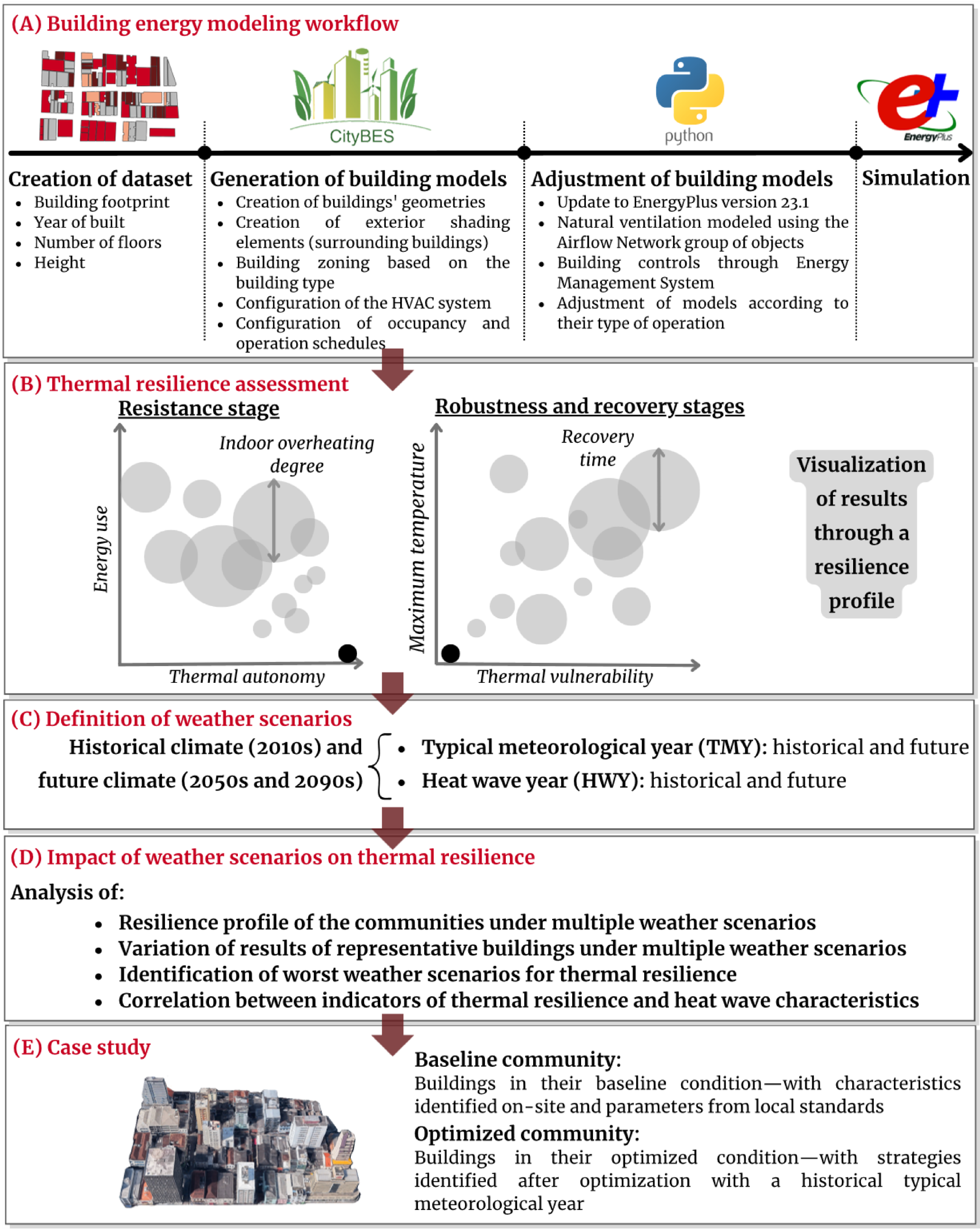


Fig. 11 - Method summary for Paper 3

5.1.1. Building energy modeling workflow and thermal resilience assessment

A dataset was created containing information about each building—number of floors, height, year of construction, and the building footprint—and inputted into the web-based platform CityBES (HONG et al., 2016). CityBES was used to generate the first version of the building baseline models, which can be downloaded through the platform as an input data file (.idf) for EnergyPlus. Each building has its own input file where surfaces of buildings in the proximity are modeled as shading elements. A Python code was developed to further adjust the building models to better represent the characteristics of buildings in Brazil. These adjustments followed the workflow shown in Fig. 11 (A).

The thermal resilience assessment followed the framework described in Paper 2 and summarized in Section 4, which proposes the creation of resilience profiles for buildings and communities composed of a set of comprehensive KPIs. See the illustration in Fig. 11 (B). KPIs are described in Table 9. In this section, energy consumption for cooling was considered instead of cooling loads, thus being measured in electricity and not thermal energy.

Also differently from Sections 3 and 4, the Standard Effective Temperature (SET) (ASHRAE, 2020a) was adopted as the parameter to describe the indoor thermal environment and used to calculate the KPIs. It is an equivalent temperature that hypothesizes a standard environment combining multi-factor effects to reflect the physiological regulation mechanism of the human body and the heat exchange with the environment (JI et al., 2022). Besides being a comprehensive parameter to describe the indoor environment, it is especially useful within this study for taking into account the cooling effect provided by elevated airspeed. The SET has long been included in ASHRAE 55 (ASHRAE, 2020a) and is also considered in the Leadership in Energy and Environmental Design (LEED) v4.1 Credit for "*Passive Survivability and Backup Power During Disruptions*", which defines livable conditions with an SET between 12.2 ºC and 30 ºC (USGBC, 2023). These thresholds were also adopted in this section. Values between these thresholds were considered to calculate thermal autonomy (TA), while thermal vulnerability (TV) considered periods with SET surpassing 30 ºC.

5.1.2. Definition of weather scenarios

The evaluation of weather scenarios consists of simulating the baseline community and the optimized community under multiple weather conditions, encompassing typical historical and projected future climates, and historical and projected future heat waves.

5.1.2.1.Historical and future climates

Historical and future weather files, in .epw format, were developed based on a method structured by the Weather Data Task Group, which is part of the IEA EBC Annex 80—Resilient Cooling of Buildings. Three time frames were considered—historical (2001-2020), medium-term future (2041-2060), and long-term future (2081-2100)—, the latter two projected considering the representative concentration pathway (RCP) 8.5 (highest baseline emissions scenario) (IPCC, 2013).

The approach consists of using regional climate models (RCM), which are climate models obtained from Global Climate Models (GCM) after a dynamic downscaling to improve spatial resolution (10 to 50 km) (MACHARD et al., 2020). RCMs were obtained from the Coordinated Regional Downscaling Experiment (CORDEX) database, where worldwide multi-year projections are available for RCP 4.5 and 8.5 (MACHARD et al., 2020).

A step-by-step procedure to create historical and future weather files is described in Machard et al. (2020), and can be summarized in four main steps: (1) collection of hourly historical data from a local weather station; (2) extraction and interpolation of CORDEX data; (3) bias-adjustment of CORDEX data using measured data; (4) creation of typical meteorological years following EN ISO 15927-4:2005 (ISO, 2005b) or Heat Wave Years (HWY) (see Section 5.1.2.2 below).

5.1.2.2.Heat waves

Scenarios that consider heat waves were simulated with weather files of specific years when heat waves have been detected. These heat wave years were selected among those generated after bias-adjustment, considering historical, medium-term future, and long-term future periods.

The screening process to identify heat wave years followed the method proposed by Ouzeau et al. (2016). Detection is made by analyzing daily mean temperatures from a given period (i.e., historical or future) in comparison with three temperature thresholds: Spic, Sdeb and Sint. These thresholds represent percentiles equal to 99,5 %, 97,5 %, and 95 % of the daily temperature distribution over the evaluated period, respectively. Detection and delimitation of a heat wave consider, according to Ouzeau et al. (2016):

- A heat wave is detected when temperature reaches the Spic threshold;

- The beginning of this event is considered from the moment temperature crosses the Sdeb threshold;
- The end is marked by temperature staying below Sdeb for at least three consecutive days, or once temperature falls below the Sint threshold.

After detection, heat waves can be characterized by three values: duration (number of days); maximum mean temperature during the event; and global intensity (i.e., severity of the event). The latter is defined by the cumulative difference between daily mean temperature and the Sdeb threshold, divided by the difference between Spic and Sdeb (OUZEAU et al., 2016). These indicators were used to select three years among each period (historical or future periods) where can be found: (1) the **most intense heat wave**, with the highest maximum mean temperature; (2) the **most severe heat wave**, with the highest global intensity; and (3) the **longest heat wave**, with the highest duration. In the end, up to nine heat wave years can be developed, considering three periods and three heat wave types. It is possible, however, that the same heat wave is the most intense and severe, for example, which would lead to fewer heat wave years being generated. Apart from Ouzeau et al. (2016), Machard et al. (2020), and Flores-Larsen, Bre and Hongn (2022), who put this procedure into practice, it was also adopted in Annex 80 Weather Data Task Group to generate historical and future heat wave years.

5.1.3. Impact of weather scenarios on thermal resilience

The impact of weather scenarios on the thermal resilience of buildings was analyzed through a combination of procedures:

- *Resilience profiles:* the resilience profile aggregates all six KPIs from Table 9, divided into two sides related to the resilience stages, as described in Section 4.
- *Variation of results across weather scenarios:* change in results due to a weather scenario in relation to Scenario 1 (historical TMY). With respect to energy consumption, values correspond to a percentage change, whereas all other KPIs were analyzed through the absolute difference (result in a certain Scenario minus result in Scenario 1).
- *Analysis of worst weather scenarios for thermal resilience:* It consists of analyzing the Pareto-optimal front (WANG; RANGAIAH, 2017), however, “optimal” corresponds to the worst results with respect to all indicators. This procedure was repeated for each subset of building type and operation type (i.e., air-conditioned, naturally ventilated, or hybrid). It should be highlighted that the Pareto front might indicate multiple scenarios

that are equally leading to the worst performance but due to different indicators. This analysis was developed using the R software (R CORE TEAM, 2020) with R-Studio (RSTUDIO TEAM, 2021) interface and the package "*rPref*" (BORZSONY; KOSSMANN; STOCKER, 2001; KIESSLING, 2002; ROOCKS, 2016).

- *Correlation between heat wave characteristics and thermal resilience indicators:* calculation of the strength of association between two variables as well as the direction of the relationship. The Spearman rank correlation test was adopted for not carrying any assumptions about the distribution of the data. Results vary between -1 (strong correlation with negative relationship) and +1 (strong correlation with positive relationship). See 5.1.2.2 for heat wave characteristics: duration (number of days), intensity (maximum mean temperature), and severity (global intensity).

5.1.4. Case study and modeling approaches

The case study is composed of a group of 92 buildings located in the downtown area of Florianopolis, Brazil. The downtown area was selected for containing different building types and also because they are mostly older compared to the rest of the buildings in the city, already requiring retrofitting. Buildings are further described in Fig. 12, being divided between four building types: office, residential, restaurant, and retail. These data were directly provided by the city hall of Florianopolis.

A field survey was also conducted to validate and complement the data provided by the city hall. Every single building has been verified during this survey conducted in July 2022. The main information obtained during this survey was the mode of operation in terms of controlling the indoor air temperature. Three options were considered: fully air-conditioned buildings (AC), naturally ventilated buildings (NV), and hybrid buildings (natural ventilation and air-conditioning being used interchangeably).

Two simplifications during the development of the case study should be highlighted: (1) all rooms inside the same building were considered having the same operation mode; and (2) only one building type was attributed to each building, which constituted the prevalent type between all rooms and floors.

Building envelope characteristics were adopted following local standards: the Inmetro's normative instruction for the energy efficiency classification of commercial, service and public buildings (INI-C) (INMETRO, 2022), and the Brazilian building performance standard, NBR 15575-1:2021 (ABNT, 2021a) for residential buildings. Characteristics are presented in Table

10 and Fig. 13. Occupancy schedules and internal heat gains of residential buildings were adopted as described in NBR 15575-1:2021 (ABNT, 2021a). Commercial buildings have internal heat gains according to INI-C (INMETRO, 2022), and schedules following United States Department of Energy (DOE) prototype models (DOE, 2023).

Air-conditioned and hybrid buildings were equipped with mini-split air conditioners, which is the prevalent device adopted in offices (SCHEIDT; WESTPHAL, 2023) and residential buildings in the region (ELETROBRAS, 2019a). Given the importance of passive building operation in Brazil (BUONOCORE et al., 2023), natural ventilation was represented using the most advanced model available in EnergyPlus, comprised of the *Airflow Network* group of objects. The *Airflow Network* models air changes inside the building according to wind data from the weather file. Detailed controls using EnergyPlus' Energy Management System (EMS) were considered to operate the air conditioning system and windows for natural ventilation. In addition to natural ventilation and/or air-conditioning, fans were also considered as a typical device used to improve thermal comfort in Brazilian buildings. They were included in all residential building models and all naturally ventilated buildings, irrespective of the building type. The effect of fans was considered through an adjustment of the airspeed from 0,2 m/s to 0,9 m/s.

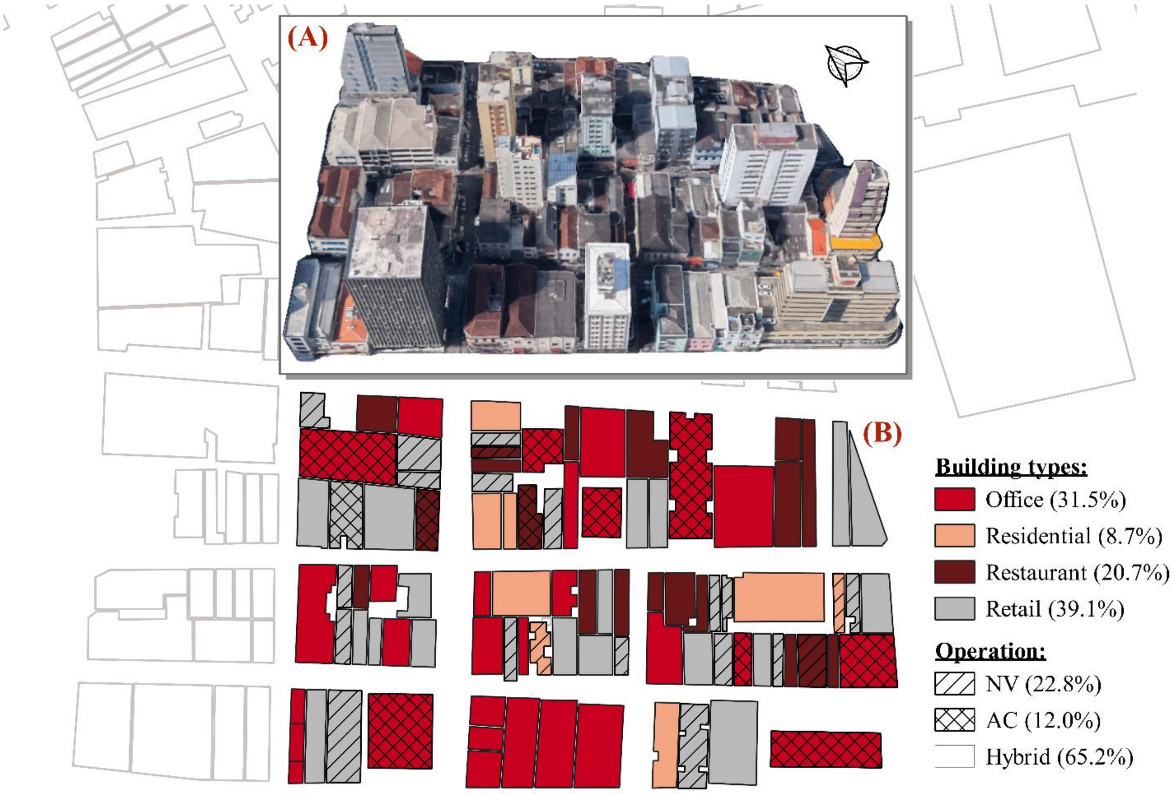


Fig. 12 - Buildings within the case study represented in 3D (A) and as footprints (B), colored and hatched according to the building type and operation

Table 10 - Description of building envelopes in the baseline

	Description	**Thermal transmittance [W/(m².K)]**	**Thermal capacity [kJ/(m².K)]**	**Solar absorptance [dimensionless]**
Exterior walls				
All buildings except for residential	Burnt clay brick masonry and stucco finishing	2.39	150	0.50
Residential buildings	100 mm wall	4.4	220	0.58
Roof				
All buildings except for residential	Concrete slab (100 mm) with a hip roof composed of fiber cement roof tiles	2.06	233	0.80
Residential buildings	Slab (100 mm) with a hip roof composed of 6 mm roof tiles	2.1	228.6	0.65
	Description	**Thermal transmittance [W/(m².K)]**	**Solar heat gain coefficient [dimensionless]**	**Window-to-wall ratio [%]**
Glazing				
Office	Single pane window with clear 6 mm glass	5.7	0.82	50
Retail	Single pane window with clear 6 mm glass	5.7	0.82	20
Restaurant	Single pane window with clear 6 mm glass	5.7	0.82	40
Residential	Single pane window with clear 3 mm glass	5.7	0.87	Variable, equivalent to 17% of the floor area

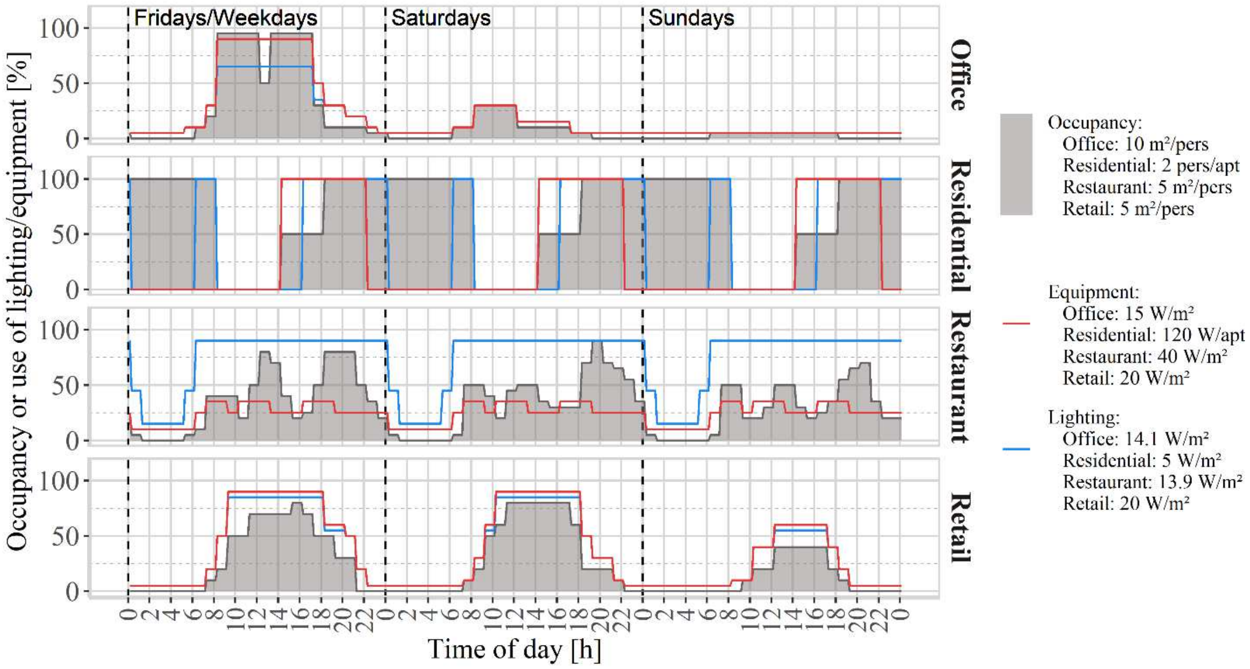


Fig. 13 - Occupancy and operation schedules and internal gains

Detailed control criteria were considered to operate windows and air-conditioners aiming to realistically represent a building's operation dynamics and capacity to respond as this is highly relevant in a thermal resilience analysis. Controls vary with the type of operation:

- *Naturally ventilated buildings:* windows open when the indoor thermal conditions are within the adaptive comfort thresholds from ASHRAE 55 (ASHRAE, 2020a), considering 80% acceptability, and the outdoor environment is simultaneously colder than the indoor environment. Windows close outside these conditions. When buildings are equipped with fans, the upper limit threshold is extended in 1.8 ºC to account for a broader acceptance of operative temperature due to increasing airspeed (ASHRAE, 2020a). Fans are used when the room surpasses the upper limit threshold.
- *Air-conditioned buildings:* windows are always closed and the air-conditioning system is operated during occupied hours to meet a set point equal to 24 ºC.
- *Hybrid buildings:* the same criteria from naturally ventilated buildings apply, but the air-conditioning system is activated once the upper limit of the adaptive comfort thresholds is surpassed. If a fan is available, it is used before turning on the air-conditioning, which is only used if exceeded the extended threshold. To avoid an unrealistic behavior of turning on and off the air-conditioning in a short timeframe, once this system is in use it is only turned off if: the room temperature reached set point and the outside air is colder than the indoor air; or the room becomes unoccupied.

To obtain an optimized design with resilience-oriented solutions, eight strategies were considered as described in Table 11, seven passive strategies and one active strategy. These strategies were applied in representative buildings within the community aiming to define an optimized combination that fosters thermal resilience. One optimized combination of strategies was defined for each building type, which could reflect, for instance, the application of possible new building codes in the region.

A cluster analysis was adopted to identify three representative cases within each building type, aiming to appropriately cover the variability within each type. Twelve representative buildings were defined based on results of all six KPIs in the baseline scenario. Strategies from Table 11 were combined parametrically and assigned to the selected representative cases, resulting in 2,304 models, including the baselines. Building models were simulated considering a historical typical meteorological year (Scenario 1) developed according to Section 5.1.2.1. This analysis was developed using the R software (R CORE TEAM, 2020) with R-Studio (RSTUDIO TEAM, 2021) interface and the package "*cluster*" (MAECHLER et al., 2022).

Table 11 - Strategies for resilient design optimization

Strategy	Description	Application
Cool roofs	Cool roof coating with solar absorptance equal to 0.29	Easy
Cool walls	Cool paint with solar absorptance equal to 0.41	Easy
Advanced glazing	Window film that, installed in a clear glass, results in a SHGC equal to 0.4	Easy
Advanced glazing	Double-pane window	Hard
Solar shading	Overhang 0.5 m deep	Hard
Insulation (roofs)	Thermal insulation under the roof with 2.56 (m².K)/W of thermal resistance	Hard
Insulation (walls)	Exterior insulation finishing with thermal resistance equal to 2.38 (m².K)/W	Hard
Increased window openable area	Replacement of windows with opening factor equal to 90%. Only applied to naturally ventilated and hybrid buildings	Hard
Pre-cooling	Activation of air conditioning 1 hour before occupancy. Only applied to fully air-conditioned buildings	Easy

A multi-objective optimization was performed to identify possible optimal solutions, known as the Pareto-optimal front (WANG; RANGAIAH, 2017). The selection of the final solution for each building type used a tiebreaker, the ease of application of the strategy, described in the right column of Table 11.

5.2. RESULTS

5.2.1. Weather scenarios

In total, nine weather scenarios were generated, three TMYs for the 2010s, 2050s, and 2090s; and six heat wave years (HWYs):

- *Scenario 1 - TMY 2010s:* historical TMY between 2001 and 2020;
- *Scenario 2 - TMY 2050s:* medium-term future TMY between 2041 and 2060;
- *Scenario 3 - TMY 2090s:* long-term future TMY between 2081 and 2100;
- *Scenario 4 - HWY 2010s SL:* year with the most severe (S) and longest (L) heat wave in the historical period;
- *Scenario 5 - HWY 2010s I:* year with the most intense (I) heat wave in the historical period;
- *Scenario 6 - HWY 2050s I:* year with the most intense heat wave in the mid-term future;

- *Scenario 7 - HWY 2050s SL:* year with the most severe and longest heat wave in the mid-term future;
- *Scenario 8 - HWY 2090s SL:* year with the most severe and longest heat wave in the long-term future;
- *Scenario 9 - HWY 2090s I:* year with the most intense heat wave in the long-term future.

Fig. 14 (TMYs) and Fig. 15 (HWYs) show the variation in dry-bulb temperature throughout the year between these meteorological years. All nine years were considered in the next steps of this analysis. Each year received a number from one to nine as shown previously.

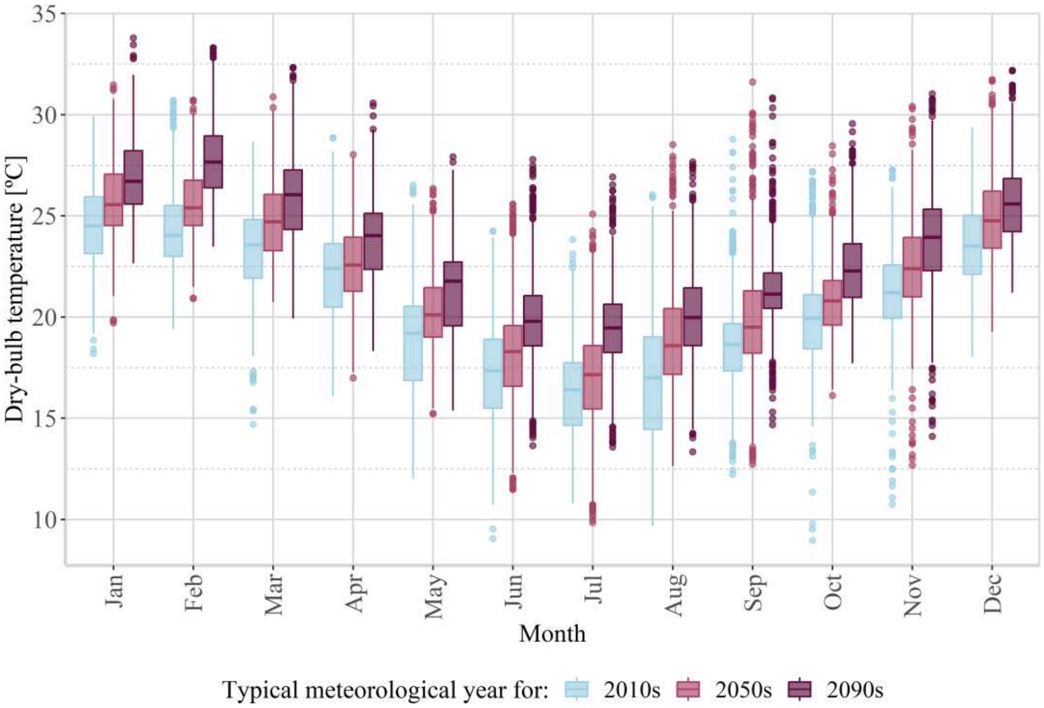


Fig. 14 - Monthly variation in dry-bulb temperature of typical meteorological years for the 2010s, 2050s, and 2090s throughout a year

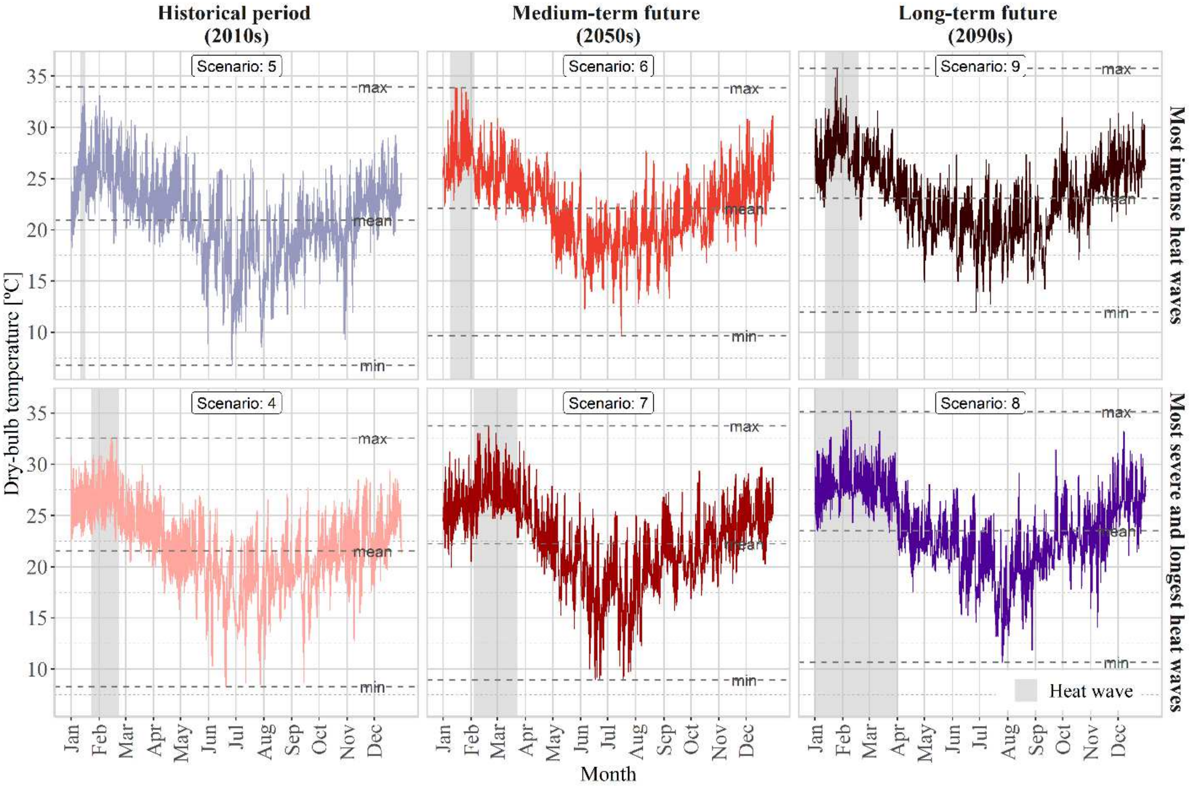


Fig. 15 - Hourly values of dry-bulb temperature of heat wave years in the 2010s, 2050s, and 2090s

5.2.2. Case study – Validation of results

To check the reasonability of the results, simulated whole-building energy consumption was compared with a comprehensive database of measured energy consumption of the Brazilian building stock. This database is explored in Soares Geraldi et al. (2022). It was verified that simulated results fall close to median energy use intensities for the Southern region of Brazil, considering the same building types.

Metered data of the actual buildings was not available for the entire community, with the exception of three buildings that host public institutions subject to the Brazilian Access to Information Law [*Lei de Acesso à Informação, Lei nº 12.527*]. We contacted other institutions within the sample and received data for an additional building, resulting in four buildings, all offices. Two of these buildings were considered fully air-conditioned and two were hybrids. We compared monthly energy consumption between metered and simulated buildings.

Models considered fully air-conditioned showed the biggest differences, indicating that even these large buildings might benefit from natural ventilation more significantly than considered. This highlights the gap previously mentioned in UBEM tools that commonly only represent air-conditioned buildings. These buildings represented only 12% of the group analyzed. Simulated energy use for hybrid buildings showed much closer results compared to metered data, with one building having four months when the difference was between 2% and 7%, and two months varying by 14%. Smaller differences were found in winter months, which corroborates the hypothesis that the correct balance between using air-conditioning and natural ventilation was one of the main influencing factors.

Considering that these are uncalibrated models that adopt standardized schedules and internal loads, as well as simplified zoning methods, we considered the results reasonable to proceed with the analysis.

5.2.3. Case study - Baseline and optimization

Results for the community in the baseline condition under a historical typical meteorological year (Scenario 1) are shown in Fig. 16 through a resilience profile.

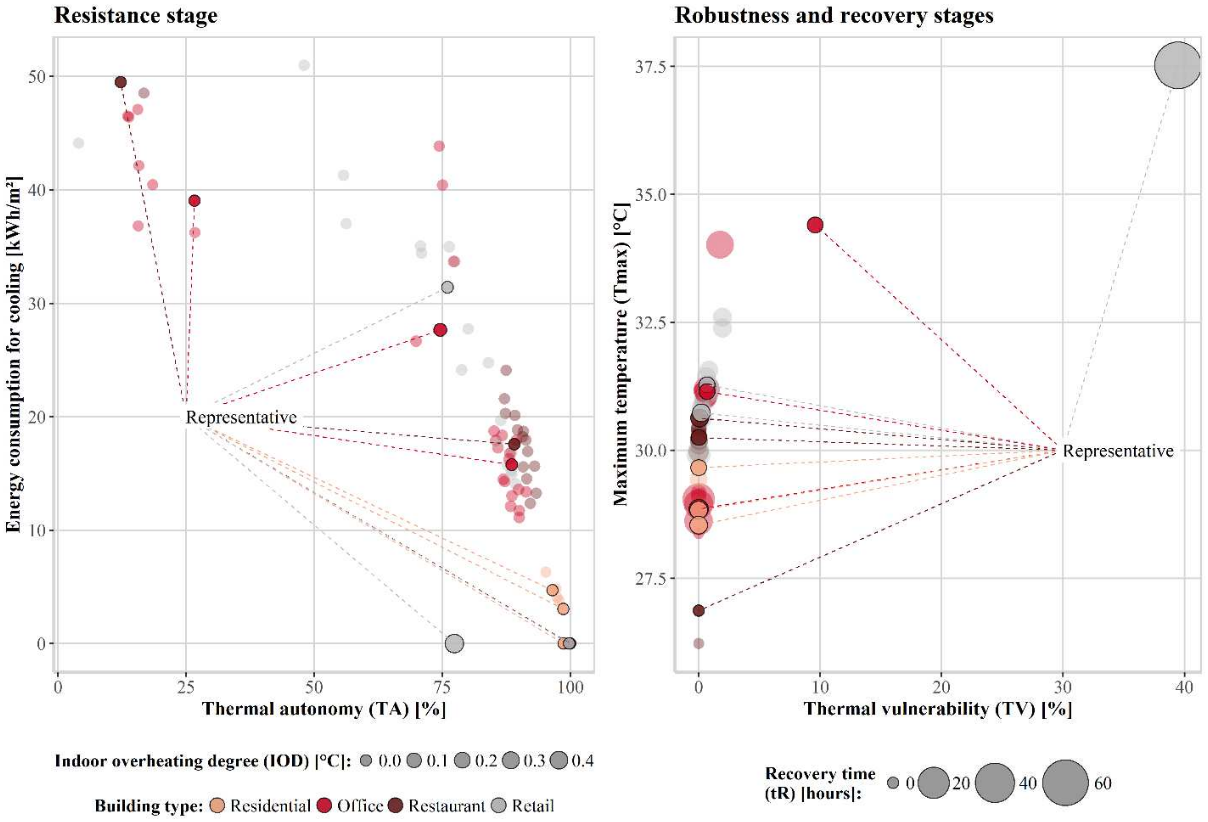


Fig. 16 - Resilience profile of the baseline community under Scenario 1

Thermal autonomy of buildings in this community varied from 4% to 100%, while energy consumption for cooling varied from 0 kWh/m² (mostly naturally ventilated buildings) to about 50 kWh/m². The worst indoor overheating degree (IOD) obtained was equal to 0.48

ºC, which means this building would be constantly surpassing the acceptable thresholds by 0.48 ºC if overheating were distributed throughout all occupied hours, considering all thermal zones. Some extreme conditions can be identified in the robustness and recovery stages, with one retail naturally-ventilated building reaching about 40% of thermal vulnerability. That is, this building has at least one zone that exhibits 40% of occupied hours with SET surpassing 30 ºC. Occupants in this building experience at least 60 continuous hours (2.5 days) in such conditions, considering the recovery time (t_R) from 37.5 ºC (Tmax) until reaching 30 ºC again.

The representative cases highlighted in Fig. 16 are those identified through the cluster analysis. In total, 12 representative buildings were identified (three per building type). These cases were used to test strategies from Table 11 to find the combinations attributed to the optimized community. Fig. 17 shows results for the three representative retail buildings, highlighting the baseline results (blue) and the combination of strategies giving optimal results considering all six indicators (red). Bubbles in shades of grey represent combinations of strategies that have not been selected.

Fig. 18 shows results for the optimized community once all representative buildings were analyzed. For instance, it was possible to significantly improve the thermal vulnerability of the retail building previously mentioned from 40% to about 10%. The best combination of strategies selected for retail buildings was applying a cool paint or coating on both walls and roof, installing overhangs for solar shading, and double-pane windows with increased openable area for natural ventilation. The same strategies were selected for office buildings, but also adding insulation to the roof. For restaurants and residential buildings, windows would not need to be replaced, but rather a window film would be enough to improve resilience. All building types benefited from cool surfaces.

It is important to highlight that a few cases had their performance slightly worsened with respect to some KPIs. This is because the selected combinations of strategies were defined based on representative buildings and only one combination was attributed by building type. Thus, it can be expected that these strategies would not be ideal for all buildings within this group. However, considering that this is how most building policies are enforced around the world, especially prescriptive standards and codes, such an approach would be closer to reality. An alternative would be to optimize thermal resilience for every single building, which would follow the same procedure described herein, but with considerably higher computational cost.

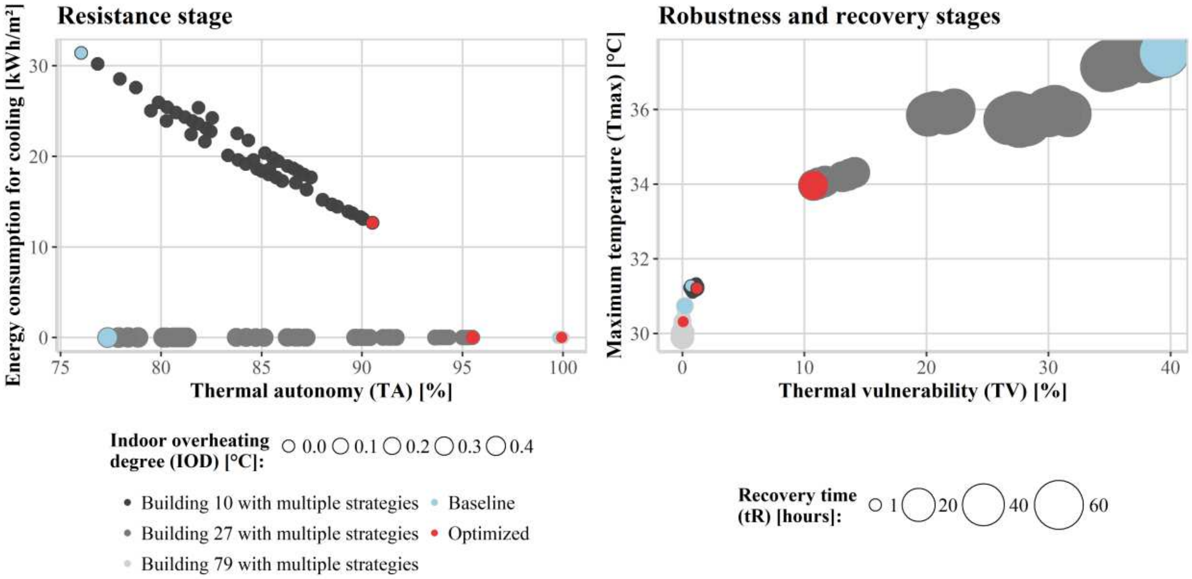


Fig. 17 - Optimization of representative retail buildings

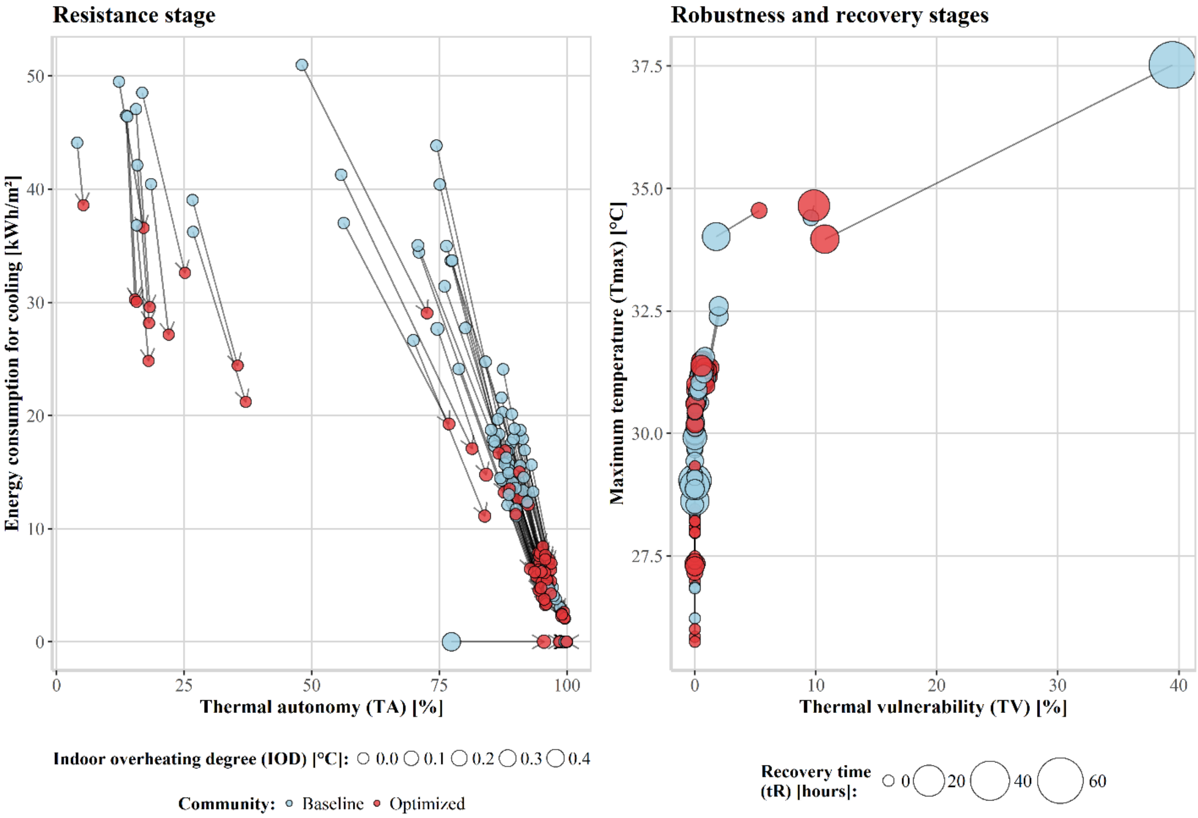


Fig. 18 - Resilience profile linking baseline and optimized buildings within a community

5.2.4. Impact of weather scenarios

Quantifying the impacts of weather scenarios on thermal resilience is complex as it involves multiple metrics. The six KPIs adopted in this study were influenced not only by the weather, but also by the building type and operation. Residential buildings, even when naturally ventilated, showed high thermal resilience with respect to most indicators even when exposed to future extreme events. Two important factors influencing these results are the low indoor heat gains in residential buildings and the use of fans to increase airspeed. In fact, fans have been used on average 18% of the occupied hours throughout the year, which was translated into lower SET outputs and consequently higher thermal autonomy. Nonetheless, when extreme indoor thermal conditions could not be avoided through ventilation or air-conditioning, these buildings presented the highest increase in maximum temperature in relation to Scenario 1. Other building types (non-residential) often presented lower thermal resilience, in part due to their high internal heat gains and floor area that reduced the impact of strategies applied to the façade. Large buildings, especially when near surrounding buildings, often had reduced area for natural ventilation, decreasing thermal autonomy and increasing energy use for cooling. This is because windows were not applied to exterior walls close to or in contact with façades from neighboring buildings, reflecting another problem of dense urban areas.

Fig. 19 and Fig. 20 illustrate the effect of multiple weather scenarios in the two communities, baseline and optimized. The adoption of simple strategies allowed reducing the median energy intensity for cooling between 11 and 17 kWh/m^2.year for both historical and future typical meteorological years, which means consuming 59% and 48% less energy by the 2050s and 2090s, respectively. Extreme indoor thermal conditions were also mitigated, with thermal vulnerability improving up to 25 percentage points for the year with the most severe and longest heat wave in the long-term future (Scenario 8). Maximum SET was also reduced across buildings in the optimized community. The baseline community reached over 40 ºC, taking weeks or even months to recover. “Weeks or months” is used in Fig. 19 to represent any recovery time longer than a month. In Fig. 20, results for the recovery time within 0 and 72 hours are plotted to improve visualization of the boxes, thus not showing all values above the 75th percentile.

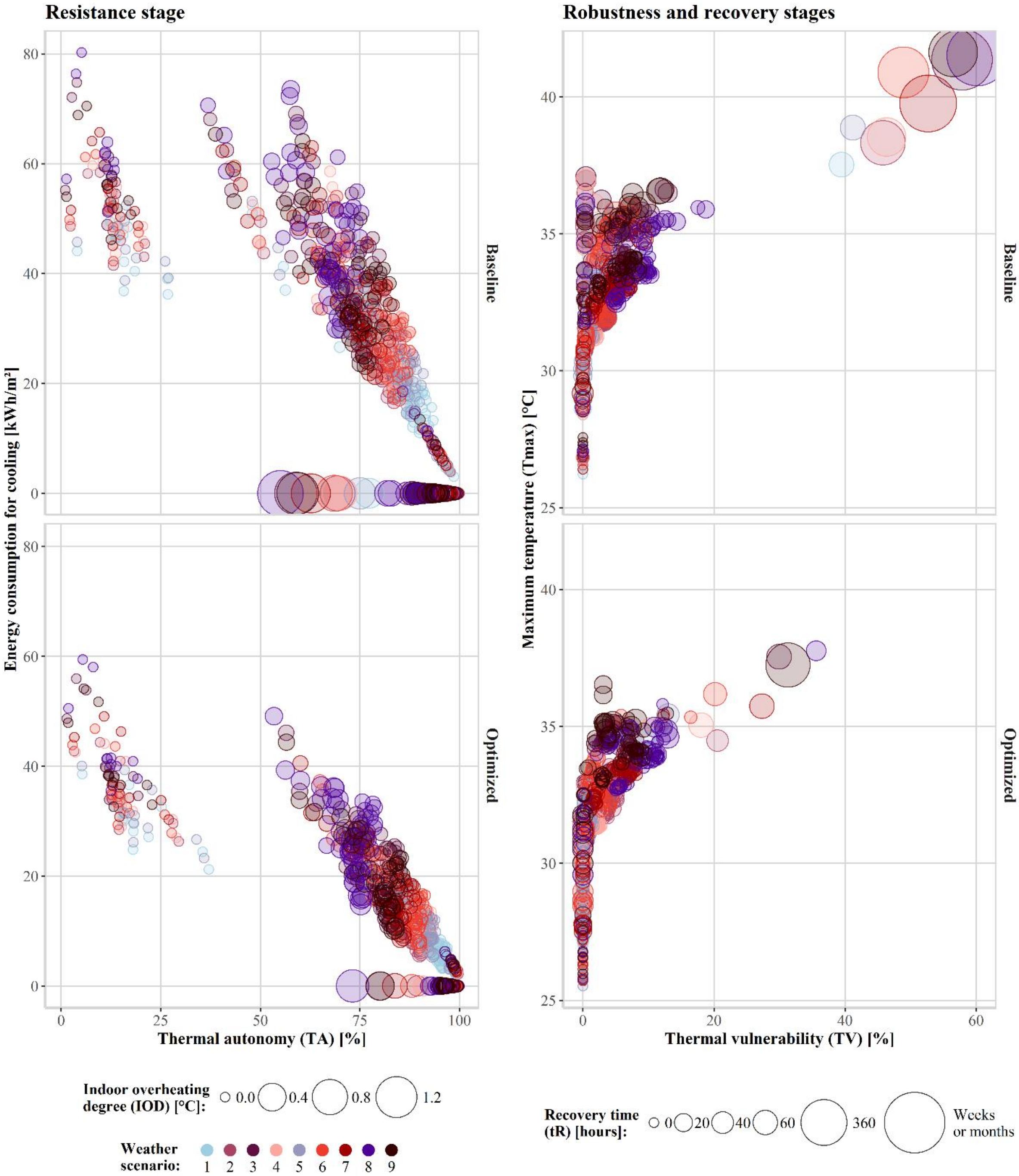


Fig. 19 - Resilience profile of the communities under multiple weather scenarios

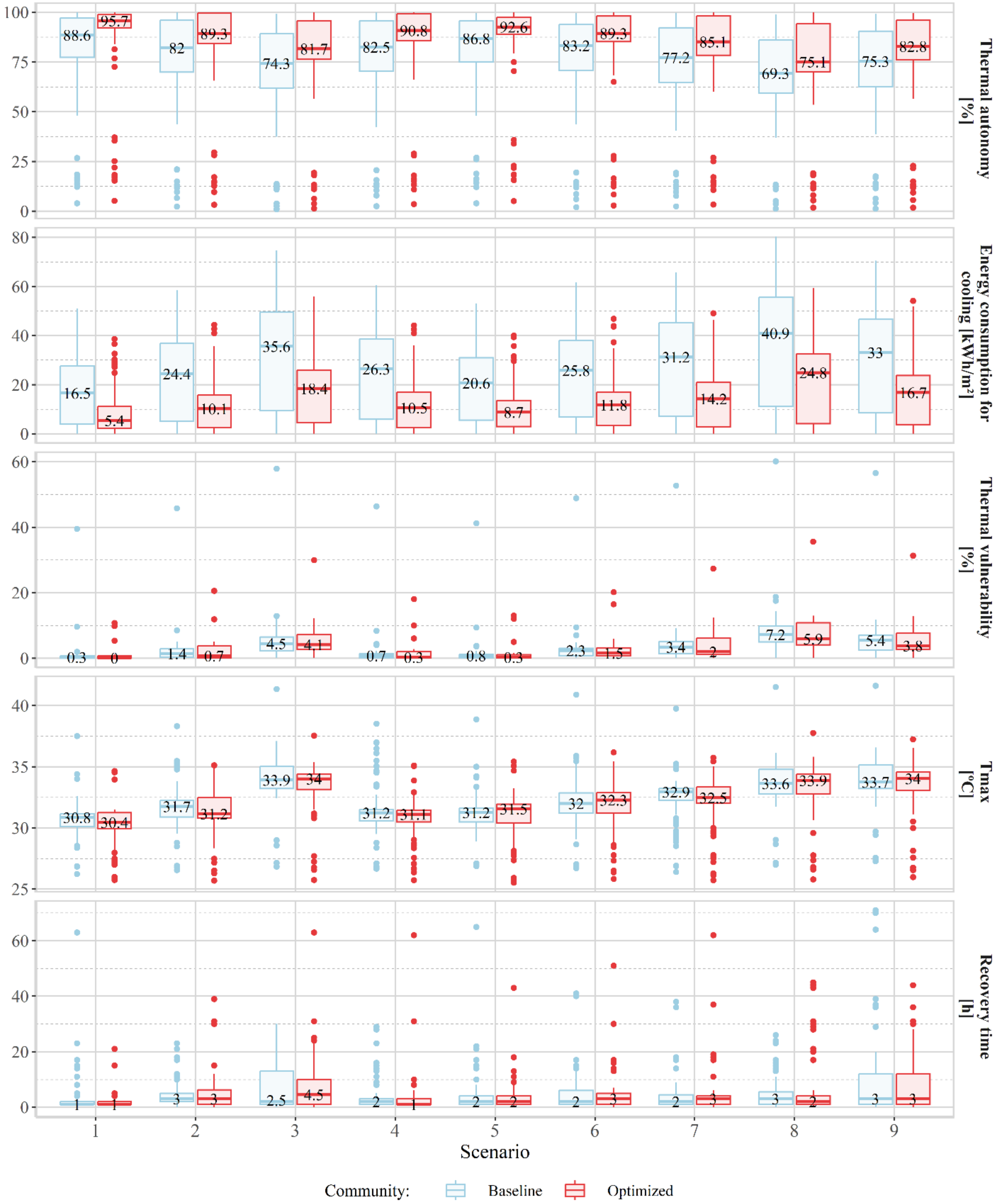


Fig. 20 - Box and Whisker’s plot showing the variation of results depending on the scenario

Fig. 21 shows the variation of results of the 12 representative buildings for each indicator in relation to the results obtained for the same building in Scenario 1 (historical TMY). IOD was not included because it showed very little variation across the scenarios. The bars represent results for the baseline community, and the dots show results for the optimized community.

The main message from Fig. 21 is that design optimization for a historical typical weather scenario will not necessarily translate into lower impact to buildings when exposed to different and more extreme scenarios. At least, not with respect to all indicators. Take the example of the three representative retail buildings (their results are also shown in Fig. 17). Building 79 was already highly resilient in Scenario 1. Its thermal autonomy was reduced by up to 10 percentage points and thermal vulnerability increased by up to 10 percentage points when considered other scenarios in the baseline condition. These results were improved to about half the impact for the optimized condition (i.e., smaller resiliency reduction). On the other hand, weather scenarios proportionally impacted more the optimized building 10 than its baseline for most of the KPIs. For example, Tmax is about 1.7 ºC higher in the optimized building 10 when comparing scenarios 2 and 1, while the baseline is only 0.5 ºC higher. Also, energy consumption varied more in the optimized condition, but absolute values are still lower than those of the baselines. The same is generally true for all the indicators: optimization improved most of the results. Still, some KPIs were harder to improve than others, especially those related to extreme indoor thermal conditions, and particularly the Tmax and recovery time.

Results for the recovery time of building 27 were not included in Fig. 21 because of their high variability in comparison to all the other buildings, compromising visualization and comparison. In summary, this building is highly vulnerable in its baseline condition and in future climate scenarios, with at least one zone with continuous exposure to extreme indoor conditions throughout several weeks. The main reason behind this performance is its high internal loads coupled with a large footprint area in comparison to the window opening area, which hinders the effect of natural ventilation. Air-conditioning is not available in building 27.

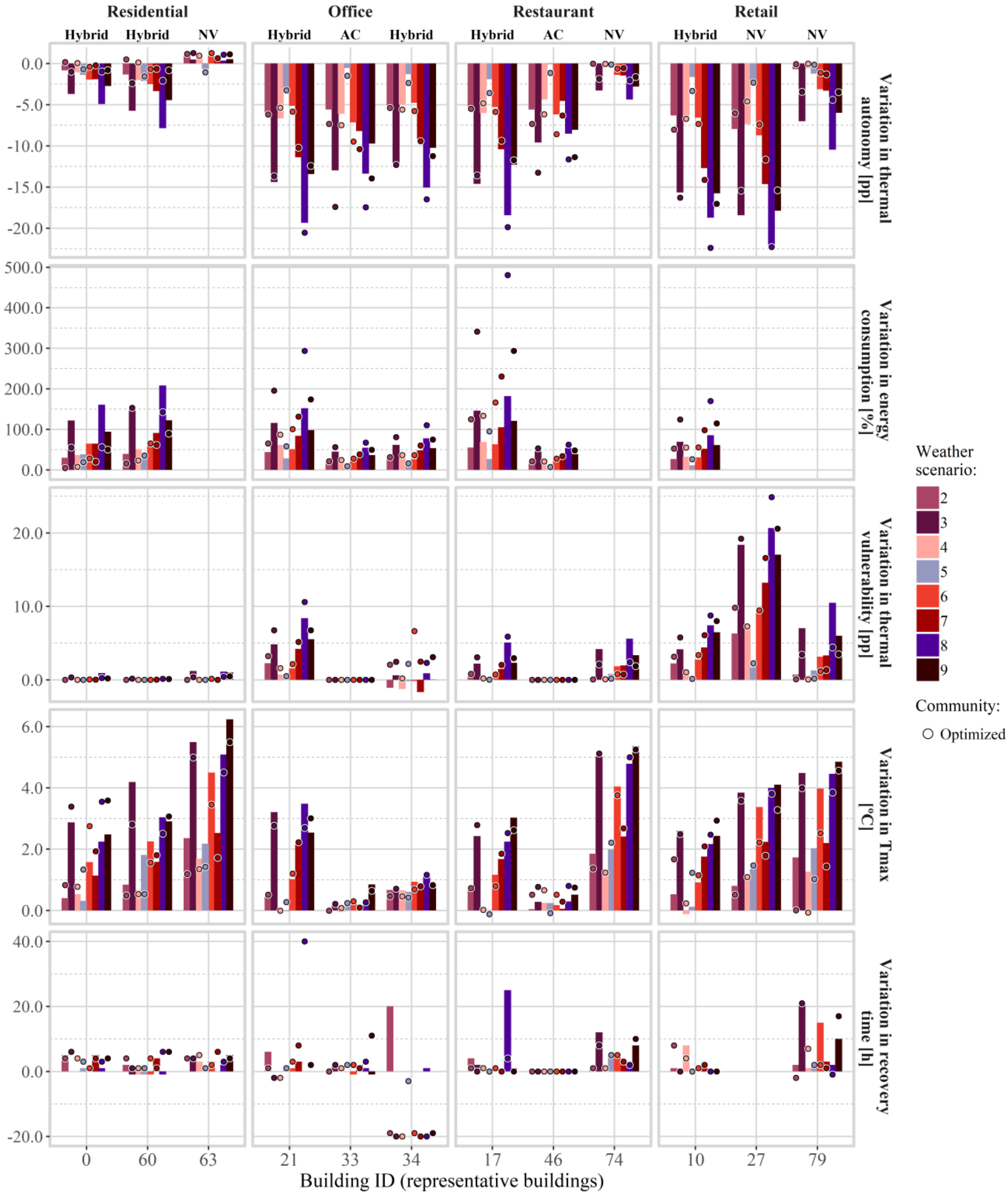


Fig. 21 - Variation of results of representative buildings under multiple weather scenarios

Fig. 22 ranks weather scenarios from the least to the most impactful for the thermal resilience of each building, which ultimately splits them into groups of different time frames—first scenarios in the 2010s, then 2050s, and 2090s—as could be expected. As previously observed, Scenario 8, the most severe and longest heat wave in the 2090s, was identified as the most impactful for nearly all buildings, irrespective of the type, operation mode, and the strategies applied (i.e., optimization). However, if one is not interested in analyzing buildings in such a distant future, the most severe and longest heat wave in the 2050s (Scenario 7), or the most intense heat wave in the historical period (Scenario 4) could be used. Scenario 7 also compromised the resilience of the majority of hybrid residential buildings in the baseline condition. This was driven especially by the increase in the recovery time in the most severe and longest heat wave. Such a problem was mitigated in the optimized community, where Scenario 7 did not appear among the worst.

The intensity of each scenario's impact on buildings is highly dependent on the building type and operation, but also other design characteristics, such as floor area and window-to-wall ratio, as previously noted. This becomes evident by looking at the hybrid operation in Fig. 22, where scenarios in the historical period can be as impactful as in the 2090s to some buildings.

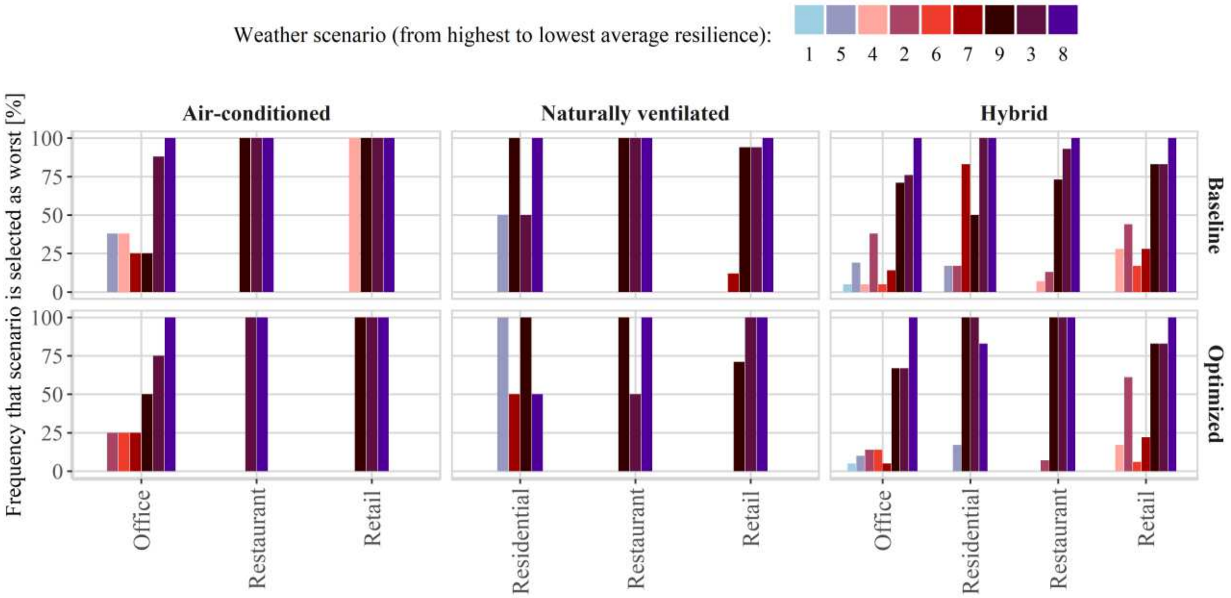


Fig. 22 - Identification of worst weather scenarios for thermal resilience

Still seeking to identify the ideal situations in which each scenario could be preferred, Fig. 23 shows the correlation between the KPIs and characteristics of the heat waves across different building types and operations. This figure only considers Scenarios 4 to 9 which are heat wave years. Only significant correlations were included, considering a significance level of 5%. The severity, duration, and intensity of heat waves correlated almost exclusively to the thermal autonomy and energy consumption of air-conditioned buildings, which may indicate that variability in the other KPIs is not explained by the type of heat wave. For the remaining buildings, the severity was the most strongly heat wave characteristic correlated to most KPIs.

Additionally, in naturally ventilated buildings, the higher the intensity of the heat wave, the higher the maximum SET values (Tmax). This indicates that, if one aims to identify extreme temperatures inside buildings during heat waves, the events with higher intensity could be prioritized. Severe heat waves are also relevant to finding high Tmax values, especially in hybrid buildings.

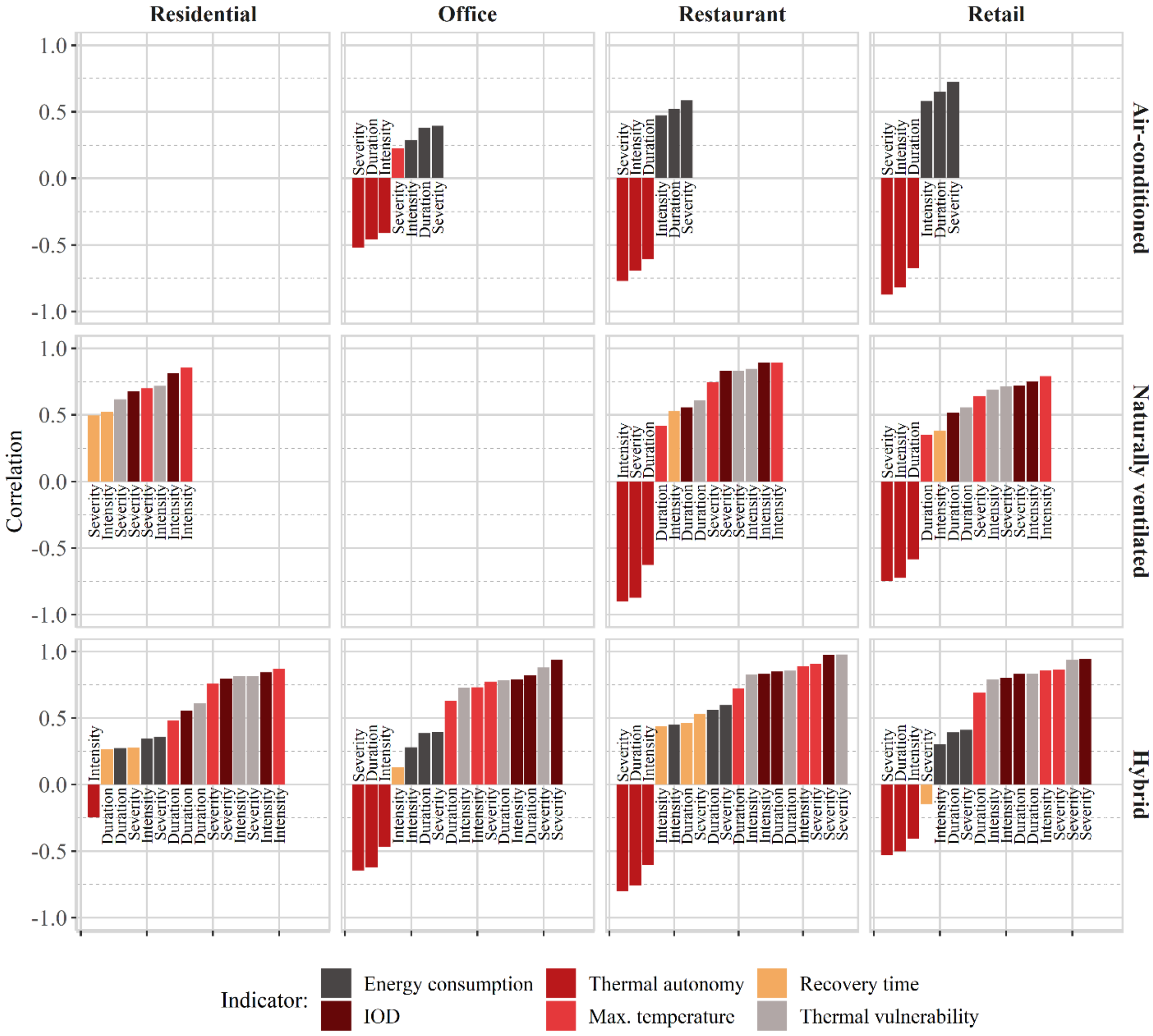


Fig. 23 - Correlation between indicators of thermal resilience and heat wave characteristics

5.3. MAIN FINDINGS

If we consider that a building is overheating when thermal vulnerability surpasses 3% (adapted from CIBSE (2013)) of the occupied hours, two of the 92 buildings (2.2%) would fail this criterion in the baseline condition under Scenario 1 (TMY 2010s). Even though this value corresponds to the most impacted zone in the building, a conservative approach may be recommended to safeguard occupant’s health as it is not guaranteed that they would be able to commute to other safer areas inside the building. In commercial buildings, such a condition could also lead to reduced productivity and limitation on service provision.

Maintaining baseline conditions in a typical year in the 2050s could result in 37% of the buildings being subject to overheating. Even though median thermal autonomy in buildings improved by up to 10% across all scenarios with the application of strategies, and median energy use for cooling was reduced by up to 60%, extreme indoor thermal conditions persist. That is, a similar number of buildings would be subjected to overheating, considering thermal vulnerability values.

Indicators communicating resistance of buildings (i.e., in the resistance stage), particularly thermal autonomy and energy use, showed higher sensibility to the application of strategies, whereas Tmax (i.e., in the robustness stage) was harder to mitigate. Thermal vulnerability (TV) could be significantly reduced when the baseline condition obtained remarkably high results. TV up to about 10% was much harder to reduce, especially through multi-objective optimization. This means that trade-offs between indicators will often need to be considered as an improvement in resistance might come at the expense of robustness and recoverability. See Fig. 17 and Fig. 18 for examples. Thus, emergency plans should be available to respond to the most extreme conditions due to the difficulty of mitigating these events solely through passive strategies. Such response might come from active strategies, emergency kits, or commuting to safer zones within the building, when possible.

Design optimization for resilience should also be performed within the context of a changing climate. This is because recommended strategies under historical weather scenarios might differ in future conditions, especially with the increasing frequency of extreme events. Thus, building design should provide flexibility to adapt throughout the building life cycle in tandem with current sources of stress. Ideally, maintenance and retrofitting plans can guide adaptation strategies if developed using a comprehensive assessment framework of resilience with multiple weather conditions.

Even though worst weather scenarios might differ depending on the building, a pattern was identified: thermal resilience tends to reduce further into the future, with years with the most severe and longest heat wave being the worst, followed by the year with the most intense heat wave or a typical meteorological year. This is a pattern we were expecting to verify, but it does not mean that a resilience analysis should simply adopt the worst possible weather scenario in the 2090s.

For building design, the choice of scenario also depends on the available resources, expected life cycle, and future adaptation plans. For instance, some of the buildings analyzed are already over 30 years old. With a life cycle expected to last at least 50 years in Brazil, a retrofit analysis considering a typical year in the 2050s might be enough. For 25% of air-conditioned office buildings and nearly 50% of hybrid retail buildings, a TMY in the 2050s was already among the worst weather scenarios, even comparable to scenarios in the 2090s. When designing new buildings, severe heat waves in the 2050s could be considered as well, as they can be highly correlated to increased thermal vulnerability and maximum SET. Ideally, this information should be shared with other stakeholders responsible for developing systems manuals and emergency plans to better operate buildings and respond to extreme events.

To forecast the impact of weather scenarios on the power grid, severe heat waves may be adopted as they are highly correlated to increasing energy consumption. However, we verified that the community's peak cooling demand occurred during the most intense heat waves (i.e., high maximum daily mean temperature), not during the most severe and longest events. We also identified that the intensity of a heat wave correlates with the maximum indoor temperature (Tmax) and thermal vulnerability (TV) in naturally ventilated and hybrid buildings. Thus, these intense events might be suitable for applications such as developing evacuation plans during extreme events.

A thermal resilience assessment including scenarios in the 2090s might be more suitable for policymakers to identify the pathways to policy change. For instance, incentivized heat mitigation and heat management strategies in building policies can evolve over time, gradually adapting to climate changes. A long-term resilience analysis could help create smooth and gradual steps throughout time to facilitate compliance.

By addressing the thermal resilience of a real community, instead of prototypical isolated buildings, it is possible to map vulnerabilities and develop action plans to respond during extreme events. For example, assistance to buildings with higher Tmax and recovery time could be prioritized by emergency responders. Such information would be particularly useful if combined with other health and comorbidity data, for example, to identify buildings with high thermal vulnerability occupied by the elderly or people with reduced mobility. Nonetheless, a detailed analysis at the building scale remains essential, especially when performed by design teams. These professionals could look in detail what are the zones most affected and what is causing such vulnerability, thus providing tailored solutions to each context. In both cases, however, the framework remains useful given the comprehensive set of indicators adopted, which can also be calculated and analyzed for single zones inside buildings.

6. DISCUSSION AND IMPLICATIONS

Extreme indoor thermal conditions should become more intense and last longer in the future, which is directly reflected into higher thermal vulnerability. Such conditions require emergency planning at the community scale and a resilience-oriented design practice at the building scale.

In Brazil, an important step to addressing the thermal performance of residential buildings was taken in 2021 with the revision of the Brazilian standard, NBR 15575-1. This national standard considers a building simulation path with key performance indicators including thermal autonomy (also known as PHFT), cooling load, and maximum temperature, thus providing the foundations to also address thermal resilience with further updates. However, a similar standard for commercial buildings still does not exist, and NBR 15575-1 is often only applied to large multi-family residential buildings due to a lack of enforcement. Considering the expected increase in overheating issues in buildings, like those identified in this study, the development and enforcement of new policies are paramount to face the effects of climate change. The resilience assessment adopted herein could help guide such a process.

Median energy consumption for cooling could increase by 48% in a typical 2050s scenario in Florianopolis, Brazil, if resilience strategies were not applied. This value reached 116% in the 2090s and up to 148% during a heat wave year. Such increased demand can heavily strain the power grid and should be addressed through policies with long implementation timelines. Nonetheless, median energy consumption could be reduced by 59% and 48% by the 2050s and 2090s if fostered simple passive strategies, respectively.

Increased vulnerability might trigger more deployment of air-conditioning for buildings that currently do not have them installed, impacting energy use and CO_2 emission. As importantly, such increased demand for air-conditioning needs to be quantified to predict necessary incentives and rebates to make them more accessible to disadvantaged populations, including discounts on the energy bill. This is relevant given that in August 2023, utility bills represented more than 24% of Brazilians' debt defaults (SERASA, 2023).

Resilience needs to be treated through long-term maintenance and retrofitting plans because ideal strategies and technologies might change over time as the climate changes. For designers, this might require analyzing solutions both at the historical period and a mid-term future (2050s) to verify what are the best strategies and if they differ in the future. If they do, ideally a flexible design would be developed, for example, by designing an appropriate structure to support installation of exterior shading devices in the future, or defining a time frame in which a cool coating should be applied on walls or roof tiles. For policymaking, on the other hand, the long-term future (2090s) could also be considered to define paths for smooth policy changing.

7. CONCLUSION

This study proposes a novel simulation framework to assess the thermal resilience of buildings and communities against overheating. At the building level, single buildings are characterized by three stages of resilience: resistance, robustness, and recovery. The building performance in each stage is measured by tailored key performance indicators that thoroughly describe the building response when exposed to different sources of stress, especially those related to extreme weather conditions. Results are aggregated from the building level to the urban level through a resilience profile, which is intended to provide a meaningful understanding of the resilience of all buildings within a group (e.g., in neighborhoods, communities, and cities). Additionally, a procedure of selecting representative buildings is proposed to facilitate the development of building policies targeted to specific vulnerable populations, identified through a cluster analysis that groups buildings according to similar resilience responses. Considering that a comprehensive analysis needs to look at buildings in different conditions to test resiliency, the impact of multiple weather scenarios was also investigated.

Through the application of the framework, alarming results were verified, particularly in the city with the hottest climate analyzed, São Luís. A vulnerable group of buildings was identified with thermal autonomy (TA) close to zero, relying on air conditioning, while exhibiting extreme indoor temperatures over 50% of occupied hours when it is not available. Buildings in this group are characterized by an envelope with high thermal mass, which has been identified as an inadequate design choice for the detached house explored in the case study. Heat builds up in the structure throughout time with little opportunity to dissipate due to climate severity. This phenomenon increases indoor temperatures and delays or even prevents recovery. The selected indicators help to build such a narrative to understand the fragilities in building design. This analysis could help policy makers, researchers, and emergency responders map and act upon vulnerabilities within a community considering multiple stressors (e.g., heat waves, power outages, and climate change) as well as promote those strategies that comprehensively increase thermal resilience.

Results reflect the necessity of planning for resilience. This is because, often, strategies and technologies recommended under current weather conditions might not be ideal in the future. Therefore, flexible design, and maintenance and retrofit planning are key. Also, different objectives might require diverse weather scenarios, sometimes even resulting in trade-offs between improving resistance or robustness of buildings. For instance, it was verified that the same strategies that were improving thermal autonomy and reducing energy consumption (i.e., increased resistance), could lead to higher indoor maximum temperatures and thermal vulnerability during extreme weather conditions (i.e., reduced robustness).

Overall, in Florianopolis, the years with the most severe and longest heat waves within a period (historical, mid-, or long-term future) impacted thermal resilience the most with respect to all six analyzed key performance indicators combined. However, specific applications may benefit from adopting intense heat waves, especially for identifying extreme indoor thermal conditions (Tmax) and peak demand. Such a decision should ultimately be accompanied by a thorough reflection on the objectives of quantifying resilience, available resources, planning horizon, and risks assumed for not being resilient.

7.1. LIMITATIONS AND SUGGESTIONS FOR FUTURE STUDIES

Findings and conclusions drawn in this study are limited by the building characteristics, occupation and operation patterns, and modeling assumptions considered in each case study, as well as the geographic locations, weather data, and method to generate future climate scenarios. Another important limitation related to the weather data is that the wind sheltering effect caused by the urban canyon was not considered, which should impact the natural ventilation potential as a strategy for thermal autonomy. Additionally, this study focused on overheating issues, which can mask necessary compromises between cooling and heating-oriented strategies.

In Section 5 (Paper 3), simplification of building models also limited the analysis. For instance, many real buildings within this case study are mixed use (e.g., retails on the first floor and residences on the remaining floors). The predominant type was adopted. Additionally, it was verified that multiple small businesses inside these buildings permanently closed during the COVID-19 pandemic. The most recent building type was adopted, but some buildings or floors remained inactive ever since, which hinder validation of results. Validation of indoor thermal conditions is still a challenge in building performance simulation, especially when analyzing multiple buildings within a community. Future studies could investigate alternatives to improve the verifiability of thermal resilience metrics, particularly for disadvantaged communities where this type of analysis is most needed and data is limited.

Future studies could also investigate other disturbances to thermal resilience, such as power outages, technical systems failures, and operation constraints (e.g., restricted ability to open windows), as well as variable populations (e.g., healthy adults, elderly, and children). These disturbances may also include extremely low-temperature events, thus requiring the adaptation of the framework considering overheating and overcooling risks to identify trade-offs between selected strategies and technologies. This is possible through the adaptation of KPIs that consider thresholds related to discomfort and distress to low temperatures. When doing so, especially for analyzing long-time frames (e.g., until the 2090s), it could also be considered how existing buildings age over time and that new buildings might be already improving as a result of evolving regulations. How to properly reflect such passage of time in thermal resilience analyses is still to be further explored across different socioeconomic, regulatory, and climatic contexts.

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APPENDIX A – Paper 1

A thermal performance standard for residential buildings in warm climates: lessons learned in Brazil

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Abstract

This paper presents the main challenges faced and lessons learned when developing a new method to assess the thermal performance of residential buildings for the recently updated Brazilian building performance standard, NBR 15575-1:2021. It touches on subjects related to the representation of occupant behavior, climate, and thermal acceptability in building performance simulation, as well as the use of reference models, key performance indicators, and performance levels in policies. NBR 15575 provides a thorough procedure to analyze thermal performance, allowing buildings to be assessed while in passive operation mode and also accounting for energy needs when active operation is necessary. Multiple key performance indicators are introduced to provide a comprehensive evaluation. The main difficulty found was dealing with diversity. Given the vast scale of Brazil's territory, a high variation in culture, climate and construction techniques is expected, thus requiring a compromise between detail and scalability. There are still many opportunities for improvement, especially regarding the representation of occupants, and adjustments of the characteristics of reference models to promote high thermal performance, considering the diverse climates, regional practices, and economic needs. This paper might help researchers and other stakeholders to develop and improve other local standards and protocols, especially for warm climates.

Keywords: thermal performance, residential buildings, building performance standard, building performance simulation.

Nomenclature

AC	Air conditioning	PHT_{upp}	Percentage of occupied hours above the upper limit temperature [%]
AWD	Ambient warmness degree	R	Thermal resistance
BBZ	Brazilian bioclimatic zone	Ref	Reference
CgTA	Heating load [kWh/year.m²]	SHGC	Solar heat gain coefficient

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CgTR	Cooling load [kWh/year.m^2]	TC	Thermal capacity [kJ/(m^2.K)]
CgTT	Total thermal load [kWh/year.m^2]	To	Operative temperature [ºC]
DBT	Dry bulb temperature [ºC]	Tomax	Maximum annual operative temperature [ºC]
$\mathrm{DBT_m}$	Annual mean dry bulb temperature [ºC]	Tomin	Minimum annual operative temperature [ºC]
HI	Heavy and insulated	t_R	Recovery time [h]
HI’	Heat index [ºC]	U	Thermal transmittance [W/(m^2.K)]
IOD	Indoor overheating degree [ºC]	WLU-RLI	Light and uninsulated walls and light and insulated roof
KPI	Key performance indicator	α	Solar absorptance
LI	Light and insulated	α_{IOD}	Overheating escalation factor
PHFT	Percentage of occupied hours within a temperature range [%]	ε	Thermal emissivity
PHHI’	Percentage of occupied hours within a heat index range [%]		

1. Introduction

Buildings determine where functions essential for human life are carried out within an urban system [1] and they also have an impact on natural resources. In fact, in 2019, building construction and operation were responsible for 35% of energy consumption, 55% of electricity energy use, and 38% of energy-related CO_2 emissions globally [2]. On considering a sustainable development scenario to reach the UN Sustainable Goals 7 (affordable and clean energy for all), 3.9 (reduced pollution and associated health impacts), and 13 (combat of climate change), it appears that these emissions could be reduced to a share of one-fifth by 2050 [3]. Buildings are key players in tackling climate change, providing protection against weather conditions, and enhancing human health and risk reduction [4]. However, if a path towards reduced energy use and stable climate policies is not followed, CO_2 emissions will significantly increase.

Energy regulations are often the only assessment tool available to define the acceptable boundaries for energy consumption. Therefore, they are of great importance in the building sector and should provide clear guidance nationally and at the consumer level [5,6]. Looking beyond energy consumption, regulators should also consider the comfort of the occupants to effectively create better buildings [6]. However, these regulations are products of the contexts and interests from which they were created. Their characteristics and evolution level are marked by factors such as the local economic structure and the available access to technology and information [7].

On analyzing how consecutive versions of the ASHRAE Standard 90.1 (Energy Standard for Buildings Except Low-Rise Residential Buildings) and the International Energy Conservation Code (IECC) are evolving with regard to passive survivability, Baniassadi, Heusinger, and Sailor [8] found that the evolution is climate-dependent. In the cooling-dominated climates of the U.S., buildings are becoming more resistant to heat disasters. On the other hand, buildings compliant with higher standards in colder climates are becoming subject to overheating during summertime when an air conditioning (AC) system is unavailable. While investigating the possible correlation between building energy rating upgrading and heat-related health hazards during a heatwave in Melbourne, Australia, Alam et al. [9] estimated that the mortality rate may be reduced to one-tenth of the current levels considering a building stock with an energy star value of 5.4 from the Nationwide House Energy Rating Scheme (NatHERS) [10].

Updating building performance codes should improve and simplify evaluation methods, separate measures into distinct issues to be addressed (e.g., overheating), evaluate the long-term impact for stakeholders, establish databases and benchmarks, and improve mandatory minimum standards to foster building stock performance and market competitiveness [11–13]. It is also paramount that building codes are integrated into the local context, leveraging the existing infrastructure and understanding the quality of the construction industry to establish stringency levels [14].

This paper presents the main challenges faced and lessons learned when developing a new method to assess the thermal performance of residential buildings for the recently updated Brazilian building performance standard, NBR 15575 (Residential buildings - Performance) [15]. It examines the choices that have been made to address the building and its thermal performance, the effect of the climate, and the interaction with people. To achieve this, five types of analysis were selected to gradually unfold the details of the procedure and to assess the impact of each decision made by comparing them to possible alternatives. Therefore, this paper covers the key factors that affect the thermal performance analysis of buildings as a whole, which might guide researchers and other stakeholders to develop and improve other local standards and protocols, especially for warm climates.

Examples of relevant performance-based standards with similar objectives in South American countries are shown in Table 1, described considering the main topics analyzed in this paper. The international standard ISO 52016 (Energy performance of buildings - Energy needs for heating and cooling, internal temperatures, and sensible and latent heat loads) [16] is also included, in light of its objective of internationally harmonizing a methodology for assessing the energy performance of buildings. IRAM 11900 (Energy performance in residential units - Calculation method and energy efficiency labeling) [17] and IRAM 11659 (Thermal conditioning of buildings - Verification of the hygrothermal conditions - Saving refrigeration energy) [18] are from Argentina, and CEV (Energy rating of homes) [19] is from Chile. Mostly focused on energy use, these standards tend to evaluate air-conditioned buildings and incentivize insulation, while natural ventilation strategies are represented superficially through fixed air change rates. Representations of the weather and the occupant behavior are also often simplified through fixed internal gain values and outdoor thermal conditions. In this context, this paper investigates the impacts of choosing the occupant behavior, the source of weather data, the building components, and the key performance indicators to assess the thermal performance of buildings in standards.

Table 1 Comparison of performance-based standards considering the main topics analyzed in this paper.

	NBR 15575	**IRAM 11900**	**IRAM 11659-2**	**CEV**	**ISO 52016**
Method	Two possible paths: simplified or computer simulation (the latter is analyzed in this table)	Application of thermal balance formulae	Application of thermal balance formulae	Application of thermal balance formulae through spreadsheets	Application of thermal balance formulae through spreadsheets
Occupant behavior	Occupancy defined through static schedules and window operation based on environmental criteria	Fixed value for internal gains	Fixed value for internal gains	Occupancy defined through static schedules	Occupancy defined through static schedules
Weather representation	Weather file of a typical meteorological year	Monthly weather data statistics	Fixed outdoor thermal conditions	Weather data embedded in a spreadsheet	Weather file
Key performance indicators	Percentage of occupied hours within a temperature range; maximum and minimum operative temperatures; cooling and heating loads	Primary energy; energy performance index	Total cooling load; volumetric coefficient of cooling; thermal load per unit area	Heating/cooling demand and consumption; hours of discomfort	Energy needs for heating and cooling; internal temperatures; heat loads
Performance evaluation	Minimum, intermediate, and superior levels	Energy efficiency level (G to A)	Compliant or not compliant	Energy efficiency level (G to A+)	To be defined by each country/region

2. Background

The Brazilian performance standard, referred to hereinafter as NBR 15575, provides two procedures for the analysis of the thermal performance of residential buildings: a simplified procedure and a computer simulation procedure. This paper addresses only the computer simulation procedure, which is the most comprehensive option to evaluate thermal performance. The simplified procedure has a prescriptive approach, which is still transitioning from the previous version of the standard to a newer edition that is more in line with the simulation procedure. This is expected to be developed in the coming years. The computer simulation procedure is based on developing and analyzing a building energy model that represents the project under evaluation. Fig. 1 synthetizes a roadmap to evaluate the thermal performance of residential buildings in Brazil.

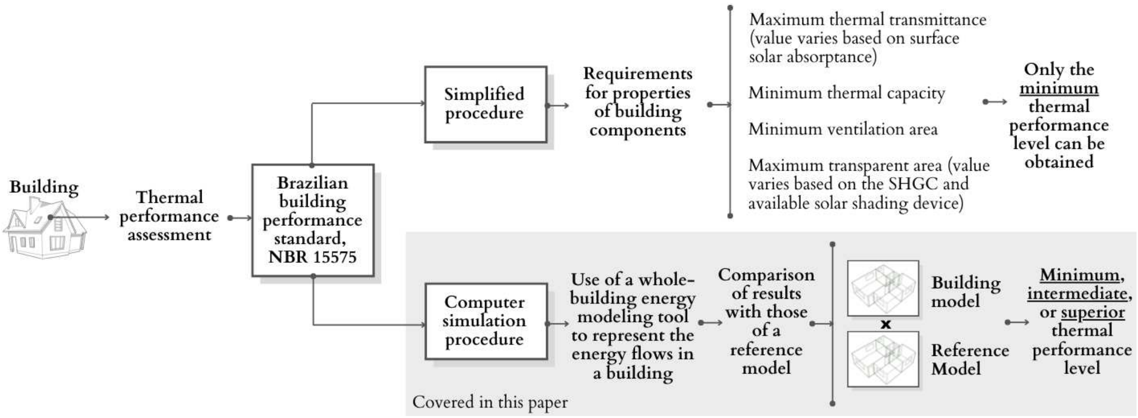


Fig. 1 Roadmap to assess the thermal performance of residential buildings in Brazil.

NBR 15575 is a national standard with widespread implementation by big construction companies, but still limited compliance in the case of small companies. Nonetheless, it is enforced by the Consumer Protection Code, which makes its application mandatory for new residential buildings across the country. Brazil’s territory is of continental proportions, being the only country in the world crossed by both the Equator and the Tropic of Capricorn. Climates vary from 0A (extremely hot) to 3A (warm), according to the ASHRAE 169 (Climatic data for building design standards) classification system [20]. Thus, mild climate conditions are abundantly present, allowing the uptake of passive strategies to enhance the thermal performance of buildings. In fact, Ramos et al. [21] identified a huge preference for naturally ventilated spaces in Brazilian homes (89% of all interviewed occupants). This preference prompts more occupants to open the windows instead of turning on the air conditioner whenever possible [21]. Moreover, only 17% of Brazilian households were equipped with an air conditioner until 2019 [22]. However, according to the Brazilian Ten-Year Plan for Energy Expansion [23], this situation is expected to change as it predicts an increase of almost 30% in the energy consumption related to air conditioning between 2021 and 2031.

To account for this scenario, it was important to express the culturally recognized preference for natural ventilation in the performance standard without neglecting the increasing use of air conditioners in the residential sector. Thus, in NBR 15575, the building energy model should be simulated under passive and active operation modes. This allows the potential of building design to deliver adequate thermal performance as a free-running building to be assessed, while also accounting for energy demands when this mode of operation is insufficient to meet acceptable performance.

This practice represents an improvement compared to the former version of NBR 15575, where the computer simulation procedure did not consider any interaction between the building and its users. In fact, the building used to be modeled without occupants and appliances, with closed windows, and subjected to constant air changes. This approach does not allow any representation of how the building would behave under realistic usage, which provoked sharp criticism from building simulation practitioners [24,25].

Building energy use is influenced by socio-demographic and psychological variables, which reflect attitudes, subjective norms, traditions, and personal values. Recognizing such variables is fundamental from a policy perspective to enhance effectiveness [26]. For instance, the adaptive behaviors of Brazilian occupants are dependent on climate, income, and individual preferences. Frequent adaptive actions taken in warm environments are opening windows and doors, turning on a fan, changing clothes, taking a cold shower, and having a cold drink, besides turning on the AC [21]. It should also be noted that occupant behavior frequently needs to be represented quantitatively, such as when building performance simulations are used for policy development and applications. Thus, a tradeoff between accuracy and scalability needs to be evaluated in order to guarantee consistency [27]. Consequently, NBR 15575 standardized the occupant interaction with the building, considering a set of schedules describing occupancy, use of lighting and appliances, and criteria to open the windows or turn on the air conditioning system.

This standardized occupant profile is intended to incorporate the Brazilian context, although it is a considerable simplification of reality. In a previous publication [28], we discussed how different behavioral patterns can impact the thermal performance of buildings, even changing the building components indicated for that specific design and location. It was concluded that, in future policy actions, it would be appropriate to offer more than one alternative to model the occupation pattern and the selection could be based on social, cultural, and economic criteria. This is also an opportunity to add stress to the model and better evaluate building performance under variable scenarios, e.g., by considering energy-conserving occupants, average occupants, and energy-wasting occupants [29].

As buildings rely heavily on passive strategies, the source of climate data is a sensitive factor in thermal performance evaluations. Thus, it became clear that standardizing the weather file database was important to improve the consistency of results. There are currently three main sources of weather files processed for building performance simulation in Brazil [30]: the Test Reference Year (TRY) database [31], the National Institute of Meteorology (INMET) database [32], and the TMYx databases [33]. At the time of developing NBR 15575, the INMET database had the largest number of weather files, representing 411 cities. The technical report ABNT TR 15575-1-1 (Standard database of weather files for the evaluation of thermal performance using the computer simulation procedure) [34] describes this database and all simulations should be run using climate data from the same source. The objective of this technical report was to ensure that NBR 15575 will be applied with adequate and known weather data quality and prevent people from selecting alternative weather files that would benefit the thermal performance of their buildings.

As a first step to portraying an urban context, NBR 15575 also requires the elements surrounding a building to be modeled, such as neighboring buildings, paving, bodies of water, and any other element that may influence its performance by shading and/or reflecting solar radiation. This is especially relevant in a megacity like São Paulo, whose population density exceeds 7,300 people/km² [35,36], but is also important countrywide. In Brazil, 87% of the population lives in cities [37]. There are still many limitations to this modeling approach in terms of accurately representing an urban context, such as not including the urban heat island, longwave radiation exchange with surrounding surfaces, and airflow around the building. However, including thermal interactions with the surroundings through shading and reflection, instead of modeling an unrealistically isolated building, can be considered a step forward.

In the Brazilian housing sector, building envelopes are usually non-insulated, with the most common building components in low-income projects comprising the following: walls made of concrete, concrete blocks, or clay bricks; concrete slabs or PVC (polyvinyl chloride) ceiling; fiber cement corrugated sheets or clay roof tiles; and glazing composed of single clear glass and aluminum or steel frames [38]. In the residential building stock, around 33% of the buildings are categorized as economic class D or E (low-income) [22]. These types of housing projects are commonly developed under a Brazilian habitational program to subsidize social housing, and similar design strategies are adopted all around the country. They are, however, known for not performing adequately everywhere, particularly in hotter climate zones [38]. Nevertheless, some of these characteristics were adopted in the reference model, reflecting the Brazilian reality, especially for the most vulnerable economic classes. The reference model was adopted in NBR 15575 as a form of evaluating the thermal performance of a building through a comparison with a known and standardized envelope. This is one way to mitigate some of the uncertainties related to building performance simulation, because the main assumptions and modeling approaches will be considered identically in both models. Thus, the reference model should be developed exactly as the designed building, except for some reference characteristics related to the building components and the dimensioning of openings.

Many thermal performance standards around the world evaluate buildings primarily or exclusively based on their cooling and heating loads, and these would not correctly reflect the Brazilian context and culture. Considering that inappropriate indicators could invalidate the whole process [5], a set of key performance indicators (KPIs) were tailored to fulfill the objectives of the regulation. NBR 15575 evaluates thermal performance through three types of KPI, two calculated from the results of the model under passive operation (free-running) and one from those of the model under active operation. This approach should provide insights regarding performance under current typical passive usage, and also cover expected results when air conditioning is more frequently present in residential buildings.

Through different criteria related to each KPI, NBR 15575 establishes three levels of thermal performance: minimum, intermediate, and superior. A housing unit needs to achieve at least the minimum level to be approved according to the normative procedure. Intermediate and superior levels are optional, but may be used to enhance market value. The newest version of the energy efficiency labeling scheme for residential buildings in Brazil (INI-R [39]) was aligned with the NBR 15575 procedure. Thus, by following NBR 15575, a building's envelope is halfway through achieving an energy efficiency label from A to E. Other regulations and initiatives are also starting to align with NBR 15575 to enhance the thermal performance of residential buildings in Brazil. The standard is expected to help reduce energy consumption for cooling and heating, which may have a significant impact given that the residential sector is the second largest electricity consumer in the country [40].

3. Workflow to access thermal performance according to NBR 15575

A summary of the computer simulation procedure can be seen in Fig. 2. The building model and the reference model are simulated twice, based on two operation modes: 1) passive operation, only considering natural ventilation to regulate the thermal conditions of the indoor space during the whole year; and 2) active operation, only considering an ideal air conditioning system (AC) for computing the annual cooling and heating loads. After simulating the building when passively operated, two performance indicators are considered: 1) the percentage of occupied hours within an acceptable temperature range (PHFT, Portuguese initials); and 2) the maximum and minimum annual operative temperatures during occupied hours (Tomax and Tomin, respectively). When simulating the actively operated model, annually integrated cooling and heating loads should be considered as performance indicators (CgTR and CgTA, respectively). The KPIs calculated for operation mode are given in Fig. 2A.

In light of the propensity of houses to be naturally conditioned during the entire year, and the occupants' willingness to take various adaptive actions, NBR 15575 considers different tolerances to indoor thermal conditions. NBR 15575 established three intervals of annual mean dry bulb temperature (DBT_m) on which the calculation of key performance indicators should be based (Table 2). Therefore, as an example, if the DBT_m of a specific climate is lower than 25 ºC, the range of operative temperatures used to calculate the PHFT is between 18 ºC and 26 ºC. Outside these limits, the assistance of mechanical systems would be necessary, leading to cooling or heating loads being actively removed or supplied. When the DBT_m is equal to or higher than 25 ºC, it is assumed that heating is not required. These operative temperature ranges are supported by field surveys regarding the thermal preferences of residential building occupants [21,41]. However, it should be taken into account that the standard is not intended to assure thermal comfort, since its psychological and physiological aspects are not within the scope of the norm. NBR 15575 should guarantee thermal performance to provide adequate living conditions [15]. For this reason, and also aiming to simplify the method to broaden its usage and acceptance, NBR 15575 does not adopt specific thermal comfort models, such as the adaptive model from ASHRAE 55 (Thermal environmental conditions for human occupancy) [42].

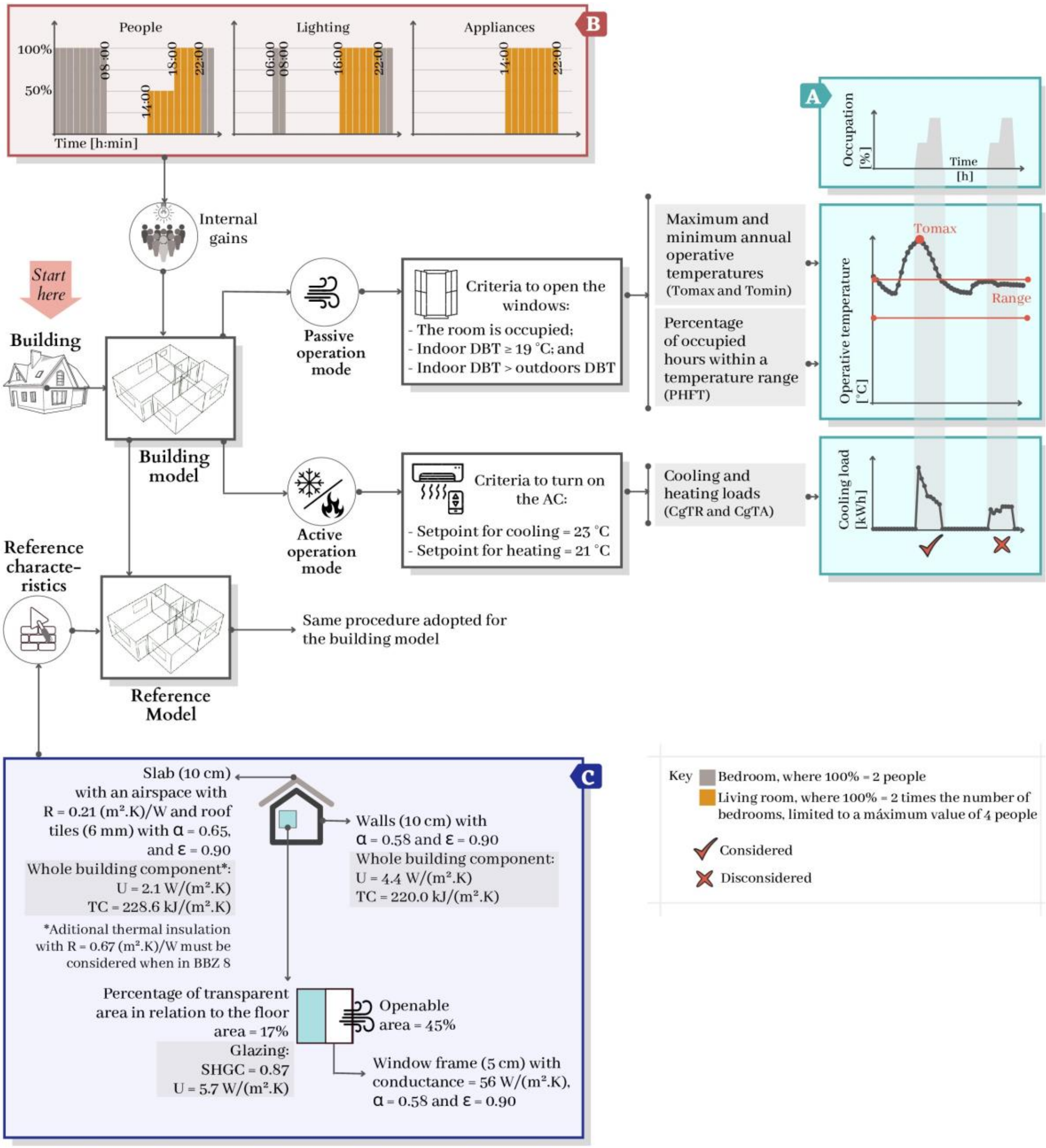


Fig. 2 NBR 15575 workflow to evaluate the thermal performance of residential buildings.

Table 2 Acceptable operative temperature ranges [15].

Outdoor temperature interval	**Annual mean dry bulb temperature (DBT_m) interval**	**Operative temperature (To) range**	**Operative temperature (To) to account for cooling loads**	**Operative temperature (To) to account for heating loads**
Interval 1	DBT_m < 25 ºC	18 ºC < To < 26 ºC	To ≥ 26 ºC	To ≤ 18 ºC
Interval 2	25 ºC ≤ DBT_m < 27 ºC	To < 28 ºC	To ≥ 28 ºC	Not considered
Interval 3	DBT_m ≥ 27ºC	To < 30 ºC	To ≥ 30 ºC	Not considered

The PHFT, calculated using Equation 1, describes the proportion of time a room is occupied and the operative temperature is within an acceptable range (Table 2). Tomax and Tomin (Equations 2 and 3, respectively) are considered indicators of extreme conditions found inside the building when it is occupied. Cooling and heating loads are calculated by comparing results from the two models, under passive and active operation conditions. Even though the model with AC is mechanically conditioned throughout the year, its thermal load is only considered when the operative temperature of the free-running model is outside the acceptable range in the same time frame. Thus, the annual summation of considered thermal load values, as given by Equations 4, 5, and 6, should translate the amount of energy to be removed from or added to the building when natural ventilation is not sufficient to guarantee acceptable indoor thermal conditions. These KPIs are calculated as follows:

$$\mathrm{PHFT} = \frac{\mathrm{N_{occ;range}}}{\mathrm{N_{occ;tot}}}.100 \tag{1}$$

$$\mathrm{Tomax} = \max(\mathrm{To_{occ;n}}) \tag{2}$$

$$\mathrm{Tomin} = \min(\mathrm{To_{occ;n}}) \tag{3}$$

$$\mathrm{CgTR} = \sum_{n=1}^{\mathrm{N_{occ;tot}}} \mathrm{Q_{cool;n}} \,.\, \mathrm{f_{To}}(n) \tag{4}$$

$$\mathrm{CgTA} = \sum_{n=1}^{\mathrm{N_{occ;tot}}} \mathrm{Q_{heat;n}} \,.\, \mathrm{f_{To}}(n) \tag{5}$$

$$\mathrm{f_{To}}(n) = \begin{cases} 0 \text{ if } \mathrm{To_{occ;n}} \text{ is within the PHFT range} \\ 1 \text{ if } \mathrm{To_{occ;n}} \text{ is outside the PHFT range} \end{cases} \tag{6}$$

In Equations 1-6, $\mathrm{N_{occ;tot}}$ is the total number of hours a room is occupied throughout the year; $\mathrm{N_{occ;range}}$ is the total number of hours a room is occupied throughout the year with operative temperatures within a predefined range in the passively operated model; $\mathrm{To_{occ;n}}$ is the hourly operative temperature when the room is occupied at hour "n" in the passive operation mode; $\mathrm{Q_{cool;n}}$ and $\mathrm{Q_{heat;n}}$ are the hourly cooling and heating loads in the actively operated model at hour "n", respectively; n is an hourly time frame considering only occupied hours; $\mathrm{f_{To}}(n)$ is a function that states whether the cooling or heating load at hour "n" should be summed in Equations 4 and 5, respectively. The PHFT is given as a percentage, Tomax and Tomin are measured in ºC, and CgTR and CgTA are given in kWh/year or kWh/m².year. These indicators only take into account rooms of prolonged stay, such as bedrooms and living rooms. Results for the whole building are calculated as: the average PHFT; the maximum Tomax; the minimum

Tomin; and the sum of all values of CgTR and CgTA, separately. The summation of hourly cooling and heating loads (CgTR and CgTA) is equal to the total thermal load (CgTT).

As internal gains, the heat emitted by people, lighting, and appliances is considered, according to the time frames and rooms of prolonged stay shown in Fig. 2B. In NBR 15575 there is no difference in the occupation patterns on weekdays and at weekends. When people are in the bedroom, they are considered to be resting (reclining) with a metabolic heat generation of 45 W/m² of the body surface area, which was defined based on the values established by the ASHRAE Handbook of Fundamentals [43]. With the same approach, people are considered seated and quiet in the living room, generating 60 W of metabolic heat per m² of body surface area. The lighting power density was considered to be 5 W/m² for both the living room and the bedroom. Appliances were considered only in the living room, with a fixed power of 120 W, equivalent to a typical television, which is a device present in 97% of houses in Brazil [22].

The reference model should consider the same building design under evaluation, changing some characteristics to those shown in Fig. 2C. To slightly improve the thermal performance of the reference model in hot climates, an insulation layer with 0.67 (m².K)/W of thermal resistance should be included in the roofs of houses built in the Brazilian Bioclimatic Zone 8 (BBZ 8), which is the warmest zone defined by NBR 15220-3 (Thermal performance in buildings - Part 3: Brazilian bioclimatic zones and building guidelines for low-cost houses) [44]. In addition to changes in building construction elements, it is also necessary to resize the windows for the transparent elements to represent exactly 17% of the zone floor area. This definition originated from an analysis of Brazilian building codes, which frequently indicate this proportion as a minimum design requirement. After resizing the windows in the reference model, it should be considered that 45% of the window area is openable, to allow natural ventilation.

Fig. 3 shows the criteria for achieving each level of thermal performance. They are based on comparing the results of each KPI for the building model with those obtained for the reference model. For instance, to reach the minimum level, the PHFT of the building model needs to be greater than 90% of the value obtained for the reference model. Additionally, the Tomax needs to be lower than or equal to the Tomax for the reference, considering a tolerance of 1 or 2 ºC, and the Tomin should be greater than or equal to the reference value, also considering a tolerance of 1 ºC. At the minimum level, a housing unit is only analyzed while passively operated, aiming to guarantee a certain level of passive survivability, always considering what is feasible in each climate. The reference model delimits this feasibility.

For the intermediate level, the building should have a better PHFT or lower thermal loads compared with the reference model. For the superior level, the thermal loads need to be reduced even further. The scale by which KPIs should be improved or reduced was determined through the creation of a simulation database with more than 60,000 evaluated housing units, considering eight representative climates of the country's eight bioclimatic zones [44] and using the weather files from ABNT TR 15575-1-1 [34]. This means that the criteria to reach these performance levels are intrinsically linked to the weather file database. Thus, if a weather file from a different source is used, the scale may not be suitable to set the difficulty to reach each level.

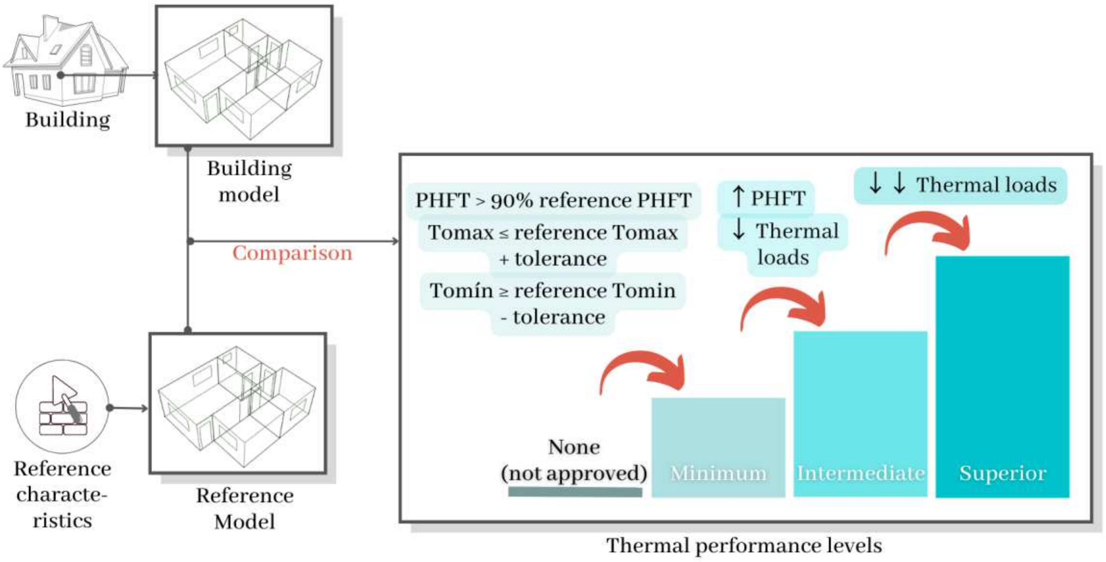


Fig. 3 Thermal performance levels.

4. Methods and results

From the procedure described in Sections 2 and 3, some questions can be addressed to reflect upon the paths that have been taken and their implications. These are detailed in Table 3. In Sections 4.1 to 4.5, several analyses were conducted to address the questions. Each analysis is delimited by these separate sections, composed of method and results.

Table 3 Questions designed to reflect upon the development of a thermal performance policy.

Theme	Questions
Representation of occupant behavior (Section 4.1)	• What is the impact of standardizing a single occupant behavior nationwide in thermal performance policies?

Theme	Questions
Representation of climate and thermal acceptability (Section 4.2)	• How should policies guide the representation of the climate in building performance simulation? • What is the impact of choosing a method to account for thermal acceptability in thermal performance policies?
Characteristics of the reference model (Section 4.3)	• How will the characteristics of reference models influence the approval of buildings according to thermal performance policies?
Key performance indicators (Section 4.4)	• Are KPIs sufficiently comprehensive to communicate the thermal performance of a building?
Performance levels (Section 4.5)	• Is this policy fostering better housing?

The case study considered throughout this paper (Sections 4.1 to 4.5) is a detached house identified by Triana, Lamberts, and Sassi [38] as representative of low-income buildings in Brazil. These buildings represent approximately 33% of all residential buildings, while 86% of the national building stock in the residential sector is composed of detached houses [45]. It has two bedrooms and a living room with an open kitchen, which will be referred to throughout this paper solely as "bedroom" and "living room", respectively. These spaces are considered rooms of prolonged stay and are targeted when evaluating the thermal performance of a building. More details of the case study are shown in Fig. 4. Characteristics of the reference model were considered for the detached house (see Fig. 2C). All models were developed using the software EnergyPlus, version 9.5.0. Natural ventilation is represented using the AirflowNetwork model, so air changes inside the house vary according to wind data from the weather file.

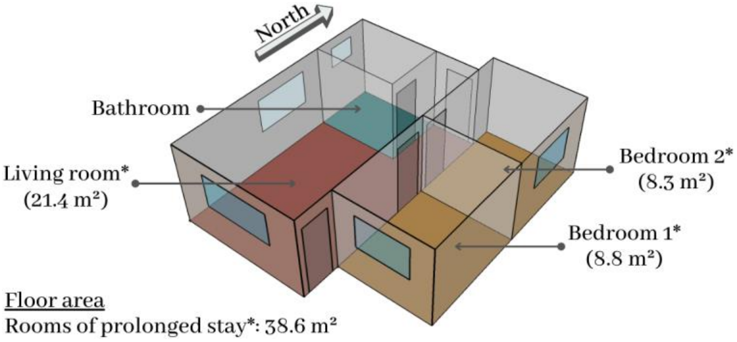


Fig. 4 Details of the case study.

The climates of Curitiba, Florianópolis, and São Luís were considered in this work, which are cities located in the South and Northeast regions of Brazil. Table 4 shows how they are described according to different climate classification systems. Fig. 5 shows their location within the Brazilian territory while juxtaposing with the ASHRAE 169 climate zones [20]. On the right side, hourly values of dry bulb temperature and relative humidity throughout the year are plotted for each city. The climate data originate from ABNT TR 15575-1-1 [34].

Table 4 Climate classification for Curitiba, Florianopolis and São Luís.

Climate classification	**Curitiba**	**Florianópolis**	**São Luís**
Brazilian bioclimatic zones [44]	1	3	8
ASHRAE 169 [20]	3A	2A	0A
Köppen-Geiger climate classification	Temperate oceanic climate (Cfb)	Humid subtropical climate (Cfa)	Bordering dry-summer tropical savanna climate (As) and tropical monsoon climate (Am)

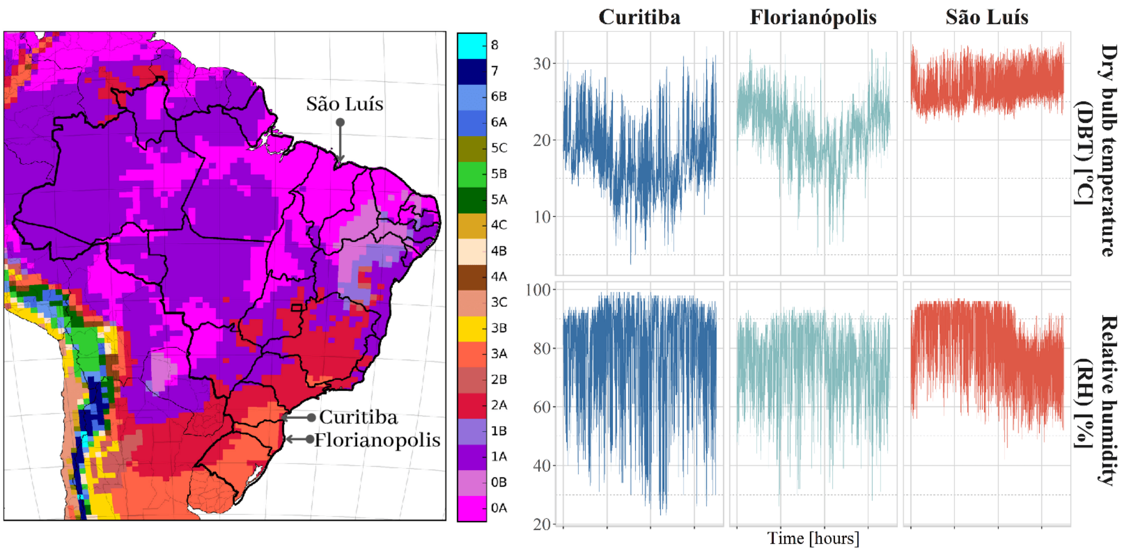


Fig. 5 Location of Curitiba, Florianópolis and São Luís within the Brazilian territory and annual variation in dry bulb temperature and relative humidity.

4.1 Representation of occupant behavior

4.1.1 Method

One of the main challenges in thermal performance policies is to choose a representative occupancy pattern. NBR 15575 uses an occupant profile in which people stay in living rooms for eight hours (from 14:00 until 22:00) and in bedrooms for ten hours (from 22:00 until 8:00). To understand how thermal performance varies with alternative occupant profiles, five different patterns were created: four of them based on location and economic class, and one to represent occupants during quarantine due to a pandemic.

The first four occupant profiles were determined based on the Electrical Equipment Possession and Usage Habits [22], which is a report developed periodically by the National Program for Electric Energy Conservation (Procel) to guide stakeholders and energy policy actions. The following occupant profiles are proposed herein: Northeast and South regions, both of them considering economic classes A and D-E (see Fig. 6). The selected regions are those where Curitiba, Florianópolis, and São Luís are located. The economic classes are defined based on the monthly income of all residents of the same house, where A represents the richest class and D-E the poorest classes [22]. Profiles tailored to represent different regions of the country and population strata should help understand the deviation level that the NBR 15575 procedure accepts by establishing a single profile countrywide. Certainly, a population cannot be defined by aspects of region and economy alone. However, these factors are associated with certain customs and traditions that will impact the thermal performance of buildings.

The quarantine profile aims to address the reality imposed on millions of people worldwide during the COVID-19 pandemic, which greatly altered occupant behavior in buildings and was not encapsulated by NBR 15575. This profile considers all occupants at home during the entire day, with half of them staying in the living room and the other half in separate bedrooms during working hours. The quarantine profile may also represent a family working from home.

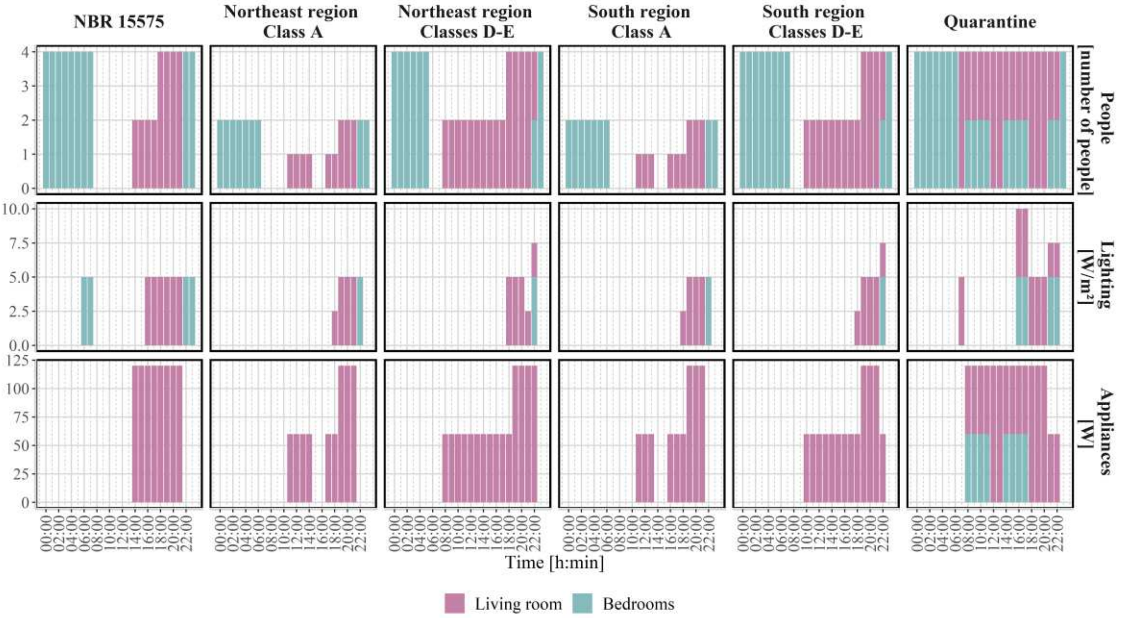


Fig. 6 Occupant profiles.

All bedrooms in the same house have identical occupancy patterns and densities. The lighting power density and power of appliances are considered the same as in the NBR 15575 in all profiles. The metabolic heat generation is considered to be 45 W/m² between 22:00 and 07:59, and equal to 60 W/m² [43] the rest of the time. Besides the occupancy pattern, a difference in occupancy density was identified [22] in classes A for the Northeast and South regions. It has half the occupants compared with the other profiles.

The analysis proposed herein considered the detached house described in Section 4 as a case study. However, it is important to note that this house is representative of a low-income residential building, which would possibly not be the choice of occupants in economic class A. Nevertheless, the same case study was applied to allow the comparison of results.

4.1.2 Results

Fig. 7 compares the results of the KPIs on varying the occupant profile according to the patterns shown in Fig. 6. Indicators calculated from operative temperature values (i.e., PHFT, Tomax, and Tomin) were less sensitive than cooling and heating loads. Eli et al. [28] found similar results when analyzing the PHFT and thermal loads.

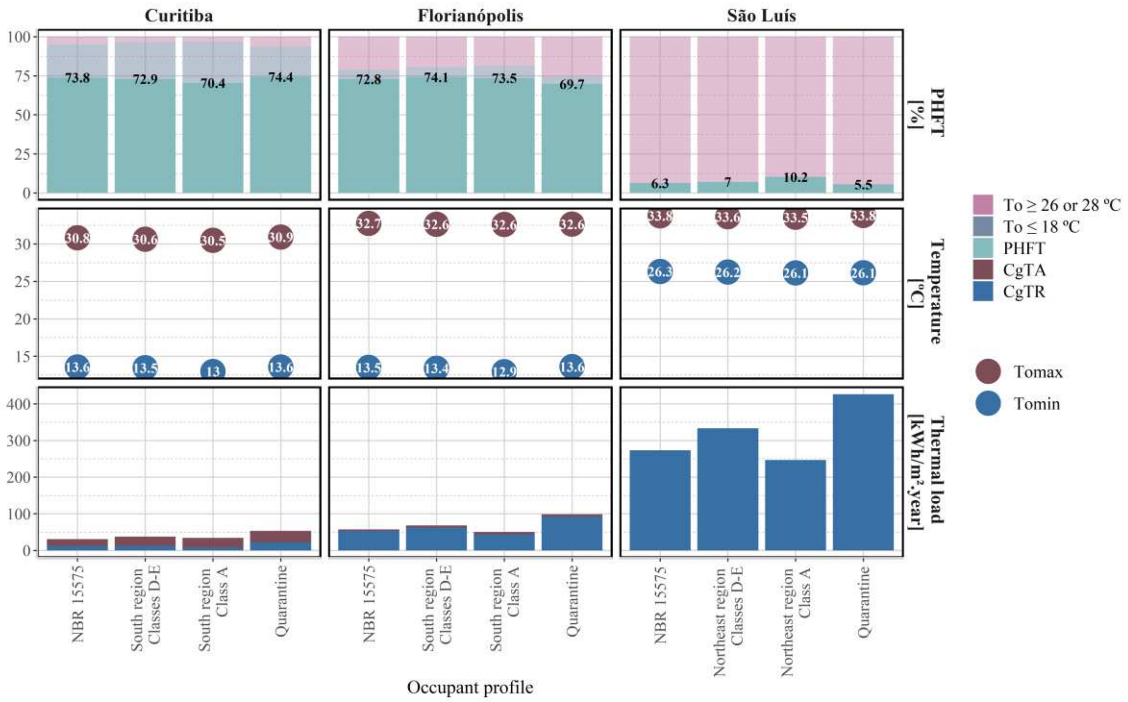


Fig. 7 Key performance indicators calculated for the reference model, when simulated with different occupant profiles.

When calculating the PHFT, the number of occupied hours with acceptable operative temperatures is standardized by dividing it by the total number of occupied hours from the specific profile. Thus, no profile moved the occupation period to hours that offer significantly more or less acceptable indoor thermal conditions compared with the NBR 15575 profile. The PHFT varied from -4.7 to +4.7 percentage points between profiles.

The Tomin is usually registered during the night while people are in the bedrooms. The Tomax occurs mostly during the daytime or in the first hours of occupation. Thus, the Tomin and Tomax occur at similar hours of the day in all occupant profiles. A more significant difference in Tomax could be found if adopted a profile where occupants are at home only during the night. Even though such a profile exists, its adoption may not be advisable since it can hide unwanted performances during the most critical periods of the day.

The PHFT, Tomax, and Tomin are the indicators evaluated when trying to reach the minimum level established in NBR 15575. The results indicate that the procedure is robust to translating the thermal performance of passively operated residential buildings, even if their occupation pattern differs from that defined in the standard. However, it is important to highlight that this analysis is not aimed at ending discussions regarding how to improve the representation of occupants in NBR 15575 or any other similar policy. Rather it tries to offer a sense of how this specific matter may or may not be boosting significant performance gaps. Additionally, only the schedules of occupancy and the use of appliances and lighting were altered, together with the occupancy density. Future studies may also change the criteria to operate windows or turn on the air conditioning system, and use other values for metabolic heat generation, lighting power density, and the power of appliances.

The thermal loads are mainly influenced by the daily number of occupied hours. The most visible distinction is between the profiles in NBR 15575 or any Class A (occupied for 18 h/day), any Class D-E (22 h/day) and Quarantine (24 h/day). The longer the period of occupation the higher the thermal loads will be. Another influencing factor is the period when the building is occupied, especially if the AC needs to be used when outdoor temperatures are very high, or after a period when the building was unoccupied, closed, and storing heat. There is also a minor impact from the number of people, which contributes to the internal heat gains. Considering this variability, the indicators of thermal loads are more suitably analyzed through a comparison with the results of a reference model that uses the same occupant profile, and absolute values should be considered with caution. A possible alternative is to weight the results according to the daily number of occupied hours [28] to enhance comparability. Future reviews of the standard could include multiple occupant profiles, but the benefits are restricted by the lack of information about future occupants during the design phase.

4.2 Representation of climate and thermal acceptability

4.2.1 Method

This section aims to investigate how the NBR 15575 simulation procedure would respond if:

- The weather file database [34] had adopted an alternative source of typical meteorological years or a Test Reference Year (TRY) (Table 5). All weather files are available in the Climate.OneBuilding.Org repository [33];
- The PHFT and cooling and heating loads were to be calculated based on acceptable thermal conditions in occupant-controlled naturally conditioned spaces (adaptive model) from ASHRAE 55 [42]. The prevailing mean outdoor air temperature ($\overline{t_{pma(out)}}$) was calculated considering the mean daily outdoor temperatures of the seven days prior to the day in question. New allowable indoor operative temperatures (To) were considered between the upper and lower 80% acceptability limits.

Table 5 Description of the weather files and their databases.

	TMY files from ABNT TR 15575-1-1	**TMYx files**	**TRY files**
Description	61% of files from reference years and 39% generated from typical months	100% of files generated from typical months	100% of files from reference years
Period or year	2001 - 2010	2004 - 2018	1969, 1963 or 1966, depending on the city
No. of files available	411	201	17
DBT_m for Curitiba	17.4	17.6	16.4
DBT_m for Florianópolis	20.9	21.1	20.7
DBT_m for São Luís	26.8	27.5	26.7
Identification	TR 15575-1-1	TMYx 2004-2018	TRY

4.2.2 Results

Fig. 8 shows hourly operative temperatures in the living room throughout the year, when the building is simulated considering weather files from the databases in Table 5. The results obtained during occupied hours are shown in darker blue, because these are the periods when the KPIs are calculated. For simplicity, only operative temperatures for the living room are shown in Fig. 8, but note that the calculation of KPIs from NBR 15575 (Fig. 9) considers also results for the bedrooms. Red lines are included in Fig. 8 to delimit the acceptable range for the PHFT, that is, between 18 and 26 ºC for Curitiba and Florianópolis, and below 28 or 30 ºC for São Luís. It can be noted that on changing the weather file for São Luís from TR 15575-1-1 to TMYx 2004-2018, the DBT_m is increased by 0.7 ºC, which is sufficient to alter the PHFT interval from 2 (To < 28 ºC) to 3 (To < 30 ºC) (see Table 2). The yellow lines show the 80% acceptability limits established in ASHRAE 55. The upper limits of ASHRAE tend to be less restrictive during the cooling season in Curitiba and Florianópolis, compared to the NBR 15575 limits. When considering the TMYx 2004-2018 file for São Luís, the ASHRAE and NBR limits are coincidental at times, with values close to 30 ºC throughout the year. For TR 15575-1-1 and TRY in São Luís, however, the ASHRAE upper limits are still close to 30 ºC, while NBR 15575 limits are reduced to 28 ºC. As previously mentioned, this is because the NBR acceptability limits are divided into three fixed intervals, which may create a sharp transition between intervals, especially for climates with a DBT_m close to 25 or 27 °C. The ASHRAE lower limits are almost always more restrictive than that of the NBR 15575, which is fixed at 18 ºC.

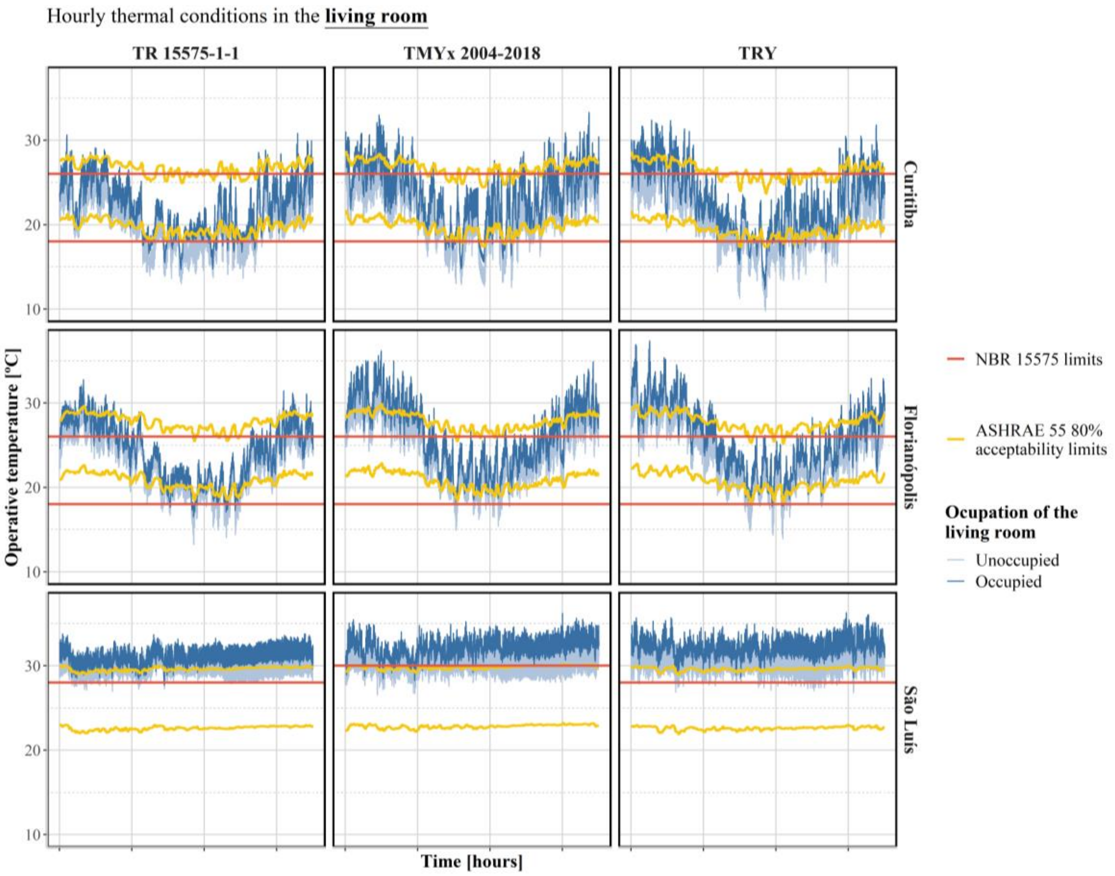


Fig. 8 Hourly operative temperatures in the living room throughout the year, together with acceptability limits of ASHRAE 55 and NBR 15575.

Fig. 9 shows the results for all KPIs established by NBR 15575, considering each weather file in Table 5, the acceptability limits in Table 2 (as they would usually be calculated for NBR 15575), and the limits given in ASHRAE 55. The latter will ultimately influence results for the PHFT, CgTA, and CgTR.

If different weather files are considered to represent the climate of Curitiba, the building analyzed would be perceived as colder when adopting TR 15575-1-1, with a higher share of heating loads (CgTA) than cooling loads (CgTR). The occurrence of colder operative temperatures is also observed with the use of the TR 15575-1-1 file for Florianópolis. Additionally, this weather file leads to lower energy needs in the building when the air-conditioner is on, reducing the thermal loads by up to 52%. The TRY file leads to the most significant amplitudes for all cities, with Tomax reaching 37.4 ºC in Florianópolis.

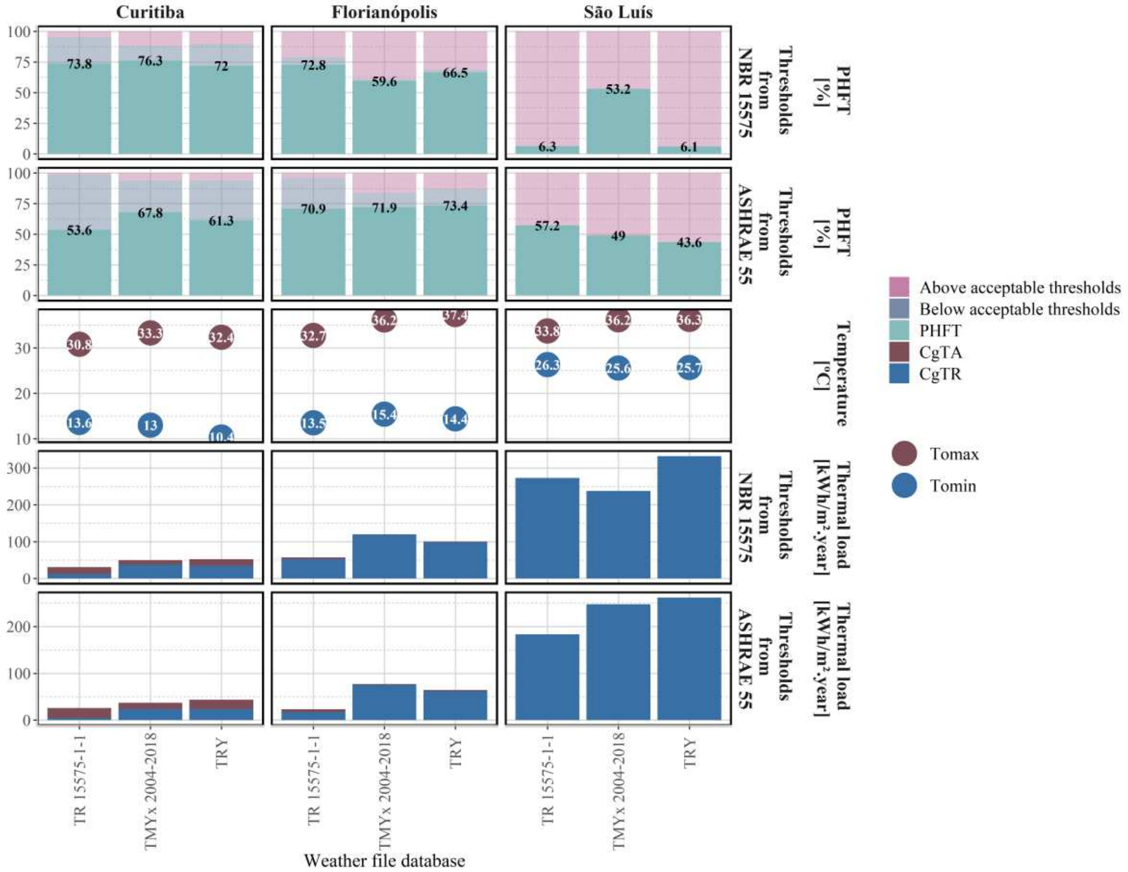


Fig. 9 Key performance indicators calculated for the reference model, when simulated with different weather file databases, and considering the acceptability limits of ASHRAE 55 and NBR 15575.

The results for São Luís evidence the most significant issues associated with changing the weather files. The PHFT results, considering the NBR 15575 thresholds, are around 6% for TR 15575-1-1 and TRY. Both of these consider an acceptable upper threshold of 28 ºC. However, when the analysis is conducted with the TMYx 2004-2018 file, the limit changes to 30 ºC, leading to an entirely different

PHFT result (53.2%). Nonetheless, it is important to highlight that the NBR 15575 procedure involves a comparison between two models, the building model and the reference model, simulated with the same weather file. Thus, the relative evaluation procedure should mitigate the differences between weather files and acceptability thresholds. Nevertheless, regarding how the thermal performance is perceived and communicated, there is clearly a significant difference between buildings with 6% and 53.2% of occupied hours within acceptable thresholds. The ASHRAE 55 adaptive method to calculate thresholds is an alternative aimed at providing a smoother transition of limits for variable climates. However, it also increases the level of difficulty of a procedure that is already considered complex in the Brazilian construction sector. Also, the adaptive comfort model described in ASHRAE 55 was developed mostly based on measured data from office buildings, which may not be representative for the analysis intended in the NBR 15575 for residential buildings. Nonetheless, changing the NBR 15575 thresholds to the ASHRAE 55 acceptable 80% limits altered the PHFT by between -12.3 and +20.2 percentage points for the two mildest climates (i.e., Curitiba and Florianópolis). In São Luís, the hottest climate, this difference reached 50.9 percentage points of occupied hours with acceptable temperatures while passively operated.

There is no rule of thumb when it comes to thermal acceptability, so the approach when establishing thresholds for NBR 15575 was to make them simple to apply when calculating the KPIs, without dismissing people's adaptation to the weather conditions. The impact of these thresholds merits consideration in a future review. Still, this approach is an important advance regarding the thermal performance analysis of buildings in Brazil, given that the previous version of NBR 15575 did not consider the aspect of human thermal acceptability and was based only on maximum temperature values.

The representation of the weather is another area that is constantly evolving to improve data quality [30] and methodological procedures. However, selecting the best weather file is a complex task, especially when a requirement is that the same procedure and quality have been reproduced hundreds of times for other climates throughout the country. Thus, it is important to ensure that the normative procedure is in line with the best resources, considering the availability restrictions and suitable coverage.

4.3 Characteristics of the reference model

4.3.1 Method

This section seeks to evaluate the suitability of the NBR 15575 reference model by 1) assessing its thermal performance in different climates throughout Brazil and 2) comparing the performance with that obtained with alternative building components.

The reference model for the detached house was simulated using 411 weather files for Brazilian cities. These files are available in the technical report TR 15575-1-1 [34]. The thermal performance was analyzed through the PHFT and the cooling load (CgTR).

After taking this first look at the reference model (Envelope 1), it was compared to the other three envelope compositions (Envelopes 2 to 4) described in Table 6. Being mainly composed of building elements made of concrete, Envelope 2 can be described as Heavy and Insulated (envelope code "HI"). On the other hand, Envelope 3 is Light and Insulated (envelope code "LI"). Case 4 is similar to Envelope 3, but its walls are Light and Uninsulated and the roof is Light and Insulated (envelope code "WLU-RLI"). All these cases have single-glazed windows with 3 mm clear glass sheets, thermal transmittance of 5.7 W/(m^2.K), and SHGC equal to 0.87. Envelopes 1 to 4 were simulated considering the climates of Curitiba, Florianópolis, and São Luís. There was only a variation in the envelope and all other characteristics were kept identical.

Table 6 Description of alternative envelopes.

Building component	**Envelope 1/ Ref**	**Envelope 2/ HI**	**Envelope 3/ LI**	**Envelope 4/ WLU-RLI**
Exterior walls	100 mm wall	EIFS composed of a concrete wall (100 mm), EPS (100 mm) and stucco	Light steel framing composed of a cement board, glass wool (50 mm), an air layer (40 mm) and a gypsum board	Light steel framing composed of a cement board, an air layer (90 mm) and a gypsum board
	U: 4.4 W/(m^2.K)	U: 0.4 W/(m^2.K)	U: 0.6 W/(m^2.K)	U: 2.5 W/(m^2.K)
	TC: 220.0 kJ/(m^2.K)	TC: 221.8 kJ/(m^2.K)	TC: 28.1 kJ/(m^2.K)	TC: 27.7 kJ/(m^2.K)
	α: 0.58	α: 0.58	α: 0.58	α: 0.58
Roof	Slab (100 mm) with a hip roof composed of 6 mm roof tiles. In São Luís an insulation layer with 0.67 (m^2.K)/W of thermal resistance is also added	Concrete slab (100 mm) with a hip roof composed of clay roof tiles (15 mm) and insulated with glass wool (50 mm)	Hip roof composed of fiber cement roof tiles (cement reinforced with synthetic fiber sheets), glass wool (100 mm), a single sided radiant barrier foil and a ceiling made of gypsum boards	
	U: 2.1 (Curitiba and Florianópolis) / 0.9 W/(m^2.K) (São Luís)	U: 0.6 W/(m^2.K)	U: 0.3 W/(m^2.K)	
	TC: 228.6 kJ/(m^2.K)	TC: 248.0 kJ/(m^2.K)	TC: 24.6 kJ/(m^2.K)	
	α: 0.65	α: 0.65	α: 0.37	

U: thermal transmittance; TC: thermal capacity; α: solar absorptance; EPS: expanded polystyrene; EIFS: exterior insulation and finish system.

4.3.2 Results

Heavy and uninsulated houses may not provide adequate thermal performance for every climate, even though this approach is common practice in the building sector from the north to south of Brazil (i.e., as in the reference model), especially for low-income housing complexes. It is clear from Fig. 10 that simply adopting the reference characteristics around the Southeast Region (latitude -20º to -25º and longitude -40º to -50º) will likely guarantee the NBR 15575 minimum level and may even deliver a good thermal performance, due to a high PHFT and low CgTR. In the case of the North and Northeast Regions, there is considerable room for improvement, with the challenge being high temperatures throughout the year, which tend to be far above the acceptable range.

Fig. 11 focuses on the cities Curitiba, Florianópolis, and São Luís, which perform differently when considering the reference building components and three alternatives. These cities represent some of the climate variability in Brazil. In Curitiba, the coldest city studied, heavy and/or insulated alternatives tend to perform better, for instance, the HI envelope showed very high performance. The opposite scenario was found in São Luís, which is a much hotter location. The highest PHFT and lowest thermal loads were obtained with the WLU-RLI envelope, but with constraints regarding the occurrence of extreme conditions (i.e., temperatures reaching 36.4 ºC). In the mild climate of Florianópolis, on the other hand, the envelopes showed relatively similar performance, with Tomax and Tomin evidencing the most significant differences (e.g., HI significantly reducing the temperature amplitude).

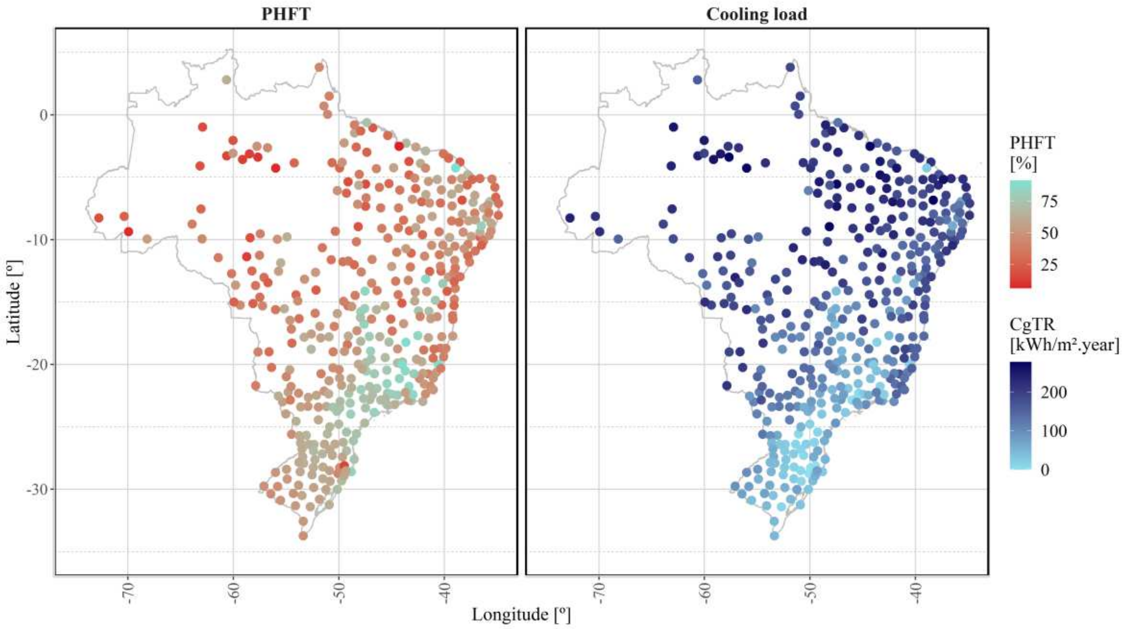


Fig. 10 Thermal performance of the reference model in 411 Brazilian cities.

The reference model may be an appropriate option for Curitiba and Florianópolis, encouraging buildings to achieve at least 65% of occupied hours under passive operation. In São Luís, a PHFT of around 6% is not a significant value to be surpassed. There are various options to enhance the performance, even by changing only the envelope. Lighter envelopes may be an alternative (e.g., LI and WLU-RLI), but caution is needed to avoid extreme thermal conditions (e.g., Tomax in WLU-RLI).

Different reference characteristics should be considered in future reviews, which could vary according to the climate zone, regional construction practices, and cost-benefit. After allowing a certain time for the construction market to adapt to the new NBR 15575 method, the rigor required to meet the minimum level can be progressively adjusted, always in line with the stage of development of the building stock.

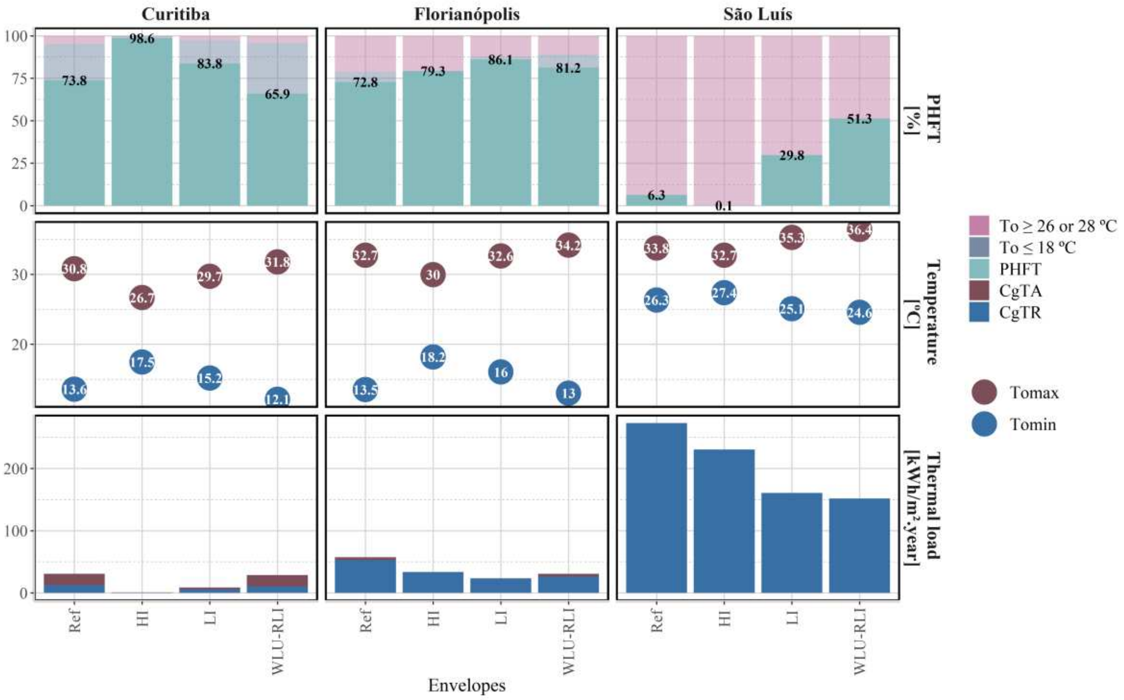


Fig. 11 Key performance indicators calculated for the reference model and three alternative envelopes.

4.4 Key performance indicators

4.4.1 *Method*

Considering the importance of selecting the best KPIs to ensure a comprehensive thermal performance analysis, this section compares the results of KPIs defined by NBR 15575 with others described in the literature. This step of the analysis seeks to investigate if alternative indicators could add important information that the NBR 15575 procedure is not able to map. Table 7 lists the KPIs analyzed, detailing the equation, unit, and information they aggregate. As in Section 4.3, this section considers the climates of Curitiba, Florianópolis, and São Luís, with Envelopes 1 (reference model), 2 (HI), and 4 (WLU-RLI) described in Table 6.

To allow comparison, the same thresholds will be considered for all indicators that require an acceptable range of operative temperatures that resemble those of thermal comfort. These are given in Table 2, from NBR 15575, varying according to the annual average dry bulb temperature (DBT_m).

Table 7 Key performance indicators for assessing thermal performance of buildings under evaluation.

KPI	**Equation or calculation procedure**	**Unit**	**Aggregated information**
Indoor overheating degree [46]	For single zone or multi-zones: $IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z}\text{-}TL_{comf,i,z}\right)^{+}.t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}t_{i,z}}$ *where z: building zone counter; Z: total number of zones in a building; i: occupied hours counter; t: time step (1 h); $N_{occ(z)}$: total occupied hours in a given calculation period; T_{fr}: free-running indoor operative temperature at time step i in zone z; TL_{comf}: comfort temperature limits at time step i in zone z.*	ºC	Quantifies the overheating risk, taking into account both the intensity and the frequency of indoor overheating
Overheating escalation factor [46]	For single zone or multi-zones: $\alpha_{IOD} = \frac{IOD}{AWD_{18ºC}}$ Calculated from IOD (above) and $AWD_{18ºC}$: $AWD_{18ºC} \equiv \frac{\sum_{i=1}^{N}[(T_{a,i}\text{-}T_b)^{+}.t_i]}{\sum_{i=1}^{N}t_i}$ *where T_a: outdoor dry-bulb air temperature; T_b: base temperature set at 18 ºC; N: number of occupied hours such that $T_{a,i} \geq T_b$*	-	Encompasses the intensity and frequency of acceptable indoor thermal conditions. When $\alpha_{IOD} > 1$, the indoor thermal conditions are worse when compared to outdoor thermal stress. When $\alpha_{IOD} < 1$, the building can suppress some of the outdoor thermal stress
Degree hours criteria [47]	For a single zone: When $\theta_o < \theta_{o,limit,lower}$ or $\theta_{o,limit,upper} < \theta_o$, $wf = \theta_o - \theta_{o,limit}$ Warm period: Σwf.time, for $\theta_o > \theta_{o,limit,upper}$ Cold period: Σwf.time, for $\theta_o < \theta_{o,limit,lower}$ *where θ_o: indoor operative temperature (ºC); $\theta_{o,limit}$: lower or upper limit of the comfort range specified; wf: weighting factor.* For multi-zones*: average value considering all zones	ºC. hours	Encompasses the intensity and frequency of acceptable indoor thermal conditions
Percentage of occupied hours above the upper limit temperature (PHT_{upp}) (adapted from [48])	For a single zone: Proportion of occupied hours with operative temperature above the upper limit temperature (T_{upp}) [48], which is 4 K above the threshold For multi-zones*: higher value among all zones	% of hours	Measures the frequency of extreme indoor thermal conditions

KPI	Equation or calculation procedure	Unit	Aggregated information
Percentage of occupied hours within a heat index range (PHHI') (adapted from [49])	For a single zone: Proportion of occupied hours that a space is occupied and its heat index (HI') [49] is within each of the different ranges [50]: ▪ Safe (HI' < 26.7 °C); ▪ Caution (26.7 °C ≤ HI' < 32.2 °C); ▪ Extreme caution (32.2 °C ≤ HI' < 39.4 °C); ▪ Danger (39.4 °C ≤ HI' < 51.7 °C); ▪ Extreme danger (HI' ≥ 51.7 ºC). For multi-zones*: average values for each range considering all zones	% of hours	Measures the frequency of indoor thermal conditions at different levels of danger towards human health
Recovery time (t_R) (adapted from [51])	For a single zone: Amount of time between the moment of maximum annual operative temperature (Tomax) and the time when the space reaches an acceptable operative temperature threshold For multi-zones*: amount of time the zone with highest Tomax takes to recover	hours	Measures the time required to recover from an extreme indoor thermal condition

*Authors did not describe a procedure to aggregate the indicator from single-zone to multi-zones (i.e., whole housing unit), thus, a procedure is established herein.

4.4.2 Results

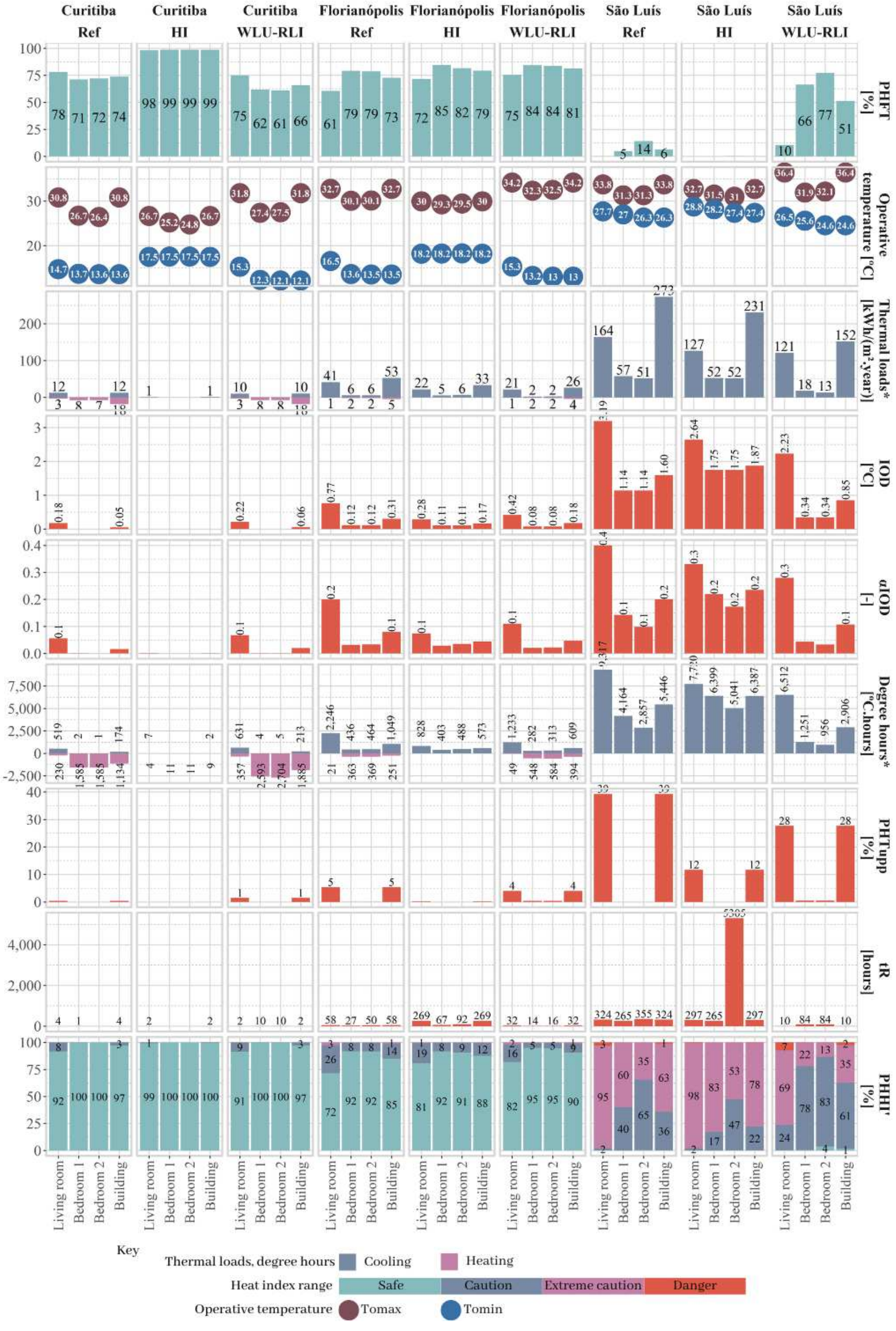
Fig. 12 shows a large mosaic where all indicators can be compared by city, envelope configuration, and room (i.e., living room, bedrooms 1 and 2, and for the overall housing unit). The main objective of this comparison is to explain the thermal performance of each case in a way that addresses, for instance, whether the building is able to maintain the design indoor thermal conditions, how often and with what intensity disruptions occur, and how the building recovers from a disruption. All of these KPIs are available to build such a narrative, but only some of them will effectively add information.

A heavy and insulated (HI) envelope provided optimal results for Curitiba, a city with a temperate oceanic climate (Köppen-Geiger's Cfb), at both the individual room and building levels, which is verified by all KPIs. It can be expected that this building, when exposed to typical meteorological conditions and with a standardized occupant behavior, could survive passively throughout the year. The maximum and minimum operative temperature ranges are close to the acceptable thresholds for the PHFT (18 ºC – 26 ºC), indicating that no extreme conditions are reported for this case. However, when moving to a light envelope (WLU-RLI), some indicators show that the building is often cold. This can be seen through the increased number of degree hours below 18 ºC, followed by the quantification of heating loads to meet desirable conditions. This effect can be noted especially in the bedrooms, which are occupied during the night, possibly because the light and mostly uninsulated envelope cannot store enough heat and loses it to the colder outdoor environment. Thus, the bedroom operative temperature can drop as low as 12.1 ºC (Tomin). One aspect to highlight is that, even though some KPIs have a component to address thermal discomfort associated with cold, the main focus herein is overheating because it tends to be the primary concern in the context being analyzed. For instance, the PHHI' cannot capture the occurrence of cold since anything below 26.7 °C is considered "safe", according to the heat index ranges. Nevertheless, a similar evaluation would be possible in cold climates with the adaptation of some of the KPIs.

In the mild climate of Florianopolis, all three selected envelopes obtained relatively good thermal performance, with some key differences. On comparing the average PHFT calculated for each envelope, WLU-RLI obtained the highest value with 81% of occupied hours with operative temperatures between 18 ºC and 26 ºC. Ref and HI obtained corresponding values of 73% and 79%, respectively. However, when looking at extreme conditions, Ref and WLU-RLI obtained considerably higher annual maximum and lower annual minimum operative temperatures (Tomax and Tomin, respectively). This can also be observed for the percentage of occupied hours above the upper limit temperature (PHT_{upp}), with these envelopes presenting between 4 and 5% of occupied hours with operative temperatures 4 K above the superior threshold of 26 ºC, considering the worst condition of the indoor spaces. PHT_{upp} for HI was negligible, that is, even when outside acceptable thresholds, the operative temperatures are rarely higher than 30 ºC. On the other hand, once an annual maximum operative temperature of 30 ºC was reached in the living room of HI, it took 269 hours (11.2 days) (t_R) to recover and reach 26 ºC again. In contrast, Ref and WLU-RLI recovered much faster from even higher temperatures. Ref recovered from 32.7 ºC in 2.4 days and WLU-RLI from 34.2 ºC in 1.3 days.

The climate in São Luís is classified as 0A by ASHRAE 169 [20], being considerably more severe with respect to heat than Curitiba and Florianopolis. Heavy envelopes (e.g., Ref and HI) in this climate do not usually perform well because the outdoor temperature is constantly high and heat tends to be stored in the envelope with few opportunities to dissipate. On the other hand, a light and almost uninsulated envelope (WLU-RLI) may not provide enough resistance against the severity of outdoor thermal conditions. In all cases, the thermal performance of the living room was low in São Luís, with none to very few moments (maximum PHFT equal to 10%) with operative temperatures within the threshold for São Luís (below 28 ºC). Even though some KPIs indicated very similar performance results for the living room in Ref and HI (PHFT equal to zero and similar PHHI'), it can be observed that the intensity of thermal discomfort was not the same. For instance, Ref was worse than HI by 1,597 ºC.hours, which is also reflected by a considerably higher proportion of time during which the room is exposed to operative temperatures above 32 ºC (39% of the time for Ref versus 12% for HI). If these overheating periods were to be distributed in occupied hours throughout the year (IOD), the living room would always be around 2.23 ºC to 3.19 ºC above the threshold. However, considering that the ambient warmness degree (AWD) for São Luís is equal to 7.97 ºC for a base temperature of 18 ºC, which indicates the severity of outdoor warmness [46], it can be considered that all envelopes are capable of suppressing some of the outdoor thermal stress ($\alpha_{IOD} < 1$). Additionally, considering all three envelope alternatives, the living room would require at least 121 kWh/m² of thermal load to be removed annually if an air conditioning system were installed.

Results obtained for WLU-RLI in São Luís could be misleading depending on the indicators adopted and the calculation procedure used to aggregate results at the building level. The bedrooms are only occupied after 22:00, allowing a light envelope to dissipate heat. This is reflected by a high PHFT value (66% - 77%) for this room. The living room, which is occupied during the day, does not follow this pattern and has a PHFT of only 10%. At the building level, however, the average performance is generally of interest, for which a high value of 51% was obtained. In this context, the observation of multiple indicators can be of value to fill in the gaps and provide a comprehensive evaluation. Even with a high average PHFT value, indicating good resistance to hazardous temperatures, stress conditions should also be verified. In this regard, a PHT_{upp} value of 28% would be obtained, indicating that more than a quarter of the hours occupied in the worst-performing room would be extremely uncomfortable. In fact, if the heat index was adopted to describe the indoor thermal conditions, 7% of occupied hours in the living room would be considered dangerous to the occupants' health. On the other hand, even when the operative temperature in the living room reaches 36.4 ºC (maximum value for all spaces), the light envelope only takes 10 hours to recover and reach the threshold again. This contrasts with the minimum of 265 hours (11 days) required by heavy envelopes in the same climate. However, it can be observed that the bedroom takes longer to recover from a lower maximum temperature (84 hours).



*CgTA and heating degree hours are given as negative values to improve visibility

Fig. 12 Comparison between key performance indicators calculated for the reference model and two envelope alternatives.

Some perceptions regarding the calculation of the recovery time (t_R) should be mentioned. First of all, the disproportional t_R of 5,305 hours obtained for bedroom 2 with the HI envelope in São Luís led to the conclusion that, after reaching its maximum, operative temperatures fluctuate between 28 ºC and 31 ºC. This could be expected given the PHFT value of zero, which leads to a second observation: especially in cases where passive survivability is very low and/or considering an envelope with high thermal mass, t_R will be greatly influenced by the time frame in which the annual maximum operative temperature occurs. For instance, if Tomax is registered at the end of the simulation period, t_R would only be calculated until the end of this period, even if no recovery has been achieved. This problem was identified only for São Luís in the following cases and rooms: bedroom 1 in the case of Ref and all spaces in the case of HI. All other t_R values were calculated normally.

Some KPIs can be chosen to enhance the thermal performance analysis. The capacity to maintain indoor thermal conditions can be portrayed by the previously adopted PHFT, which measures the frequency of events (i.e., temperatures within acceptable conditions). The IOD could also be included as a measure of intensity, giving an average degree to which the acceptable thresholds are surpassed. In addition, Hamdy et al. [46] provided a procedure to aggregate results from the space level to the building level. Alternatively, degree-hours can be selected as a measure of intensity, but the significance of the magnitude of the values (i.e., which values are good and which are not) may be unclear to those unfamiliar with this indicator. The PHFT could also be changed to the “safe” range of the heat index. In fact, even though most of the indicators analyzed herein consider the operative temperature as the main input, the same procedure could be applied to indicators based on other parameters that describe indoor conditions, such as the heat index [49], humidex [52,53] and SET [42]. Also, the adaptive thermal comfort model could be adopted, with a variable thermal comfort range based on outdoor air temperature [42,48].

As a complementary measure related to the depletion of energy resources, cooling and heating loads (CgTR and CgTA) should reflect the need for active technologies to provide acceptable indoor thermal conditions. A total annual value is considered, which is the sum of the annual cooling and heating loads (CgTT). In the future, this indicator could also be translated into energy consumption and cost. To enhance comparability, thermal loads are divided by the building floor area.

To account for the intensity of uncomfortable conditions, the annual maximum operative temperature (Tomax) is adopted by NBR 15575, which could be followed by recovery time (t_R) to estimate how long it takes to recover from this maximum temperature. Additionally, the frequency of these uncomfortable events may be accounted for by the percentage of occupied hours above the upper limit temperature (PHT_{upp}).

4.5 Performance levels

4.5.1 Method

This last method section analyzes whether the thermal performance of buildings is improved by complying with the criteria that delimit each level of the NBR 15575. An excellent thermal performance is perceived as follows: PHFT close to 100%; CgTT close to 0 kWh/m².year; low Tomax, especially close to 26 ºC; high Tomin, especially close to 18 ºC. Evidently, it is not possible for all buildings in all climates to reach a PHFT close to 100%. For this reason, prioritization should be given to looking for a trend in the improvement in the KPI results, rather than considering the absolute values.

To observe such a trend, a new simulation database was developed with a total of 9,375 cases, divided equally between the three cities: Curitiba, Florianópolis, and São Luís. Sobol's sampling method was used to generate combinations of the characteristics described in Table 8, following the method described in the literature [54–58]. These were applied to the case study described in Section 4.

Table 8 Characteristics of the cases contained in the sample

Element	Property	Unit	Minimum	Maximum
Walls	Thermal transmittance (U)	W/(m².K)	0.22	4.35
	Thermal capacity (TC)	kJ/(m².K)	18	440
	Solar absorptance (α)	-	0.2	0.9
Roofs	Thermal transmittance (U)	W/(m².K)	0.44	3.85
	Thermal capacity (TC)	kJ/(m².K)	22	550
	Solar absorptance (α)	-	0.2	0.9
Floors	Thermal transmittance (U)	W/(m².K)	0.72	5.00
	Thermal capacity (TC)	kJ/(m².K)	23	440
Glazing	Thermal transmittance (U)	W/(m².K)	2.50	6.00
	Solar heat gain coefficient (SHGC)	-	0.2	0.9
	Window-to-wall ratio	%	5	90
	Window opening factor	%	5	100
Overhangs	Depth	m	0.01	2.50
Blinds	Presence (1) or absence (0)	-	0	1

4.5.2 Results

The thermal performance of each one of the 9,375 cases was classified based on the criteria for each level detailed in the NBR 15575, that is, minimum, intermediate, or superior. Fig. 13 focuses on cases that were not approved and also cases classified as superior. It shows the relation between the PHFT and the thermal loads (CgTR + CgtA), and is colored according to the Tomax. This relation resembles a linear relationship with some noise. Thus, it can be observed that it is possible to have results of very poor passive autonomy (i.e., PHFT equal to 0%) while requiring 150 kWh/m² of thermal loads a year, or almost 400 kWh/m².year. This is especially noticeable in cases from São Luís. The cases which would not be approved include houses with PHFT higher than 60%, but Tomax reaching over 45 ºC. In fact, an excessively high Tomax value was among the reasons for disapproving between 55% and 81% of the cases that did not reach the minimum level, while the PHFT was responsible for between 29% and 59%, and Tomin was responsible for less than 11% of such cases. When cases reach the superior level, the results are less dispersed and concentrated towards higher PHFT values, with lower thermal loads and Tomax values.

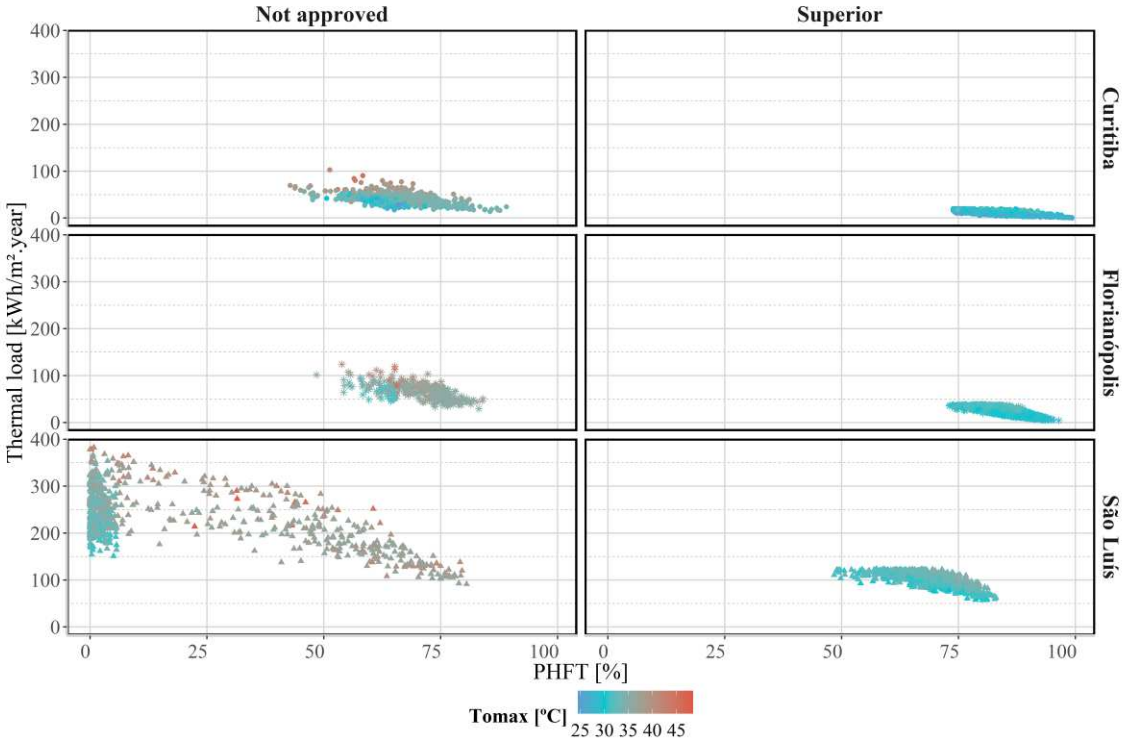


Fig. 13 Relationship between the PHFT and the thermal loads of cases not approved applying the NBR 15575 procedure and cases classified as superior level.

Fig. 14 shows how the thermal performance evolves as cases comply with higher levels in the NBR 15575. The lower right frame is empty because the Tomin is not analyzed in hot climate zones like that of São Luís. The dashed black line marks the results of the reference model. The arrows in the corners show the direction in which the results need to move to achieve an improvement in thermal performance.

On approaching the superior level, houses tend to rely on passive conditioning over 75% of the occupied time in Curitiba and Florianópolis. Consequently, the energy used for air conditioning should be kept at a minimum. Also, the relatively mild climates in these cities mean that the improvements are more subtle compared to the extremely hot climate [20] of São Luís. Buildings in hot climates are highly sensitive to the building techniques and strategies applied to cope with the outdoor environment. Thus, the right incentives (i.e., intermediate and superior levels) may dramatically improve their thermal performance, even allowing for a significant share of passive autonomy and reduced energy use by up to a quarter.

Extreme conditions tend to be less severe when reaching higher thermal performance levels, for example, significantly mitigating the occurrence of temperatures over 35 ºC. NBR 15575 considers +2 ºC and -1 ºC of tolerance to the reference values of Tomax and Tomin for single-family buildings, respectively. In some cases, these criteria may not be rigorous and can be adjusted in future reviews after the procedure has matured within the construction market. It is important to highlight that these values reflect instances when the temperature reached the extremes, but these conditions did not necessarily happen often. Thus, caution is needed when applying the criteria related to Tomax and Tomin. A measure of the frequency of extreme events (e.g., the PHT_{upp} from Section 4.4) could also be used to gain a better understanding of the thermal stress to which the occupants are exposed.

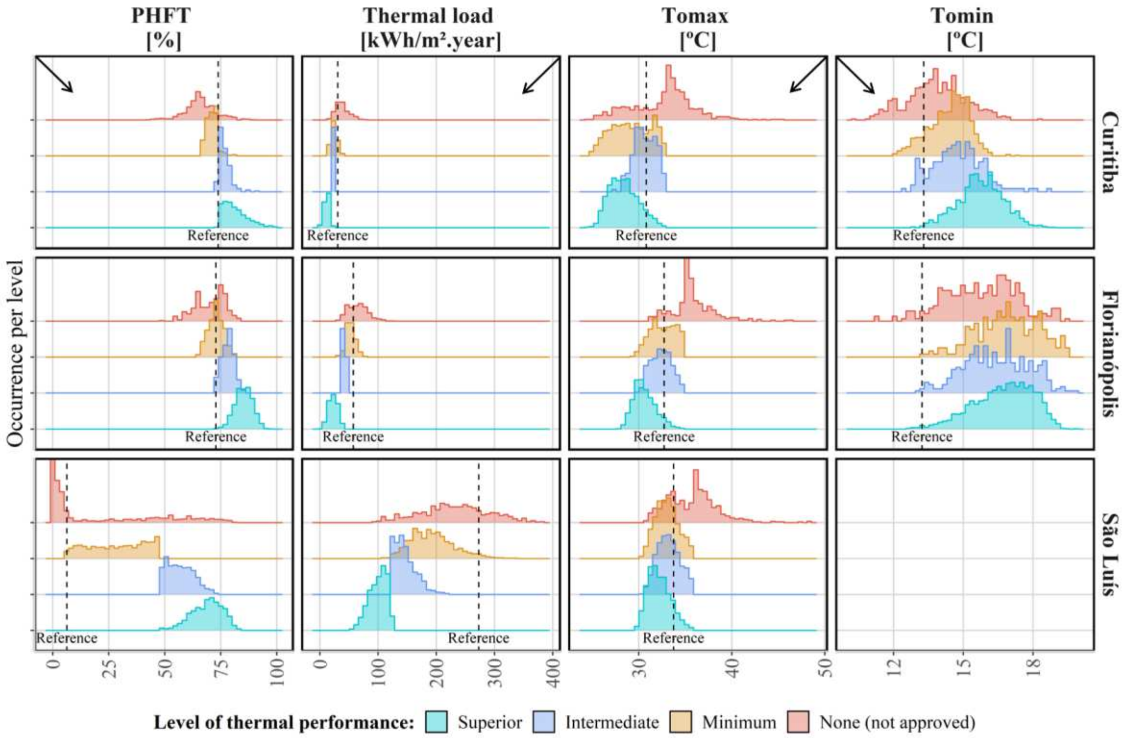


Fig. 14 Frequency distribution of results by city, key performance indicator and thermal performance level.

5. Conclusions

This article examines some of the choices involved in developing a national thermal performance standard for residential buildings. Herein, the Brazilian standard NBR 15575-1:2021 is explored, aiming to shed light on the particularities of buildings in hot developing countries whose reality is seldom adequately represented by international standards. Besides describing the method itself, this paper also touches on subjects related to the representation of occupant behavior, climate, and thermal acceptability in building performance simulation, as well as the use of reference models, key performance indicators, and performance levels. These themes are discussed below while answering the questions raised in Section 4.

- *What is the impact of standardizing a single occupant behavior nationwide in thermal performance policies?*

The occupant behavior is still overly simplified in building performance simulation, especially when integrated into building policies [29,59], despite its capacity to completely modify the thermal balance of a building [60]. NBR 15575 is not an exception, since developing complex occupant models that are applicable nationwide remains a challenging next step. Considering these limitations, an evaluation of whether simple modifications to the occupancy pattern and density would significantly impact thermal performance was carried out. The results varied with the key performance indicator. The KPIs calculated from the passively-operated building (i.e., the PHFT, Tomax, and Tomin) were fairly insensitive to changes in the occupant profile. For instance, the PHFT only varied from -4.7 to +4.7 percentage points between profiles. These are the KPIs analyzed for the minimum thermal performance level, which defines which residential buildings can or cannot be built. Consequently, this is a positive outcome as it indicates that the procedure is robust enough to absorb a certain level of variability in the occupant behavior.

Conversely, the thermal loads increase as the occupation time increases and this is also influenced by the period of the day in which the air conditioning system is used. Thus, absolute values should be looked upon with caution by practitioners in the construction industry, as well as by the building owner. Nonetheless, the NBR 15575 procedure mitigates some of this impact by defining criteria to reach each thermal performance level (intermediate and superior) according to a comparison with results from the reference model.

Future studies could examine greater disturbances in the human-building dynamics, such as varying the interaction with windows, air conditioning systems, lighting, and appliances. Future reviews of NBR 15575 could include multiple occupant profiles. However, a further step to better represent the occupant is constrained by the lack of data with the necessary quality, detail, and coverage. Also, data related to future occupants are scarce or nonexistent during the design phase of a residential building, which prevents modelers from making an informed decision.

- *How should policies guide the representation of the climate in building performance simulation?*

The representation of the climate is another critical aspect for building performance simulation. This paper demonstrates that a single-family house in the same location is perceived as colder, hotter, or with a significantly different temperature amplitude in free-running mode when the weather file database is changed. Additionally, the thermal loads to be removed by an air conditioning system could be reduced by as much as 52% when actively operated. Thus, it is advisable to establish a standard database of weather files to enhance the consistency of the results on applying a certain building performance policy. In the case of NBR 15575, this is achieved through a technical report [34] recommending weather files from a known source, with the maximum available coverage of the national territory. Nonetheless, extensive data quality control is necessary to properly represent the climates, which can be challenging in large and diverse areas such as the Brazilian territory.

The next step to represent the climate in building performance simulation is to model the effect of the urban context. In NBR 15575, a simplified approach was chosen to account for the shading and reflections caused by surrounding elements. Other aspects that could be further explored are the inclusion of methods that modify weather files to account for urban heat islands, and/or that change wind speed and direction data from the weather file to consider the impact of surrounding elements. Additionally, policies are still mainly focused on addressing building performance exposed to climates from the past. As new buildings are expected to last over 50 years, it is important to also predict their performance in future scenarios. This is becoming increasingly possible with the diffusion of techniques for projecting future weather conditions (e.g., see [61]) and could also be a viable next step for building performance policies.

- *What is the impact of choosing a method to account for thermal acceptability in thermal performance policies?*

The definition of acceptable indoor thermal conditions should be rooted in a good understanding of the targeted population and its typical behavior, the local climate, and the policy scope. In the context where NBR 15575 is applied, people are willing to adopt adaptive behaviors, since residential buildings are usually operated in free-running mode. NBR 15575 considers fixed intervals of acceptable operative temperatures, adjusted according to the local climate. This is an intermediate step before establishing a prevailing mean outdoor temperature, as in the ASHRAE 55 adaptive model [42], which aims to reflect an adaptive capacity without introducing additional complexity to an innovative procedure in the Brazilian construction market. Moreover, the adaptive comfort model [42] is mainly based on measured data from office buildings, which may not be representative of residential buildings in Brazil. Changing the NBR 15575 thresholds to the ASHRAE 55 acceptable 80% limits altered the PHFT by up to 50.9 percentage points and thus the thermal performance of a building would be perceived and communicated completely differently. Further studies are recommended to find the best approach to consider thermal acceptability, taking into account not only the value of thresholds *per se*, but also how it fits within the overall procedure and its reception by practitioners in the field.

- *How will the characteristics of reference models influence the approval of buildings according to thermal performance policies?*

The thermal performance of the reference model delimits which buildings are considered acceptable to be built, according to NBR 15575. Currently, the characteristics considered therein reflect those typically found in the Brazilian construction sector, especially for low-income housing. However, given the diversity of climates in Brazil, these characteristics lead to a range of thermal performance from high to poor. In mild climates, like in Curitiba and Florianópolis, having a heavy and uninsulated envelope as reference means incentivizing buildings to have at least 65% of occupied hours of a single-family house operated passively throughout the year. In a hot climate (e.g., in São Luís), however, buildings are allowed to have a poor passive operation of less than 6% of occupied hours. While it may be appropriate to vary the reference characteristics nationwide, it is also necessary to thoroughly evaluate their performance with multiple key performance indicators, especially verifying their capacity to mitigate extreme thermal conditions. Different reference characteristics should be analyzed in future reviews of NBR 15575, which may vary with the climate zone, regional construction practices, and cost-benefit.

- *Are KPIs sufficiently comprehensive to communicate the thermal performance of a building?*

Choosing adequate key performance indicators is challenging and needs to consider what the stakeholders are and how they will use these metrics. In the context of NBR 15575, a comprehensive set of KPIs should appropriately map major impacts on the thermal performance of a building to be used by design teams. Most widespread KPIs describe the frequency, intensity, or duration of events, i.e., indoor thermal conditions being negatively affected. Selected KPIs should be those that provide a clear path to guide necessary design improvements, in light of identified compromises to obtain the best feasible solution.

NBR 15575 evaluates thermal performance through multiple KPIs: the PHFT, maximum and minimum operative temperatures (Tomax and Tomin), and cooling and heating loads. These indicators cover thermal performance while passively and actively operated. The PHFT, which is a measure of the frequency of acceptable indoor thermal conditions, could be complemented by the IOD to enhance the thermal performance analysis. The IOD provides a measure of intensity by which acceptable thresholds are surpassed. It is measured in degrees Celsius. To have a better idea of the performance under stressful conditions, the Tomax could be complemented by the recovery time (t_R). This estimates the amount of time a building needs to recover from an extreme condition (i.e., the Tomax). The frequency with which these extreme conditions occur can also be accounted for by the percentage of occupied hours above the upper limit temperature (PHT_{upp}). It measures the proportion of occupied hours for which the worst performing room reaches operative temperatures 4 K above the acceptable upper threshold. Even though indoor thermal conditions are described herein mostly by the operative temperature, they could also be analyzed through the heat index [49], humidex [52,53], and SET [42], if found to be appropriate. Additionally, besides the cooling and heating loads, the depletion of energy resources could be addressed through energy consumption and energy cost.

- *Is this policy fostering better housing?*

As buildings reach higher levels of thermal performance (i.e., intermediate and superior), a visible progression is perceived regarding the proportion of time a building can be operated passively and the required thermal loads when it cannot. Such a progression is prominent in hot climates like that of São Luís, where the cooling loads of a single-family house ranged from almost 400 kWh/m^2.year when not approved by NBR 15575 to 57 kWh/m^2.year with a superior level.

Extreme conditions, described by the Tomax and Tomin, are significantly reduced when buildings reach at least the minimum level. However, even if a building design is able to remove the most dangerous thermal conditions, the frequency of weather extremes is expected to increase [62]. Thus, besides fostering good thermal performance under typical conditions, it is increasingly necessary to plan for adverse weather and address the thermal resilience of buildings. NBR 15575 was not developed to analyze resilience, but the method it describes could provide an adequate foundation to be expanded upon.

The main lessons learned while taking part in the development of a national thermal performance standard for residential buildings in a warm developing country can be summarized as follows:

- International best practices are welcome to support the development of a new method. However, these practices often do not correctly represent the context of tropical countries, which may lead to the selection of strategies that are ineffective or that will not be properly used during the operation phase. Cultural, behavioral and climate characteristics should guide each step of the analysis;
- Lack of data and resources often constrain the adoption of state-of-the-art procedures (e.g., limited availability of measured weather data, and occupant behavior parameters). In this context, building the foundations of a comprehensive thermal performance analysis should be prioritized, which

involves defining the boundary conditions of the analysis and suitable key performance indicators. Necessary improvements should be made clear, together with well-defined demands and next steps;

- Expectations from all stakeholders should be aligned, from researchers to market players, often requiring compromises to facilitate the approval of the standard and its subsequent application;
- Key performance indicators should be thoroughly chosen based on the targeted audience. Especially in free-running and mixed-mode buildings, a comprehensive judgment is often possible only through a set of indicators, instead of only one. For instance, pointing to the energy demand and the occurrence of overheating. These indicators should work together to identify the problems that need to be addressed, e.g., by the design teams;
- Standards can encourage the design of better buildings through the delimitation of different performance levels, which can organically increase the market value of those with higher levels or can also be addressed through economic incentives.

These conclusions are limited to:

- The adopted case study, which is representative of a single-family house in Brazil;
- The three climates used for building performance simulations; and
- The particularities of the NBR 15575 procedure, which are not necessarily applicable to other thermal performance policies.

CRediT authorship contribution statement

A.F. Krelling: Conceptualization, Methodology, Formal analysis, Visualization, Writing - Original Draft. **L.G. Eli:** Methodology, Visualization, Validation, Writing - Original Draft. **M.S. Olinger:** Methodology, Visualization, Validation, Writing - Review & Editing. **R.M.E.S. Machado:** Methodology, Data Curation. **A.P. Melo:** Writing - Review & Editing, Supervision. **R. Lamberts:** Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX B – Paper 2

A simulation framework for assessing thermally resilient buildings and communities

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Abstract

The increasing frequency and severity of weather extremes caused by climate change evidence the need to assess buildings beyond their typical thermal and energy performance under normal operation. It is also essential to evaluate thermal resilience to safeguard occupants' health during extreme events and power outages. This study proposes a simulation framework to evaluate and enhance the thermal resilience of buildings against indoor overheating using an integrated set of performance metrics. This work also addresses how to aggregate resilience profiles of single buildings into the urban scale, supporting the evaluation of thermally resilient communities. This is the first step to connecting building and urban scales in a resilience analysis, seeking to further address other stakeholders' needs in the future. The application of the framework is exemplified through a case study considering three different climates in Brazil. This analysis allowed identifying cases with poor thermal resilience and essential dependence on air conditioning to guarantee the survivability of occupants during extreme hot weather. Nonetheless, by only changing the envelope's thermal transmittance and thermal mass, buildings' thermal autonomy increased up to 65 percentage points and cooling loads were reduced by up to 61% in the hottest climate, São Luís. However, additional strategies are

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necessary to mitigate remaining indoor extreme thermal conditions, such as solar shading and increased air movement.

Keywords: thermal resilience; building performance simulation; building resilience; community resilience.

1 Introduction

1.1. Background

The frequency and intensity of weather extremes have increased in the past decades as a consequence of human-induced climate change [1]. In 2019 there were 361 natural disasters recorded globally; 29% of them related to extreme weather or extreme temperatures [2]. In this context, the term "resilience" has been flooding academic literature. Nevertheless, this is not a new concept. In fact, it has been discussed since roughly 1973, when C.S. Holling [3] published his seminal paper about "resilience and stability of ecological systems." Holling [3] addresses resilience in terms of the persistence of relationships within a system, despite future unexpected changes. These changes can be understood mainly based on three equilibrium viewpoints [4,5].

Under the first, the equilibrium-centered viewpoint, resilience describes "how fast the variables return towards their equilibrium following a perturbation" [6]. The equilibrium-centered viewpoint is thoroughly contested by Holling [5], who describes it as "the policy world of a benign nature where trials and mistakes of any scale can be made with recovery assured once the disturbance is removed." Notwithstanding, this is the basis for many resilience studies. It is also termed "**engineering resilience**" [7].

The second viewpoint describes multiple equilibria states, with the system being able to adapt and change, reaching a stable state that is not necessarily the same. This second viewpoint is also called "**ecological resilience**" and is focused on "maintaining existence of function," while the former engineering approach is focused on "maintaining efficiency of function" [7].

The third viewpoint considers a non-equilibrium dynamic, where the focus is to stay "in the game" rather than reaching a stable condition [3,8]. According to Holling [5], "successful efforts to constrain natural variability lead to self-simplification and so to fragility of the ecosystem." This viewpoint is called by some authors "**evolutionary resilience.**" For example, Davoudi [9] states that "faced with adversities, we hardly ever return to where we were."

Throughout the years, the concept of resilience has been reshaped to fit many scientific fields. This approach has an upside and a downside: on one hand, divergent conceptions and approaches may convey vagueness and ambiguity to its adoption; on the other hand, its malleability can foster communication between distinct areas and stakeholders [10,11].

The urban environment is a fruitful field to study resilience, given the concentration of people and economic activities that make risks and damages less acceptable. Also, this very urbanity often enhances hazards, especially those related to climate change [12]. The built domain determines where functions essential to human life are carried out [13] within an urban system. It is a source of protection against weather conditions, enhancing human health and risk reduction [14]. Among several disruptive events that may affect the built environment, the extreme temperature hazard [15] stands out for affecting occupants' health and well-being, while also depleting natural resources through an increasing need for air conditioning, which is the fastest-growing use of energy in buildings [16].

Studies that tackle the resilience of buildings regarding indoor thermal quality can be found in literature, mainly through terms such as thermal resilience [17–19], robustness [20–22] and resilient cooling [15,23]. The latter comes from the work of the International Energy Agency's Annex 80: Resilient Cooling of Buildings, whose objective is to support low energy and low carbon solutions for addressing cooling and overheating issues in buildings [24]. As a product of Annex 80, the work of Attia et al. [23], together with that of Miller et al. [15], provide a thorough definition of resilience in the built environment. To sum it up, Attia et al. [23] describe resilience against overheating and power outages through stages of vulnerability, resistance, robustness, and recovery. A vulnerability assessment that considers foreseeable risk factors is conducted during the design stage. The resistance stage encompasses the period when the building is exposed to usual and extreme weather conditions, yet its design features and embedded coping strategies are able to prevent critical thermal conditions. The robustness stage is characterized by the failure of these features and strategies. When a robust building reaches critical conditions after failure, it is able to survive and adapt its performance, leading to a recovery stage.

This, or similar definitions, may be applied to numerous buildings, but still, it does not easily translate thermal resilience of the group of buildings (i.e., within the urban scale). An aggregation procedure is already common when analyzing energy consumption or carbon emissions of groups of buildings, e.g., in bottom-up approaches for urban building energy modeling (UBEM) [25,26]. However, a framework to quantitatively evaluate thermal resilience on an urban scale, covering multiple stressors and strategies, is still missing. This is especially sensitive when considering passive strategies, such as natural ventilation, or when addressing disruptions that affect energy availability (e.g., power outages).

1.2. State-of-the-art

1.2.1 Characteristics and indicators of thermal resilience

To better understand a certain phenomenon, the logical first step is to try to measure it; this has already been attempted in resilience analyses in a variety of ways [17,23,27]. Beyond the challenge of not having a common definition, thermal resilience cannot be directly measured. Such a setting leaves plenty of space for interpretation, choices of metrics, time frames, and stressors, ultimately leading to all sorts of "resilient buildings." To suitably cover the major aspects of resilience against overheating, it is necessary to identify the characteristics expected from a resilient system. Measuring the satisfaction of these characteristics may be a proxy for measuring resilience itself [28].

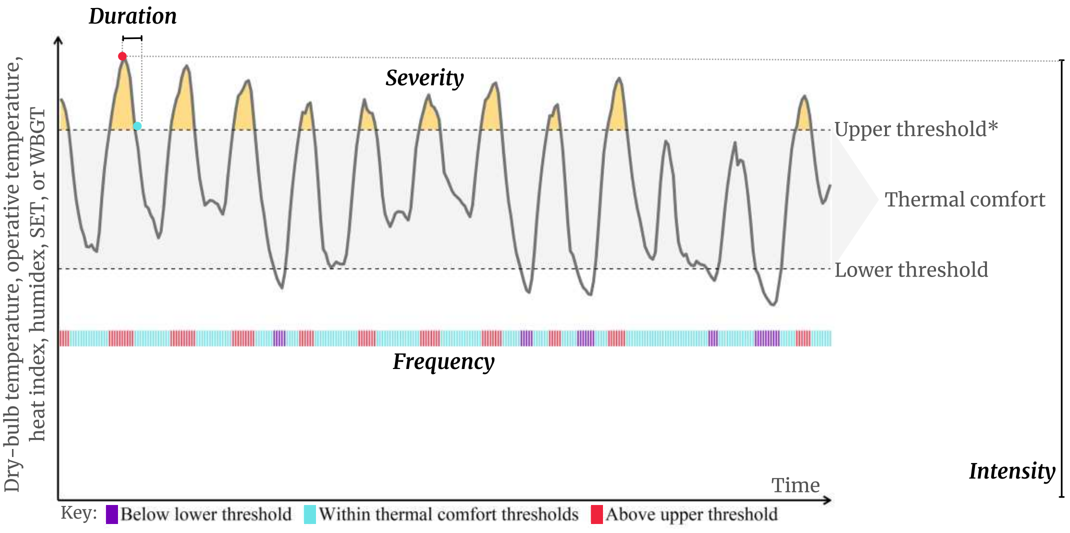
Table 1 summarizes the definitions of characteristics related to resilience in the literature. Most of these characteristics can be perceived as qualities that should be observed to enhance resilience (e.g., adaptability and learning capacity) whereas aspects of resilience related to resistance, robustness, and recoverability can be evaluated through performance metrics directly measuring responses to predefined hazards towards indoor thermal conditions. Building performance simulation can be used to quantify such characteristics (highlighted in bold in Table 1), thus being the focus of the framework proposed in this article.

Building performance metrics are calculated through long-term comfort evaluation methods [29,30], which have been thoroughly reviewed by Carlucci et al. [31] and, more recently, by Rahif et al. [32]. However, performance indicators have not yet been directly associated with characteristics of resilience.

Table 1. Characteristics of resilience

Characteristic	Definition
Vulnerability	The intrinsic properties of something, resulting in a propensity to be adversely affected. In buildings, it may involve the sensitivity of indoor comfort conditions to disruptions [1,15,23,27,33].
Adaptability	The ability to adjust to potential damage and to take advantage of opportunities while focused on anticipated future change. It reflects the capacity of actors to influence resilience with proactive strategies aiming to protect the system [1,15,34–39].
Transformability	The capacity to correct vulnerabilities when the existing system is untenable, even by changing fundamental attributes [28,34,35,37,39–41].
Learning capacity	The capacity to learn from past experiences and failures in order to adjust, reorganize, and prepare for future decisions, uncertainties, and surprises [28,37,41].
Dependency (on local ecosystems)	“Resilient urban systems exercise a greater degree of control over the essential assets required to support well-being, securing access to and quality of such resources. This involves recognising the value of the services provided by local and surrounding ecosystems (often described as the city’s green and blue infrastructure) and taking steps to increase their health and stability” [28].
Mitigation (to climate change)	“A human intervention to reduce emissions or enhance the sinks of greenhouse gases” [1].
Resistance	**The ability to maintain initial conditions and prevent disturbances from translating into impact** [23,39,42]**.**
Safe failure / Robustness*	**The “ability to absorb shocks and the cumulative effects of slow-onset challenges in ways that avoid catastrophic failure if thresholds are exceeded”** [28]**.** ***Authors diverge about the definition of “robustness.” For instance, in** [22] **“robustness” is described similarly to “resistance.” On the other hand, in** [23] **the presence of failure is essential to represent “robustness,” thus it can be related to “safe failure.” The latter interpretation is considered throughout this work.**
Responsiveness / Recovery	**“The ability to re-organise, to re-establish function and sense of order following a failure”** [28]**.**
Flexibility	“The ability to change, evolve and adopt alternative strategies (either in the short or longer term) in response to changing conditions” [28].
Smartness	“Quality of contributing to sustainable development and resilience, through soundly based decision making and the adoption of a long- and short-term perspective [...] It implies a holistic approach, including good governance and adequate organization, processes and behaviours, and appropriate innovative use of techniques, technologies and natural resources [...] Smartness is addressed in terms of performance, relevant to technologically implementable solutions” [43].
Diversity	The ability to respond to a disturbance in a diversity of ways [44,45].
Redundancy	The presence of components, strategies, or actors that can compensate for each other (e.g., in case of disruptions). Redundancy comes with investment and performance costs that require thorough evaluation [28,44–46].
Modularity	Modularity provides a system with different functional modules that can evolve somewhat independently. Modules may be loosely linked by design so that failure of one module does not severely affect the others [44].

Indoor thermal conditions can be described through many parameters, usually chosen based on what is being assessed (i.e., minimum or critical conditions) and data availability. The dry-bulb temperature (DBT) is an easy and common parameter to evaluate the thermal environment, but its translation to thermal comfort or thermal distress lacks additional information. Operative temperature incorporates the DBT and the mean radiant temperature, more frequently used as a simplified approximation to evaluate thermal comfort. The standard effective temperature (SET) [47] is another alternative, but it is relatively complex to obtain from field measurements as it requires six parameters for calculation, including indoor air velocity, humidity, occupant metabolic rate, and clothing insulation [48]. Nonetheless, if solely using building performance simulation, the SET would be a comprehensive alternative, and simulation tools such as EnergyPlus calculate and directly output SET. The heat index [49], humidex [50,51], and the Wet Bulb Globe Temperature (WBGT) [52] are often measures of thermal stress. These parameters provide measures of indoor thermal conditions in a certain moment, while a screening analysis throughout time is conducted mainly by indicators describing intensity, frequency, duration, or severity of events (see Fig. 1). This procedure may depend on comfort models (i.e., static or adaptive) and comfort categories to set appropriate thresholds to calculate key performance indicators (KPIs). Table 2 describes types of KPIs, their application, limitation, and examples in the literature.



*Limit to provide minimum thermal conditions to prevent overheating.
Thresholds to represent critical thermal conditions can be drawn above this line

Fig. 1. Key performance indicators for indoor thermal conditions

Table 2. Types, limitations and examples of key performance indicators for indoor thermal conditions

Application	Limitations	Examples in the literature
Indicators that describe intensity		
Describe the worst thermal conditions	Do not communicate whether this is a frequent event or an isolated occurrence	Maximum and minimum air temperatures or operative temperatures when an air conditioning system is unavailable [53–55].
Indicators that describe frequency		
Describe how often (i.e., the proportion of time) a certain condition happens (e.g., thermal comfort or thermal stress)	Do not communicate how far indoor thermal conditions are from thresholds. For example, they may consider crossing the threshold by 0.5 ºC or by 4 ºC the same way)	Thermal autonomy [56], percentage of occupied hours above the upper limit temperature (PHT_{upp}) [57]
Indicators that describe duration		
Describe the length of time in a certain condition. They are especially meaningful to assess the risk of thermal conditions affecting human health, sometimes indicating whether a building should be evacuated [55]	Insufficient to characterize alone thermal resilience, especially when considering whole-year analyses	Hours of safety [58] and Heating Passive Habitability (HPH) [55], both accounting for the length of time before a building becomes uninhabitable. The recovery time (t_R) [57] indicates the time required to recover from an extreme indoor thermal condition
Indicators that describe severity		
Aggregate information from both intensity and frequency	The magnitude of results may be hard to grasp, often lacking a definition of what range of results is acceptable for an indoor thermal environment	Degree hours [29,59], SET-hours [60], Indoor Overheating Degree (IOD) [61]

A major challenge regarding characteristics of resilience measured by indoor thermal conditions is that they are calculated for a thermal zone. Methods of calculating these results for the whole building (i.e., multiple thermal zones) are already broadly applied (e.g., in [17,54,61]) but translating them to a group of buildings is not common. An appropriate summary of results needs to be developed in such a way that it still holds meaning regarding the overall performance of urban buildings, as well as indicating best practices and points of caution.

It is important to highlight that more than one indicator may be necessary to describe each characteristic of resilience, as well as to cover the effectiveness of different strategies. An appropriate set of indicators should be chosen based on their capacity to communicate additional information that helps to portray the whole picture of resilience in buildings and groups of buildings.

1.2.2 Sources of stress in building performance models

At the core of any resilience study is the response of the system to stressors through available coping strategies. In this article, the term "stressor" is used to describe a source of disturbance to the building thermal dynamics that can lead to overheating. Table 3 lists examples of stressors, only considering those that can be directly represented through building performance simulation.

Table 3. Sources of stress and modeling approaches for building performance simulation

Stressors	**Modeling approach**
Variation in occupant behavior and occupation density/ patterns (e.g., during a pandemic)	Modeling of multiple occupation patterns [62–64]
Extreme weather events (e.g., heat waves)	Adoption of weather files encompassing the event (historical or projected future) [65–67]
Urban heat island	Adoption of weather files with variables measured onsite or adapted through tools that simulate the urban heat island effect [60,68]
Power outages	Modeling of power availability constraints [53,69]
Occupants' physical limitations	Modeling of building operation constraints
Wildfires, air pollution, technical failure of building systems, or other events that affect building operation, especially those related to AC operation or the ability of opening windows	Modeling of building operation constraints

Even the building occupant can be considered a source of stress. This is because occupants' presence and activities will influence the building's thermal balance [70] through actions like operating windows and solar shadings, light switching, adjusting thermostats, and using appliances [70,71]. Rouleau et al. [72] found that the hours of discomfort varied by 74% on average when changing occupant profiles, prompting the authors to conclude that offering a range of possible energy consumption values may be more realistic than unitary values. O'Brien et al. [73] also argued that providing alternative validated occupant models could be an opportunity for stressing the model and better evaluating building performance under uncertain scenarios.

Another source of stress to urban buildings is the occurrence of power outages, which prevent the use of technical building systems, with a special impact on air conditioning. The absence of power may jeopardize the safety and health of building occupants, especially those of vulnerable populations, and particularly when outages occur simultaneously with extreme cold [58] or hot [15,55] weather events. For example, Samuelson et al. [53] reported the possibility of occupants facing high nighttime temperatures inside insulated buildings during longer power outages.

The climatic response of buildings would be better understood if evaluated under a varied range of weather conditions, instead of only focusing on an average year [66]. Also, openly available weather files (e.g., Test Reference Year [TRY] and Typical Meteorological Year [TMY] files) are already known for commonly not representing the urban microclimate of cities, given that many weather stations are in a distant and rural location. Thus, building performance simulation for resilience assessment would benefit from considering weather files encompassing: urban microclimate, extreme weather conditions (e.g., eXtreme Meteorological Year [XMY] by Crawley and Lawrie [66,67]), heat waves, cold spells, and projections for future weather conditions based on various climate change scenarios.

1.2.3 Thermal resilience assessment through building performance simulation

Building performance simulation is an important tool to assess thermal resilience. However, a standardized modeling framework is still missing [18]. Homaei and Hamdy

[17] described a resilience test procedure that encapsulates the building performance during the disruptive event and a few days after it. They proposed the overall Weighted Unmet Thermal Performance ($\mathrm{WUMTP}_{\mathrm{Overall}}$) to quantify resilience, which is based on degree-hours [29,59], but different penalties are applied depending on the phase when the temperature differential is calculated (during or after disruption), the hazard level (i.e., how far the operative temperature is from the acceptable level), and the exposure time in a given hazard level. This is a novel approach that takes into account the intensity and frequency of events, while also encapsulating how buildings respond to failure and how they recover from it. However, its applicability is restricted to a short time frame analysis centered on a disruptive event about which a few parameters need to be defined to build specific boundary conditions (e.g., the duration of phases during and after the event, and the initiation time of the disruptive event). This framework [17] is also subjected to the definition of suitable penalty values applicable to 12 segments in a resilience curve which would heavily depend on inputs from physiological research. Such dependency on penalty values may hinder its broad application, especially when considering multiple sources of stress and compound events.

Among efforts from IEA Annex 80 researchers, Rahif et al. [74] described a method to evaluate and compare the overheating resistivity of cooling strategies. They propose the Climate Change Overheating Resistivity (CCOR) as the rate of change in the Indoor Overheating Degree (IOD) (related to the indoor environment) with an increasing Ambient Warmness Degree (AWD) (related to the outdoor environment). This is a synthetic metric that provides an overall understanding of how buildings are suppressing outdoor thermal stress under multiple future climate scenarios. However, being a rate of change in resistivity, it does not directly describe the thermal resilience of buildings in a way that allows identifying what is causing a vulnerability to overheating (e.g., describing the indoor thermal conditions in a specific scenario). Thus, such an approach is highly valuable for the intended comparative analysis of climate scenarios and cooling strategies, but less suitable to understand resiliency.

Flores-Larsen et al. [75] used building performance simulation and field measurements to understand the correlation between overheating metrics and the outdoor thermal stress in a bioclimatic office in Argentina. The authors argue that the previous thermal history and the solar irradiance level highly influence the thermal resilience of free-running buildings.

In a similar approach to that of Rahif et al. [74], the dynamic simulation guideline proposed by Annex 80 researchers [76] adopts the CCOR and additional thermal comfort, energy, and emission metrics, aiming at evaluating and comparing resilient cooling solutions across multiple climate scenarios worldwide. Nevertheless, the metrics included are broadly described, still lacking a consistent structure behind their selection and application. That is, describing the reasons why the specific metrics quantify resilience and how they work together for a robust resilience diagnosis. Additionally, a method to visualize results and compare the different selected metrics is still absent in the second version of the guidelines, requiring further development.

Within the urban context, Sun et al. [77] modeled two vulnerable communities in the U.S. through the web-based platform CityBES [78], seeking to evaluate the effect of passive cooling strategies towards heat resilience. In the most severe scenario, buildings were exposed to a heat wave during a power outage while aided by several strategies, including natural ventilation. Katal et al. [79] used CityFFD and CityBEM to evaluate the resilience of a group of buildings exposed to an extreme snowstorm coupled with a three-day power outage. Nevertheless, a structured resilience assessment of urban buildings has not matured yet, with very different procedures adopted in the literature: e.g., an individual building sampled to be analyzed within a certain urban context and microclimate [80,81] and multiple buildings only represented by demand profiles [82,83].

1.3. Objectives

This article aims to propose a novel simulation framework to assess thermal resilience of buildings at individual as well as the urban scale. The framework will allow consideration of diverse stressors whose consequence to the indoor thermal environment is overheating, and enable evaluation from short (from days to a season) to long time frames (whole-year). The proposed framework can be adopted by architects, engineers, or energy modelers to improve thermal resilience modeling and analysis at scale and support a variety of stakeholders such as building owners, property managers, insurance companies, public health agencies or government agencies to make informed decisions for resilience planning. The goal is to guarantee adequate indoor thermal quality and consequently reduce the cooling demand of buildings in the urban setting, which should reduce carbon emissions and help mitigate climate change.

In this work, the urban environment condition outside the buildings is not directly evaluated, rather it is a source of stress to the built environment. However, it is known that strategies at the building level will affect outdoor conditions [53]. Fig. 2 summarizes the dimensions of time, scale, and consequence addressed in this study.

By applying this framework, one will obtain the resilience profile of a building, which contains the results of a set of integrated key performance indicators that allow a better understanding of the strengths and fragilities of building design. The procedures described herein aim to be flexible and applicable to a variety of contexts and scenarios, thus addressing the limitations identified in the literature. At the community scale, the framework provides a profile for the group of buildings, which allows mapping populations with different levels of resilience and targeting the most vulnerable groups.

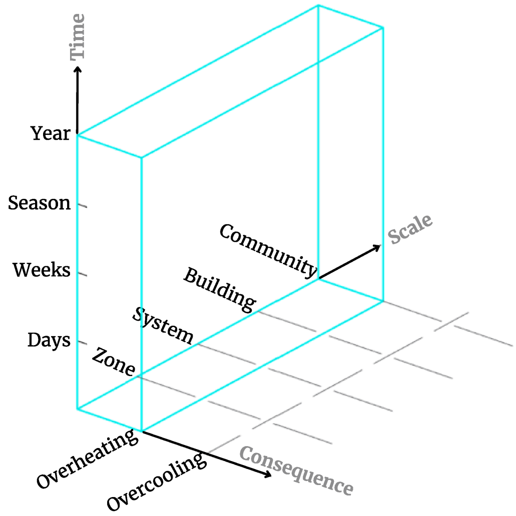


Fig. 2. Dimensions of time, scale, and consequence addressed in the framework

2 Method

2.1. The simulation framework

Fig. 3 and Fig. 4 illustrate the proposed thermal resilience simulation framework, starting from the building diagnosis (Fig. 3) and aggregating it to the urban buildings' diagnosis (Fig. 4). The building diagnosis is divided into the stages of resilience defined by Attia et al. [23], namely: resistance, robustness, and recovery. The building' performance should be assessed based on KPIs suitable for each stage. In the resistance stage, KPIs will be based on maintaining minimum thermal conditions, while the robustness stage requires KPIs based on surpassing critical thermal conditions. In turn, the recovery stage is based on moving from critical conditions and reaching minimum thermal conditions again. Considering the capacity of occupants to adapt themselves and their buildings in multiple forms—not necessarily the same (non-equilibrium states)—

that will allow them to endure adversities, we consider this approach to fit within the third viewpoint on resilience, evolutionary resilience (see Section 1.1).

Krelling et al. [57] evaluated buildings through several KPIs to diagnose their thermal performance comprehensively. Considering the authors' results, the resistance stage could be measured through three indicators: (1) thermal autonomy (also called PHFT in [57]) to describe the frequency in which buildings are able to sustain indoor thermal conditions within minimum thresholds without the assistance of active cooling systems (i.e., air-conditioning); (2) indoor overheating degree (IOD) [61] as a measure of severity that thermal conditions surpass minimum thresholds; and (3) cooling load to provide a measure of depletion of energy resources related to overheating (alternatively, energy use can be adopted to capture the efficiency of building technical systems). For the robustness stage, two indicators are suggested: (1) the frequency in which the worst performing room in the building is in this stage—that is, when indoor thermal conditions exceed critical thresholds (thermal vulnerability [TV], called PHT_{upp} in [57]); and (2) the annual maximum operative temperature (Tmax) to reflect the intensity of extreme thermal conditions during the occupation period in a robustness stage. To account for the recovery stage, the recovery time (t_R) could be adopted to estimate the time taken to recover from a maximum temperature (i.e., Tmax) until reaching minimum thresholds again. In this way, the recovery time (t_R)—which is an indicator of duration—would complement the maximum temperature. Such combination provides a better understanding of continuous exposure to extreme thermal conditions. Table 4 describes each KPI in detail.

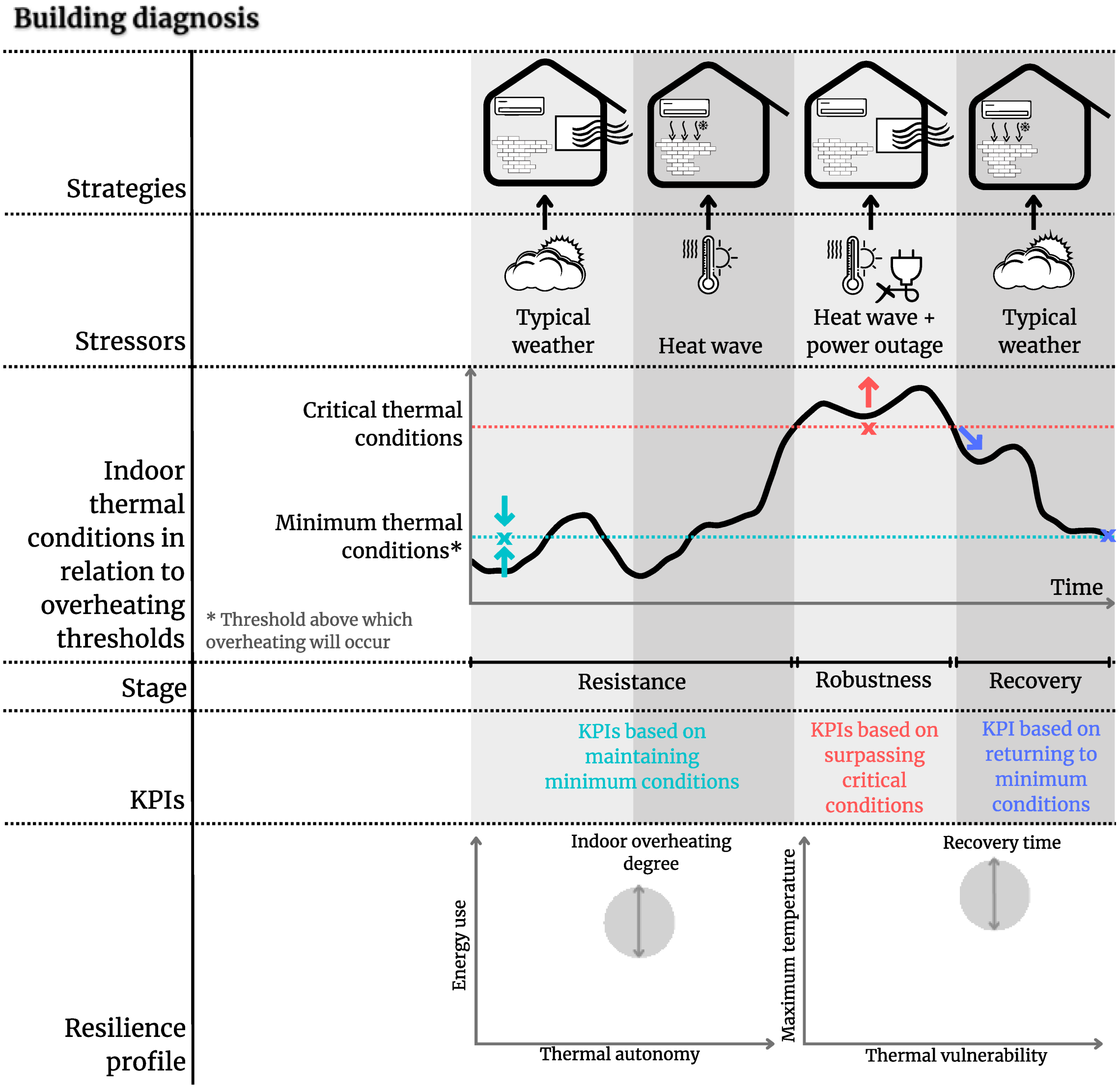


Fig. 3. Thermal resilience simulation framework for single buildings

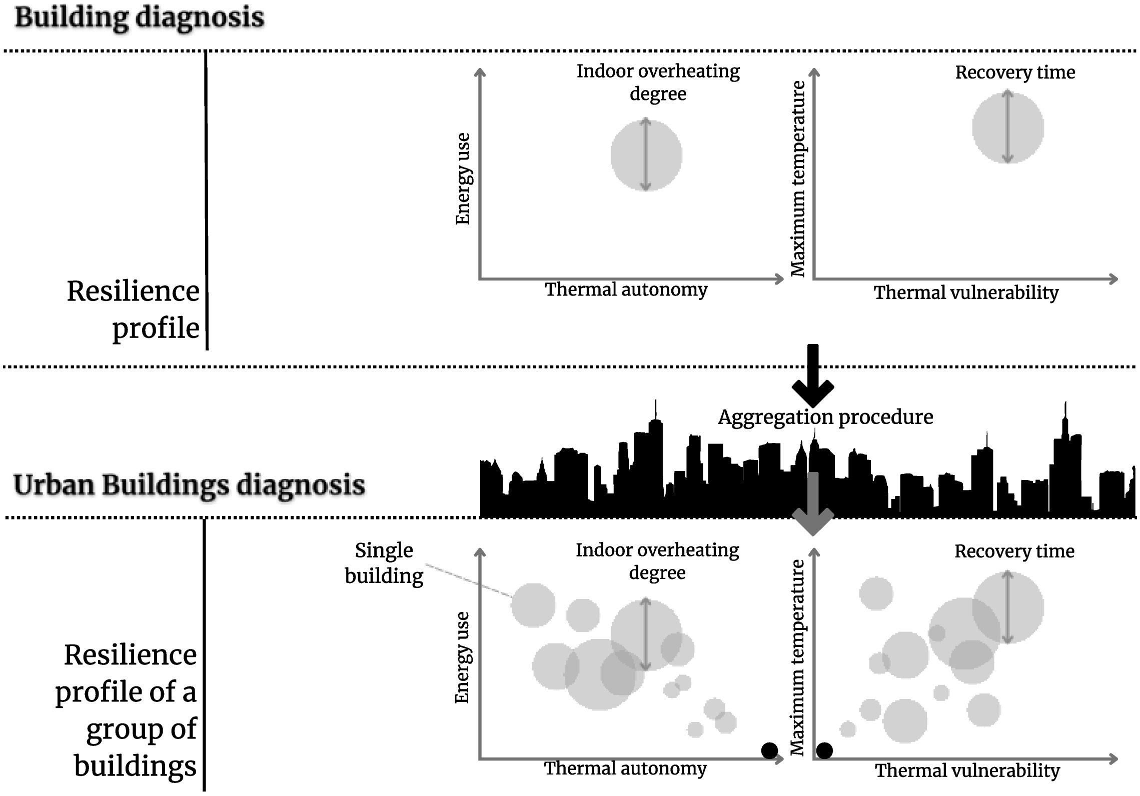


Fig. 4. Thermal resilience simulation framework for groups of buildings

Table 4. Key performance indicators suggested to assess thermal resilience in each stage

KPI	Equation or calculation procedure	Stage of resilience
Thermal autonomy (TA) [%] [57]	**For a single zone:** $TA = \frac{N_{occ;range}}{N_{occ;tot}}.100$ *Where: $N_{occ;tot}$ is the total number of hours a room is occupied throughout the year; $N_{occ;range}$ is the total number of hours a room is occupied throughout the year with operative temperature within a minimum range of thermal conditions without the assistance of active cooling systems* **For multi-zones:** average value between all zones	Resistance
Indoor overheating degree (IOD) [ºC] [61]	**For single zone or multi-zones:** $IOD \equiv \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)}\left[\left(T_{fr,i,z}-TL_{comf,i,z}\right)^{+}\times t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}(z)} t_{i,z}}$ *Where: z: building zone counter; Z: total number of zones in a building; i: occupied hour counter; t: time step (1 h); $N_{occ(z)}$: total occupied hours in a given calculation period; T_{fr}: free-running indoor operative temperature at the time step i in zone z; TL_{comf}: comfort temperature limits at the time step i in zone z*	Resistance
Cooling load* [kWh/m²]	**For a single zone:** Quantity of heat that must be removed from a space to maintain setpoint. Measured in thermal energy.	Resistance

KPI	Equation or calculation procedure	Stage of resilience
	*Can be replaced by energy use, considering the summation of the zone's annual HVAC electricity consumption. **For multi-zones:** summation of values of all zones divided by the building floor area or by the conditioned floor area	
Thermal vulnerability (TV) [%] (adapted from [57])	**For a single zone:** Proportion of occupied hours with operative temperature above the upper limit temperature (T_{upp}) [84] (i.e., critical threshold), which is 4 ºC above the minimum threshold **For multi-zones:** highest value between all zones	Robustness
Maximum temperature (Tmax) [ºC] [57]	**For a single zone:** $Tmax = \max(T_{occ;n})$ *Where: $T_{occ;n}$ is the hourly operative temperature when the room is occupied at hour "n"* **For multi-zones:** highest value between all zones	Robustness
Recovery time (t_R) [h] [57]	**For a single zone:** Amount of time between the moment of maximum annual operative temperature (Tmax) and the time when the space reaches an acceptable operative temperature threshold **For multi-zones:** amount of time the zone with highest Tmax takes to recover	Recovery

The urban buildings' diagnosis is based on translating the data collected during several individual building diagnoses into meaningful information regarding whether a certain group of buildings is bound to resist or face disruption. This final diagnosis should be detailed enough to portray aspects of strength and frailty within the group in a way that enhances learning capacity and preparedness.

A resilience profile is proposed to gather all the information from every single building, predefined KPI, and resilience stage. Fig. 3 (building scale) and Fig. 4 (urban scale) exemplify this profile, which is designed as two bubble plots separated between the resistance stage (left) and the robustness and recovery stages (right). These plots are derived from a scatter plot where the relationship between two of the indicators on axis *x* and *y* is shown, while a third dimension is considered by scaling the size of each point according to another indicator. In the resistance stage, better performing cases would have the smallest bubble located in the lower-right corner. In the robustness and recoverability stages, it would be better to be in the lower-left corner, with a smaller bubble size. Examples of ideal results are marked with black bubbles in Fig. 4. This type of profile should allow a quick comparison between multiple buildings, comprising up to six indicators.

It is recommended to use this framework considering whole-year scenarios; that is, running simulations through the course of a year to account for seasonal variability. Stressors can be applied in different periods of the year and with increasing intensities, creating scenarios that test resilience. The framework nonetheless is flexible to be applied in shorter time frames during specific events. For instance, it could be applied in the time frame of the most severe, longest, or most intense heat wave [85], based on historical or future weather scenarios, possibly coupled with a power outage.

2.2. Mapping populations based on thermal resilience profiles

After gaining an overall understanding of how buildings perform, a mapping procedure is proposed to identify populations with similar resilience profiles as well as building samples that represent these populations. Such an approach is conducted through a cluster analysis based on the key performance indicators previously selected. Evaluating the performances of tens or hundreds of buildings, each one of them with multiple key performance indicators, would be unpractical. Thus, this procedure aims to display some actual buildings that are representative of a group of buildings as a way to materialize the tendencies and distributions explored through the resilience profiles.

The cluster analysis is a multivariable analysis technique with the objective of grouping objects in the same class or cluster, so that the same cluster displays very similar characteristics (high internal homogeneity), while objects from different clusters display low similarity (high external heterogeneity) [86,87]. A non-hierarchical method was applied in this study, considering the k-medoids clustering method to select representative cases. The Euclidean distance was adopted as the similarity measure, which is a well-known and common measure for clustering [88,89]. The representative building, also known as medoid, is the most centrally located case in the cluster. Considering that indicators have different measurement units, they were rescaled before clustering. The standardization method was applied; it rescales data to have a mean equal to 0 and a standard deviation equal to 1. This analysis was developed using the R software [90] with R-Studio interface [91] and the package "cluster" [92].

2.3. Illustrative case study

The framework was applied considering the Brazilian context, which is characterized by climates varying from warm to extremely hot (3A to 0A, respectively, according to ASHRAE 169 [93]). Despite overheating already posing a significant threat to the building stock, there are still few tools to adapt buildings to extreme heat and minimal incorporation of resilience into local codes [94]. Such a scenario, together with the significant prevalence of energy poverty [95] and informal settlement issues [96], highlights the urgency to foster thermal resilience in warm developing countries like Brazil.

Curitiba, Florianópolis, and São Luís are the cities considered in this study. They are located in the South and Northeast regions of Brazil. They have climates classified as 3A (Curitiba), 2A (Florianópolis), and 0A (São Luís) according to ASHRAE 169 [93], and have been chosen to incorporate variable climate scenarios, from colder (Curitiba) to hotter (São Luís) climates (Fig. 5).

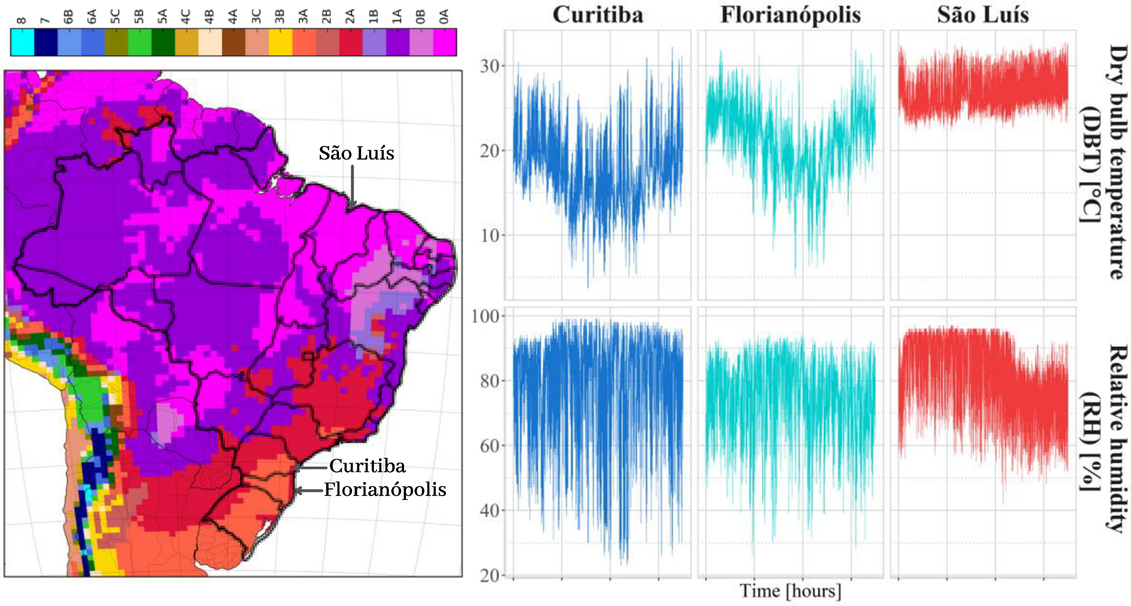


Fig. 5. Location of Curitiba, Florianópolis, and São Luís within the Brazilian territory, juxtaposed with the ASHRAE 169 climate zones, and annual variation in dry bulb temperature and relative humidity

Whole-year simulations were run for each case, considering TMYs obtained through Ref. [97]. The results obtained herein should verify the thermal resilience of buildings under typical conditions, thus providing a baseline to compare results if included other stressors. Nevertheless, if one adopts an XMY [66,67], a weather file with a heat wave or with prospected future climate conditions, the same procedure would be followed.

2.3.1 Building characteristics

The framework was applied to a group of detached single-family residential buildings, considering the representative design for low-income houses [98] shown in Fig. 6. Low-income buildings represent approximately 33% of all residential buildings [99], while 86% of the national building stock in the residential sector is composed of detached houses [100]. Residential buildings in Brazil are mostly operated in a free-running mode, given that natural ventilation is the preferred strategy to improve indoor thermal conditions and only a small portion of houses are equipped with an air conditioning system [99,101]. Thus, evaluating the resilience of such buildings throughout the year is significant to verify adequate living conditions, supporting the development and revision of policies that foster resilience-oriented design, especially those focused on vulnerable populations that are at a higher risk of facing severe consequences due to extreme weather events.

The group of buildings was created through the variation of building components of the envelope to create 448 unique cases. These cases are the result of a parametric combination of 14 different compositions of exterior walls, 2 interior walls, and 16 different roofs. The thermal properties of each component are shown in Fig. 7. All cases have the same building design and occupant profile. There are two reasons to take this approach. The first is to provide the same boundary conditions, to allow comparisons of the effect of the envelope over thermal resilience and to verify if the building diagnosis is reasonably describing resilience and its different stages within a controlled experiment. Second, even with fixed boundary conditions, the variability of results obtained from changing building components was considered sufficient to conduct the illustrative example intended herein.

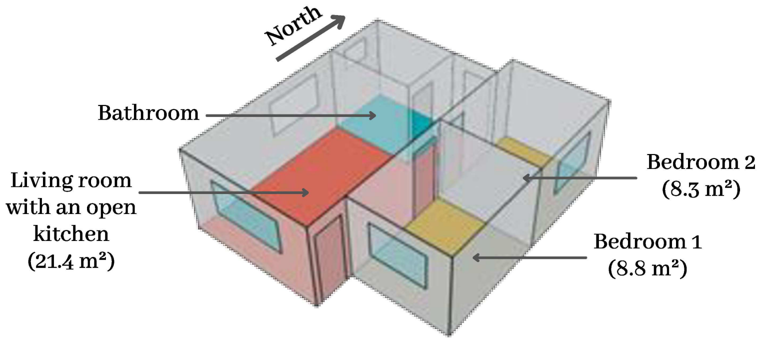


Fig. 6. Representation of the case study

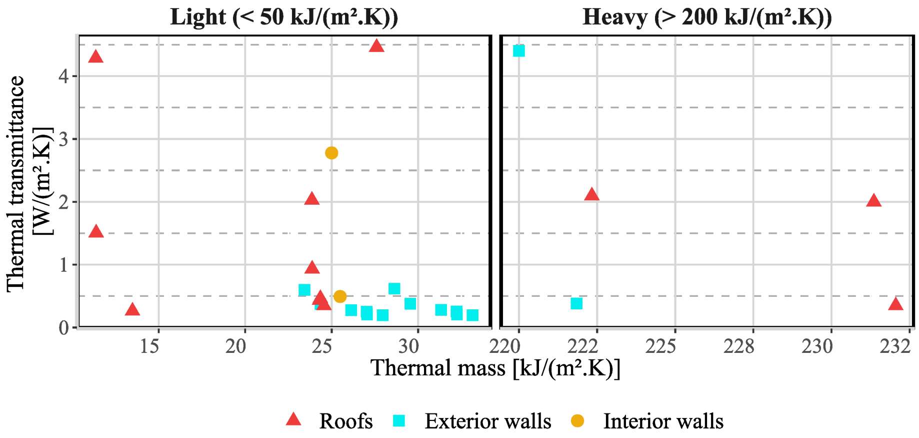
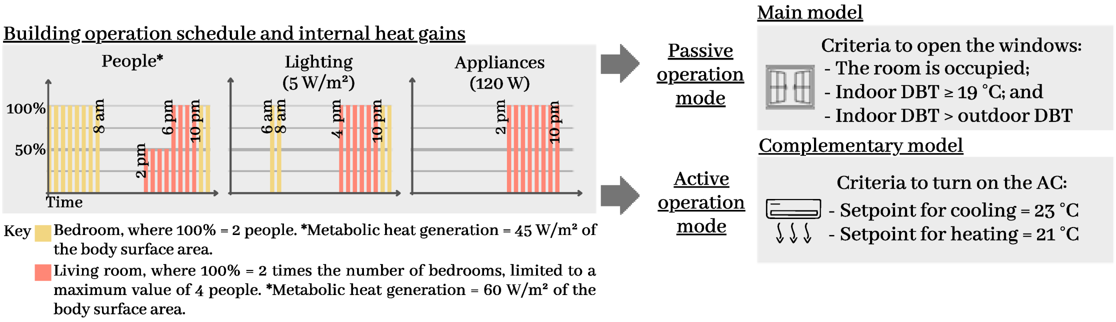


Fig. 7. Thermal properties of the building components

The operation of buildings was considered as described by the Brazilian performance standard, NBR 15575 [54] (see Fig. 8), being analyzed under passive (i.e., naturally ventilated) and active (i.e., air-conditioned) operation modes. These two modes are modeled separately (i.e., different building models), with the passively operated building being the main model and the actively operated used solely to estimate the thermal loads to be met by air conditioning when natural ventilation alone cannot provide adequate thermal conditions. The development of models based on NBR 15575 is thoroughly discussed in Krelling et al. [57].



Criteria to open the windows:
- The room is occupied;
- Indoor DBT ≥ 19 °C; and
- Indoor DBT > outdoor DBT

Criteria to turn on the AC:
- Setpoint for cooling = 23 °C
- Setpoint for heating = 21 °C

Key 🟨 Bedroom, where 100% = 2 people. *Metabolic heat generation = 45 W/m² of the body surface area.
🟥 Living room, where 100% = 2 times the number of bedrooms, limited to a maximum value of 4 people. *Metabolic heat generation = 60 W/m² of the body surface area.

Fig. 8. Building operation according to NBR 15575-1

All models were developed using EnergyPlus, version 9.5.0. Natural ventilation was represented through the most detailed procedure available in EnergyPlus, using the *AirflowNetwork* group of objects. The *AirflowNetwork* models air changes inside the building according to wind data from the weather file. The complementary model under active operation adopts an ideal air conditioning system with infinite capacity called *IdealLoadsAirSystem*.

2.3.2 Expected indoor thermal conditions and what defines failure

To exemplify the application of the framework, the range of operative temperatures from Table 5 was considered as minimum thermal conditions, in line with the national standard procedure for considering acceptable indoor living conditions in residential buildings in Brazil. Minimum thresholds vary according to the annual average dry bulb temperature (DBT_{annual}) of the climate. The DBT_{annual} of Curitiba, Florianópolis, and São Luís fall into intervals 1, 1, and 2 of Table 5, respectively.

Failure was considered when operative temperatures surpassed the minimum thermal conditions by 4 ºC; that is, being equal to 30 ºC (Curitiba and Florianópolis) or 32 ºC (São Luís). This threshold represents a limit beyond which normal adaptive actions will not be able to restore comfort [84]. They are supported by studies that associate the occurrence of nonoptimal temperatures with the mortality risk in cities in Brazil [102,103].

Table 5. Acceptable operative temperature ranges [54,57]

Outdoor temperature interval	**Annual mean dry bulb temperature (DBT_m) interval**	**Operative temperature (To) range**
Interval 1	$DBT_m < 25$ ºC	18 ºC < To < 26 ºC
Interval 2	25 ºC $\leq DBT_m <$ 27 ºC	To < 28 ºC
Interval 3	$DBT_m \geq 27$ ºC	To < 30 ºC

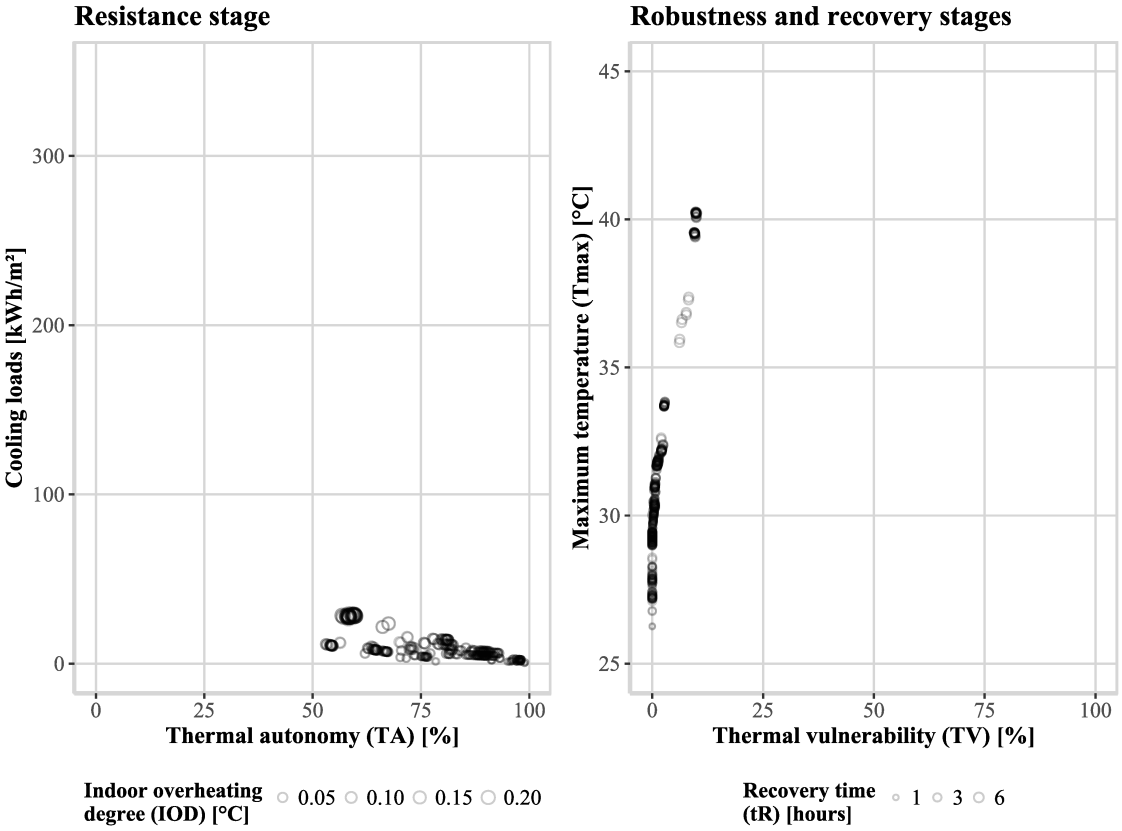
It is important to highlight that thresholds to represent heat stress are usually assessed through simplified biometeorological indices or heat-budget models. The choice of method will depend on available resources [104]. Even though only values of operative temperature are considered in this analysis, the framework is open to include thresholds that encompass additional parameters, such as relative humidity, air speed, metabolic rate, and clothing level.

3 Results of the case study

In this example, indicators described in Table 4 were calculated for every single building in three different climates. In Section 3.1, results are shown through the construction of resilience profiles. Section 3.2 presents these same profiles while mapping different populations and highlighting representative buildings to facilitate analysis and decision-making in the context of communities.

3.1. Thermal resilience profiles

Fig. 9, Fig. 10, and Fig. 11 illustrate the resilience profile for Curitiba, Florianópolis, and São Luís, respectively.


Resistance stage

Robustness and recovery stages

Fig. 9. Thermal resilience profile for cases in Curitiba

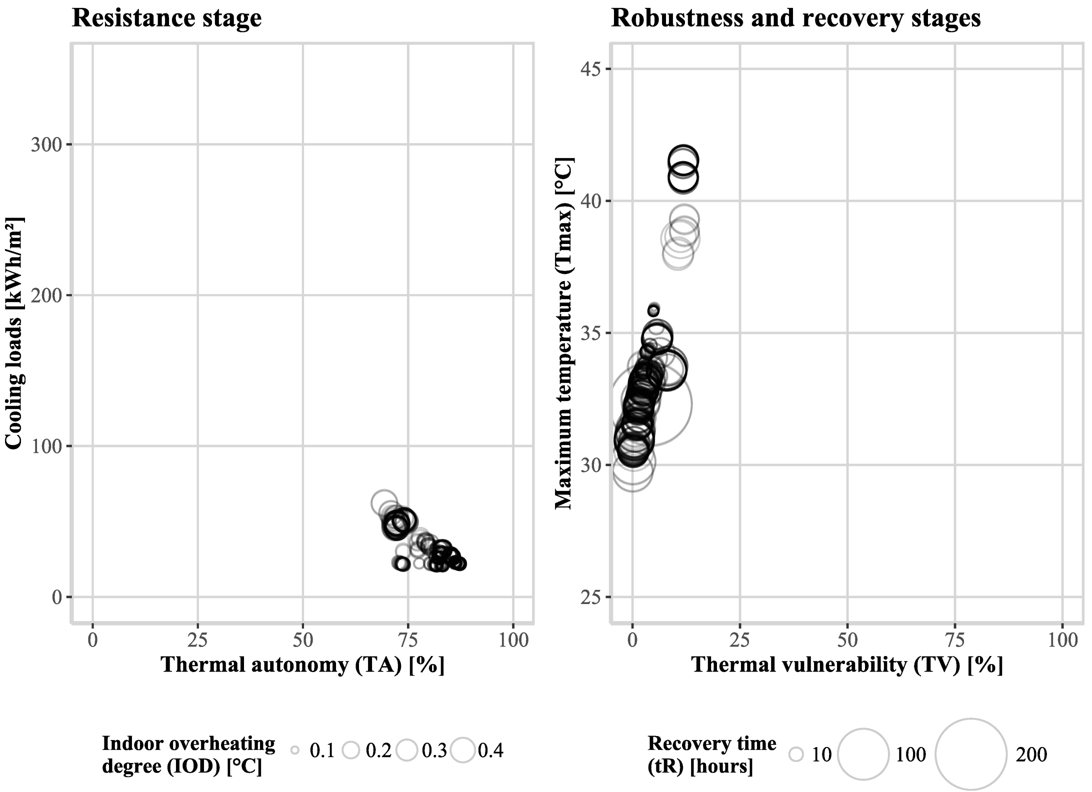


Fig. 10. Thermal resilience profile for cases in Florianópolis

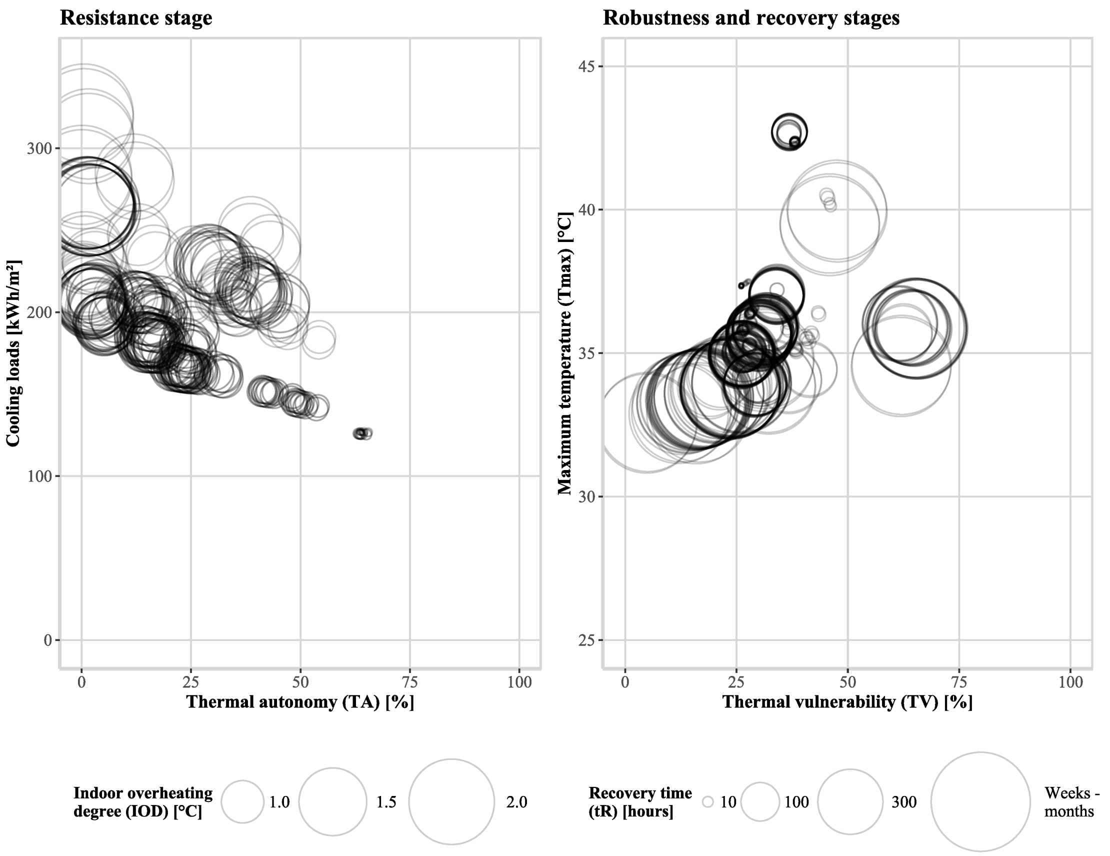


Fig. 11. Thermal resilience profile for cases in São Luís

In Florianópolis, a very small variation in results in the resistance stage was identified by changing the building components of the envelope. It can be verified that this group of buildings would offer at least 69% of occupied hours with operative temperatures within minimum thresholds (i.e., thermal autonomy). When outside these thresholds, a maximum overheating degree (IOD) of 0.44 ºC can be expected, which means that, if the overheating periods were equally distributed throughout occupied hours over the year, the case with the highest IOD would constantly surpass the upper thresholds by 0.44 ºC. In the robustness stage, the difference between cases becomes more evident, indicating the importance of looking at indicators that account for extreme indoor thermal conditions. These conditions, delimited herein as being 4 ºC above the minimum threshold and measured by the TV, can happen up to 12.1% of occupied hours in a year within cases in Florianópolis, but it is more often that buildings in this group would experience it less than 4% of the occupied hours throughout the year. Nonetheless, 48 of these buildings (about 10%) can reach more than 40 ºC (Tmax). This may be a population to target when developing policies to improve the thermal performance of buildings. When reaching maximum temperatures, buildings often take about 33 hours to recover to minimum indoor thermal conditions, however, some cases may take between 100 and 200 hours (about 4 and 8 days, respectively).

Among cases in Curitiba, the buildings very often do not require an air conditioning system, with many cases being reported as surviving passively for almost 100% of occupied hours. Building design in these cases involves the combination of high thermal mass and insulation on both walls and roofs, which leads to a very good performance according to all indicators. A different fraction of cases reported TA between 50% and 60%, part of them with TV between 5% and 10%. Also, it is possible to find buildings that can reach a maximum value of 40 ºC (Tmax), but they are likely to recover quickly towards the 26 ºC threshold. The maximum t_R is equal to six hours.

The performance of the group of buildings in São Luís is opposite of those in Curitiba, leading to different recommended design practices. Walls and roofs with low thermal mass are preferred, often involving the addition of insulation to one of these elements. Nonetheless, it is often that a building would not provide adequate indoor thermal conditions without an air conditioning system, requiring between 125 and 321 kWh/m² of cooling load to be removed annually. There are, however, very few cases with TA equal to 65%. Unlike the cases in Curitiba and Florianópolis, overheating is intense, to a point of reaching an average degree (IOD) equal to 1.2 ºC and a maximum of 2.5 ºC. Cases in the previous cities never reached 0.5 ºC of IOD. Many buildings can reach a maximum temperature of 42 ºC, but recovery can vary from six hours to weeks and months, mostly depending on the building's thermal mass. In hot climates like the one in São Luís, high thermal capacity often acts as a permanent heat reservoir that can never be released due to the severity of outdoor thermal conditions. Besides adjusting insulation and thermal mass, additional strategies are necessary to mitigate indoor extreme thermal conditions, such as solar shading and increased air movement.

3.2. Thermal resilience mapping and representative buildings

For Curitiba and Florianópolis, three clusters (i.e., populations) were considered sufficient to provide representative cases to illustrate the performance of buildings within the group. For São Luís, where results of indicators showed higher variability, five clusters were considered more suitable. We tested different numbers of clusters until finding the minimum quantity that would appropriately describe the results. A low number of cases is preferred to facilitate the analysis and decision-making. However, the ideal number of clusters may differ depending on the intended application and community analyzed. Fig. 12 shows the thermal resilience profile for São Luís, this time highlighting the results of the representative buildings of each cluster. Buildings within the same population have the same color adopted for their representative case. Profiles for Curitiba and Florianópolis were included in Appendix A.

Marked in purple, Fig. 12 shows the cluster of buildings with the best performances in the resistance stage, being closer to the lower right corner of the graph. By looking at its representative, it can be said that it is common for a building within this population to have a thermal autonomy of about 50% and require to remove 145 kWh/m²·year of cooling loads when natural ventilation cannot provide minimum thermal conditions. However, this group faces disruptive conditions over 25% of the occupied hours of the worst performing room, which happens when operative temperatures surpass the threshold for critical thermal conditions (i.e., 32 ºC in São Luís). Regardless of the intensity of extreme indoor conditions, the buildings are able to recover in a short period of time, requiring about nine hours to reach the minimum threshold.

The cluster colored in yellow stands out for reaching the most extreme indoor thermal conditions, with its representative having a Tmax equal to 42.4 ºC, while temperatures above 32 ºC happen 38% of the time (TV) in at least one room. Even though buildings from the cluster colored in red most commonly have lower Tmax than those from the yellow cluster, extreme thermal conditions happen more often and last longer. Considering that their thermal autonomy is close to zero, buildings rely heavily on air conditioning and may face disruptive conditions for entire weeks or months when it is not available. Thus, it is valuable for researchers, utilities, and policy makers to be aware of this low performance within an urban context as they consider suitable solutions tailored to a disadvantaged population.

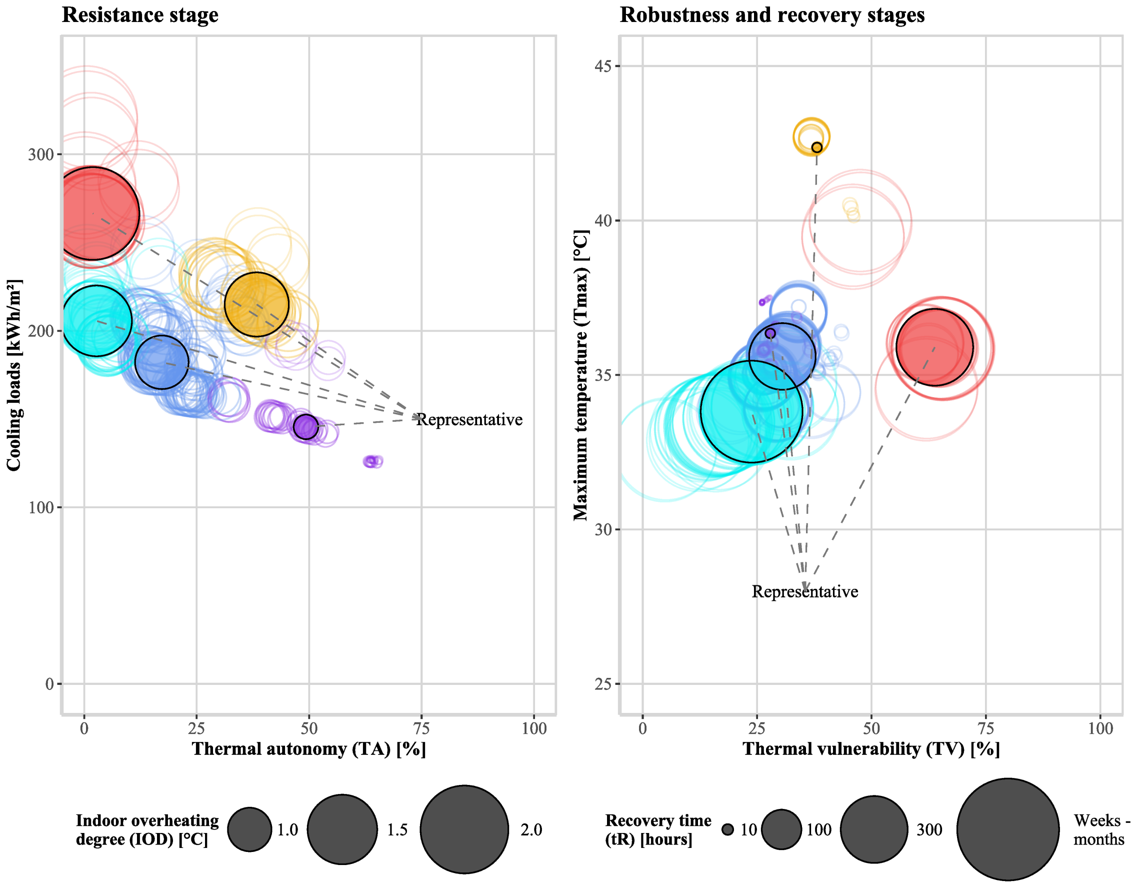


Fig. 12. Thermal resilience profile with representative cases for São Luís

4 Discussion

Even though this analysis has been applied with a focus on free-running residential buildings, the same procedure could be applied to other building types and operation strategies, and be only impacted by the distribution of bubbles in the resilience profile. For example, an office building could be fully air-conditioned, therefore having no thermal autonomy.

During the design phase, the framework can be applied by design teams and building technology experts to prescribe adequate design features and strategies to endure all possible foreseeable stressors, beginning with average weather conditions, and also encompassing extreme and future weather and energy availability constraints. The resilience profile could also be used to better visualize the performance of different design strategies to find an optimal solution.

Translating the results obtained by the application of this framework to other audiences would involve adapting the key performance indicators depending on the stakeholder. Thresholds could be adjusted considering vulnerable populations; for instance, the elderly, children, and people with psychiatric, cardiovascular, and pulmonary illnesses [105], as well as those with reduced mobility. Insurance companies could use metrics such as heat-related mortality [106], which could be determined through correlations with the indicators adopted in this study (e.g., using the intensity, duration, and frequency of exposure to high temperatures, that is, Tmax, t_R, and TV). Other existing public data such as building age, energy label, census data, and socioeconomic indicators could be used to support these correlations [107]. Commissioning providers and building owners could be better informed to provide training plans, system manuals, and maintenance programs to help occupants prepare and respond to disruptive events.

At the urban level, the framework should enable users to diagnose resilience at the current state and project the effect of policies and regulations on the performance of urban buildings when exposed to present and future threats, covering all stages of resilience. By contrast, first responders would be less interested in buildings during a resistance stage, but more so when a failure occurs, which characterizes the robustness and recovery stages. Vulnerability maps and emergency protocols could be developed through the application of the framework, indicating populations likely to require assistance when exposed to certain scenarios (e.g., heat waves with power outages). In this context, researchers should bridge the gap between the simulation-based method described in this study and other formats suitable for different stakeholders' needs.

4.1. Contributions

The proposed framework provides the following contributions:

- The thermal resilience quantification is based on solid resilience literature, relating consolidated key performance indicators to primary characteristics expected from resilient buildings;
- This comprehensive set of KPIs allows design teams, energy modelers, and researchers to deeply understand and address fragilities in a resilience-oriented design. The selected KPIs have objective and easy-to-understand dimensions and meanings, which facilitate future adoption by different stakeholders;
- The proposition of a visualization approach of results through a resilience profile that covers the three stages of resilience;
- The flexibility to consider multiple stressors and strategies in short and long time periods;
- The proposition of an aggregation approach to translate detailed diagnoses at the building scale to the urban scale, facilitating identification and decision-making regarding thermally vulnerable populations.

4.2. Limitations

This study has the following limitations:

- It only considers the operative temperature to describe the indoor thermal environment, which dismisses the effect of humidity, air speed, metabolic rate, and clothing towards the perception of thermal comfort or heat stress. However, the framework is flexible to consider alternative parameters to calculate the selected KPIs. For instance, the heat index, SET, or humidex could be adopted.

- It considers fixed thresholds to account for minimum and critical thermal conditions. Alternatively, limits from the adaptive model from ASHRAE 55 [47] could be adopted, or other preferred models depending on the population (e.g., healthy adults, seniors, or people with medical conditions) [108–111].
- It applied the framework to a simplified case study with reduced diversity between buildings and did not consider stressors beyond typical weather conditions. Also, buildings were simulated independently, not reflecting interactions between buildings in the urban setting, such as solar shading or radiant heat exchange between buildings' exterior surfaces.
- It focused on overheating, which can mask necessary compromises between cooling and heating-oriented strategies.

4.3. Future studies

Future studies can focus on defining a minimum set of scenarios to apply the simulation framework to evaluate thermal resilience. These scenarios may also include extremely low-temperature events, thus requiring the adaptation of the framework considering overheating and overcooling risks to identify trade-offs between selected strategies and technologies. This is possible through the adaptation of KPIs that consider thresholds related to discomfort and distress to low temperatures. A future study also can analyze a real group of buildings exposed to multiple sources of stress (e.g., urban heat island, heat waves, and power outages considering historical and projected future weather data) and aided by diverse coping strategies.

5 Conclusion

This study proposes a novel framework to assess the thermal resilience of buildings and communities against overheating. At the building level, single buildings are characterized by three stages of resilience: resistance, robustness, and recovery. The building performance in each stage is measured by tailored key performance indicators that thoroughly describe the building response when exposed to different sources of stress, especially those related to extreme weather conditions. Results are aggregated from the building level to the urban level through a resilience profile, which is intended to provide a meaningful understanding of the resilience of all buildings within a group (e.g., in neighborhoods, communities, and cities). Additionally, a procedure of selecting representative buildings is proposed to facilitate the development of building policies targeted to specific vulnerable populations, identified through a cluster analysis that groups buildings according to similar resilience responses.

The application of the framework was illustrated using a group of 448 residential buildings in three Brazilian cities. Alarming results were obtained, particularly in the city with the hottest climate, São Luís, where a vulnerable cluster of buildings was identified with significantly low thermal resilience. This group can be described through its representative building, whose thermal autonomy (TA) was close to zero. That is, this cluster of buildings relies on air conditioning, exhibiting operative temperatures surpassing 32 ºC over 50% of occupied hours when it is not available. Buildings in this group are characterized by an envelope with high thermal mass, which has been identified as an inadequate design choice for the detached house explored herein. Heat builds up in the structure throughout time with little opportunity to dissipate due to climate severity. This phenomenon increases indoor temperatures and delays or even prevents recovery. On the other hand, thermal mass is an excellent strategy in a mild climate like that of

Curitiba, allowing buildings to be operated passively the entire year. The selected indicators help to build these narratives to understand the fragilities in building design.

Such analysis could help policy makers, researchers, and emergency responders map and act upon vulnerabilities within a community considering multiple stressors (e.g., heat waves, power outages, and climate change) as well as promote those strategies that comprehensively increase thermal resilience. Diverse strategies can be tested to improve the coping capabilities of buildings against overheating, while also mitigating the depletion of energy resources through passive or low-energy technologies.

CRediT authorship contribution statement

Amanda F. Krelling: Conceptualization, Methodology, Formal analysis, Visualization, Writing - Original Draft. **Roberto Lamberts:** Writing - Review & Editing, Supervision. **Jeetika Malik:** Writing - Review & Editing. **Tianzhen Hong:** Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

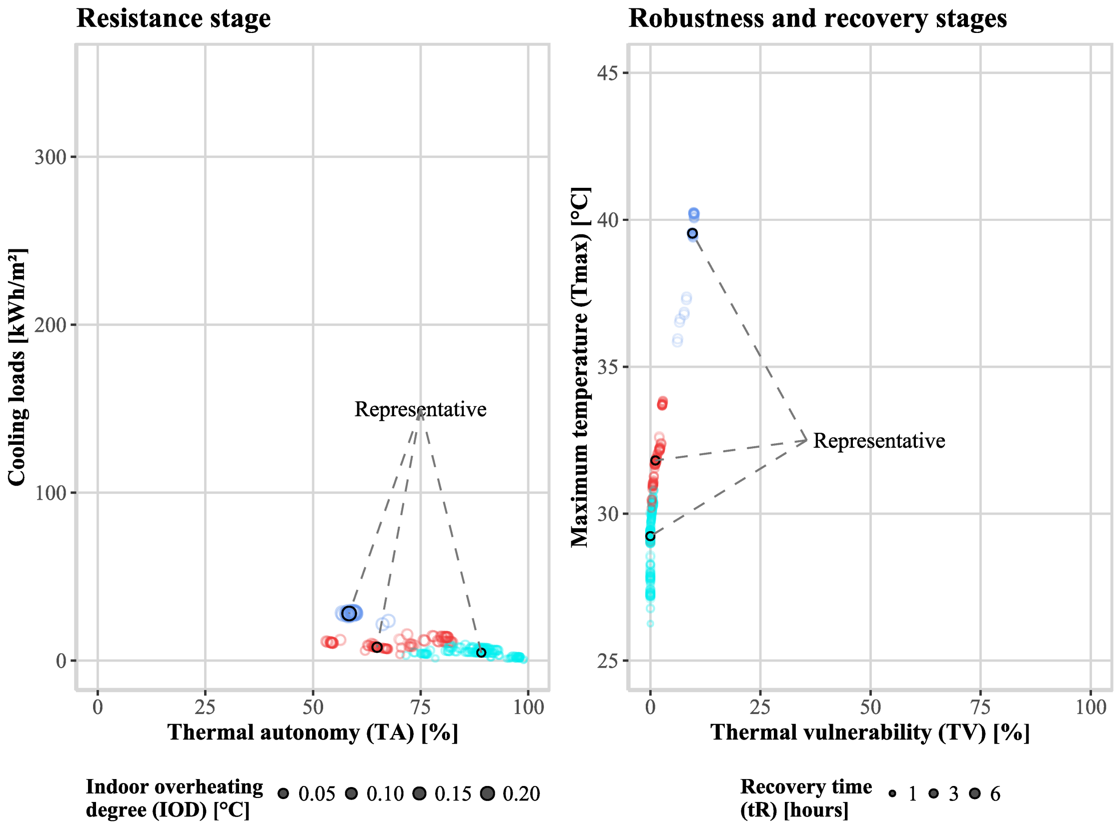

Fig A.1. Thermal resilience profile with representative cases for Curitiba

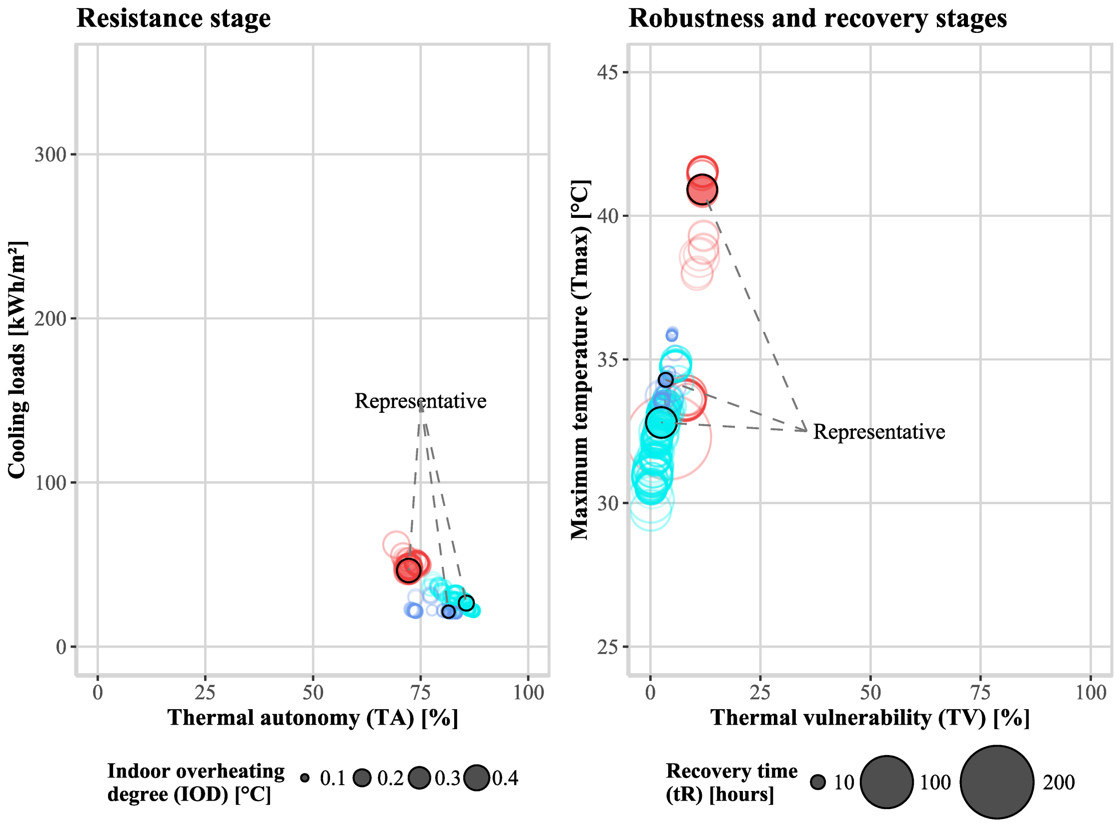

Fig A.2. Thermal resilience profile with representative cases for Florianópolis

APPENDIX C - Shared authorship agreement

Shared authorship agreement

This document attests that all coauthors of the article entitled "*A thermal performance standard for residential buildings in warm climates: Lessons learned in Brazil*" **AGREE** with its use as part of the Doctoral thesis of **Amanda Fraga Krelling**, supervised by Professor Roberto Lamberts from the Graduate Program of Civil Engineering (PPGEC) at the Federal University of Santa Catarina (UFSC).

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This document attests that all coauthors of the article entitled "*A simulation framework for assessing thermally resilient buildings and communities*" **AGREE** with its use as part of the Doctoral thesis of **Amanda Fraga Krelling**, supervised by Professor Roberto Lamberts from the Graduate Program of Civil Engineering (PPGEC) at the Federal University of Santa Catarina (UFSC).

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