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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% points and cooling loads were reduced by up to 61% in the hottest climate, São Luís. However, additional strategies are necessary to mitigate remaining indoor extreme thermal conditions, such as solar shading and increased air movement.

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:

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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
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 Ref. [22] "robustness" is described similarly to "resistance." On the other hand, in Ref. [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].

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.

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.

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 Refs. [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.

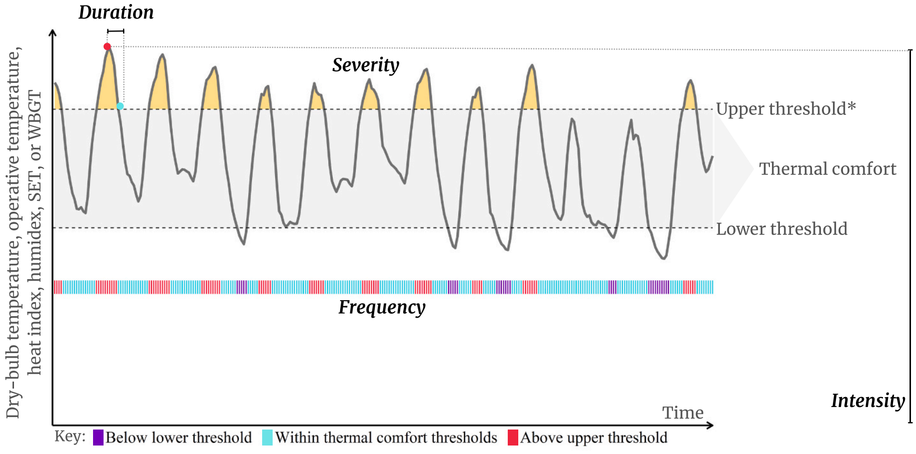
Table 2
Types, limitations and examples of key performance indicators for indoor thermal conditions.

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 °C or by 4 °C 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]

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.

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



*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 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

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 ($\text{WUMTP}_{\text{Overall}}$) 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.

2. Method

2.1. The simulation framework

Figs. 3 and 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 Ref. [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 $\mathrm{PHT_{upp}}$ in Ref. [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.

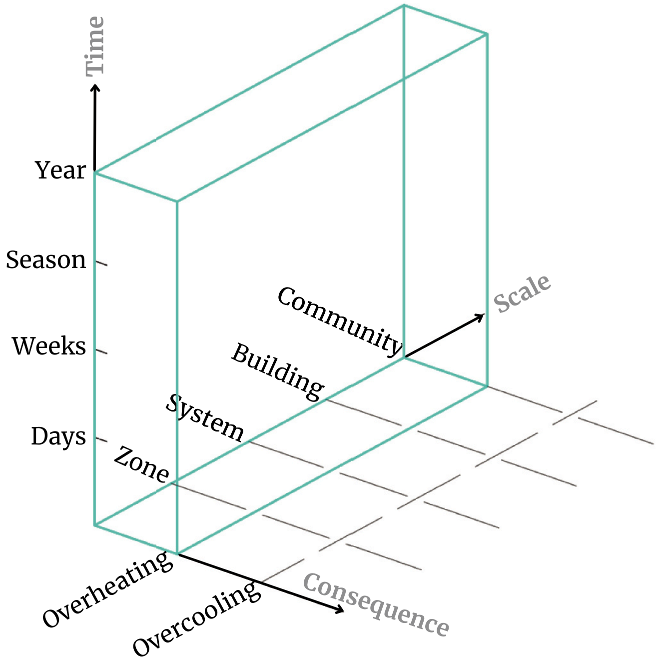


Fig. 2. Dimensions of time, scale, and consequence addressed in the framework.

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

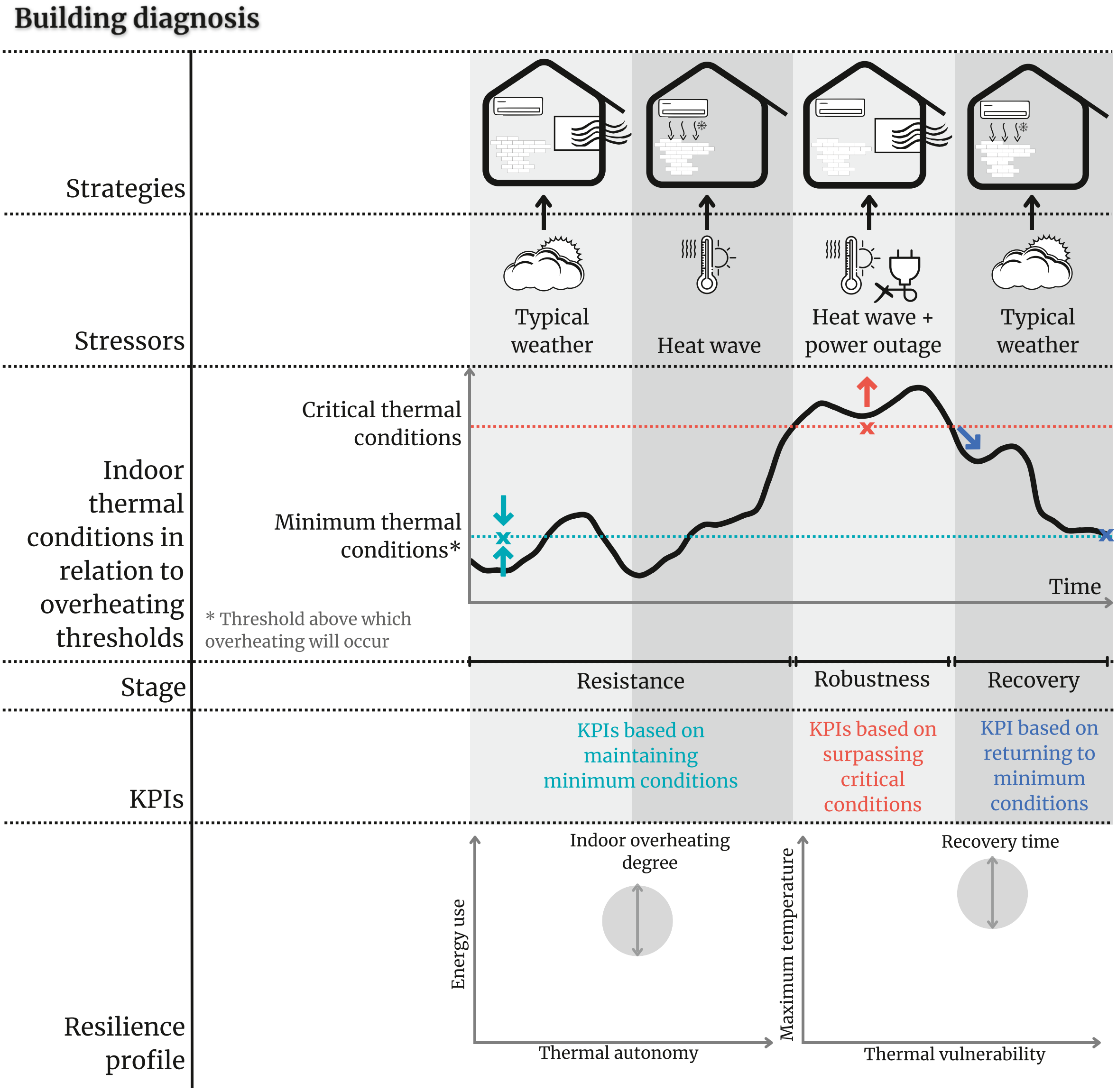


Fig. 3. Thermal resilience simulation framework for single buildings.

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–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).

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

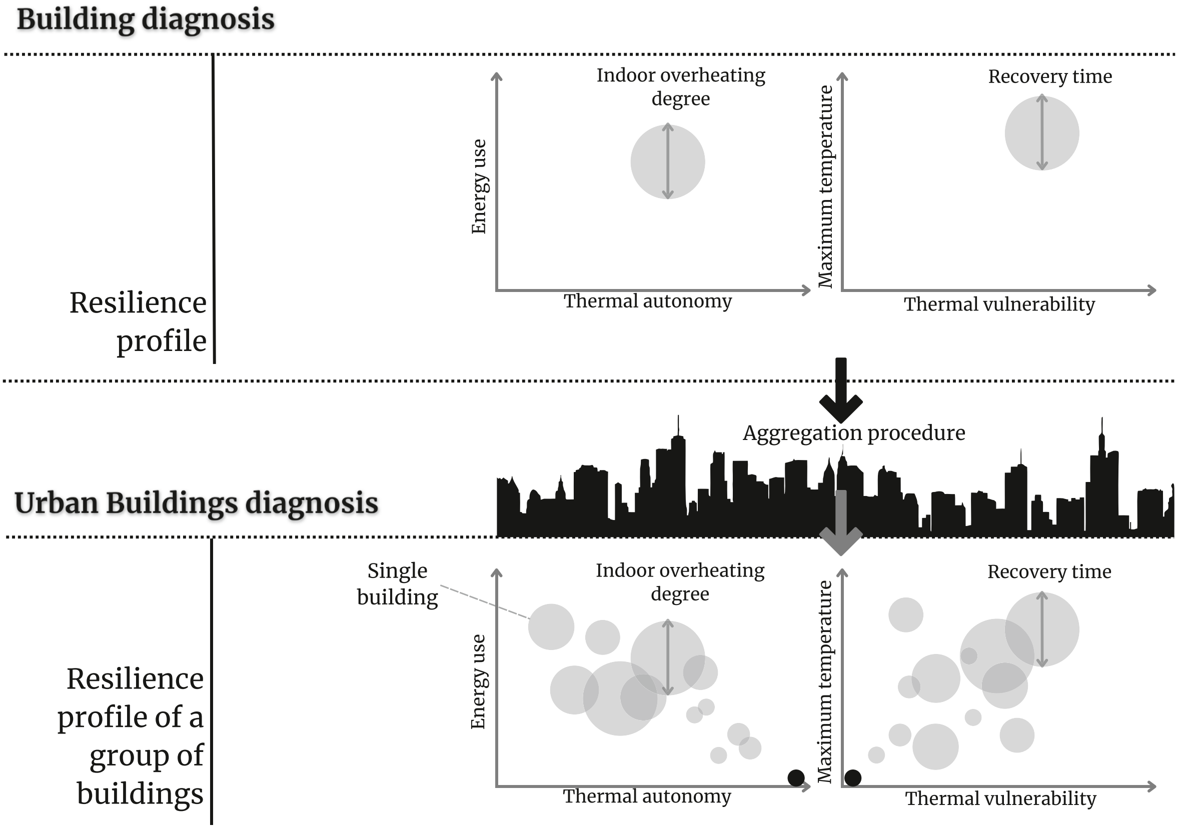


Fig. 4. Thermal resilience simulation framework for groups of buildings.

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.

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].

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 °C; that is, being equal to 30 °C (Curitiba and Florianópolis) or 32 °C (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].

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.

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:** $\mathrm{TA} = \frac{N_{occ;range}}{N_{occ;tot}}.100$ *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) [°C] [61]	**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/m^2]	**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) [%] (adapted from Ref. [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 °C above the minimum threshold **For multi-zones:** highest value between all zones	Robustness
Maximum temperature (Tmax) [°C] [57]	**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] [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

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.

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 °C 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 °C. 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 °C 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 °C (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 h to recover to minimum indoor thermal conditions, however, some cases may take between 100 and 200 h (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 °C (Tmax), but they are likely to recover quickly towards the 26 °C threshold. The maximum t_R is equal to 6 h.

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/m^2 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 °C and a maximum of 2.5 °C. Cases in the previous cities never reached 0.5 °C of IOD. Many buildings can reach a maximum temperature of 42 °C, but recovery can vary from 6 h 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

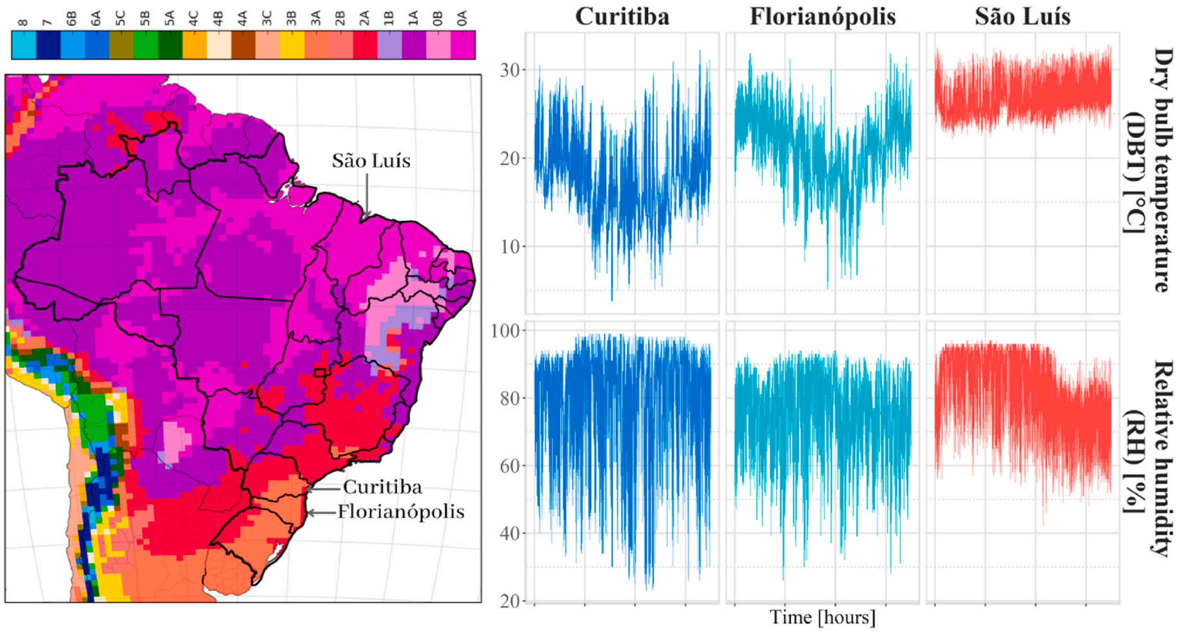


Fig. 5. Location of Curitiba, Florianópolis, and São Luís within the Brazilian territory, juxtaposed with the ASHRAE 169 climate zones, and annual variation in dry bulb temperature and relative humidity.

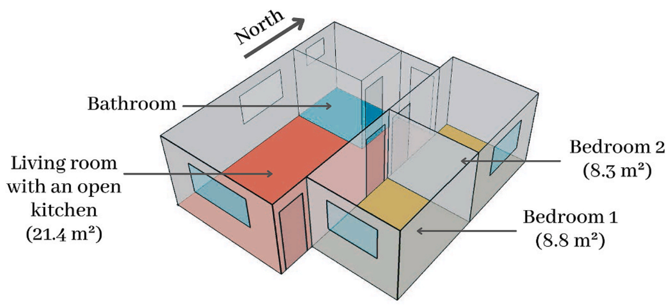


Fig. 6. Representation of the case study.

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/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 °C 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 9 h 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 °C, while temperatures above 32 °C 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,

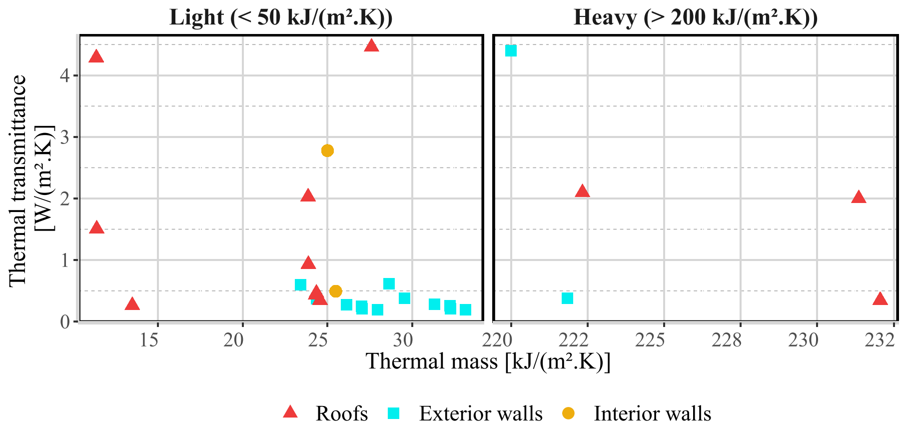


Fig. 7. Thermal properties of the building components.

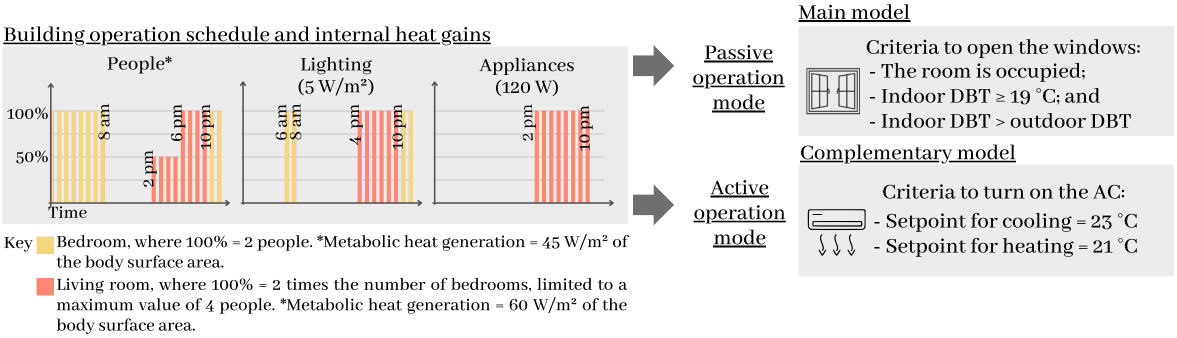


Fig. 8. Building operation according to NBR 15575-1.

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	$DBT_m < 25\ ^\circ C$	$18\ ^\circ C < To < 26\ ^\circ C$
Interval 2	$25\ ^\circ C \leq DBT_m < 27\ ^\circ C$	$To < 28\ ^\circ C$
Interval 3	$DBT_m \geq 27\ ^\circ C$	$To < 30\ ^\circ C$

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.

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

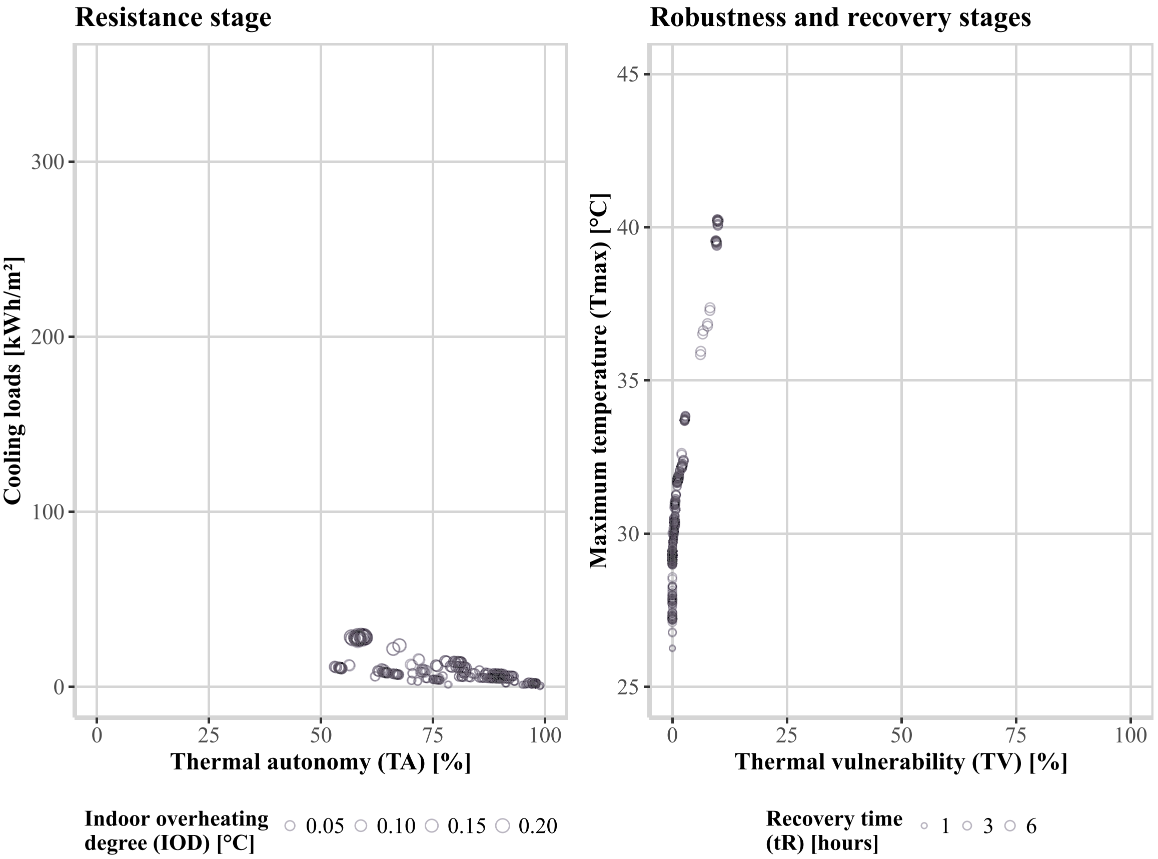


Fig. 9. Thermal resilience profile for cases in Curitiba.

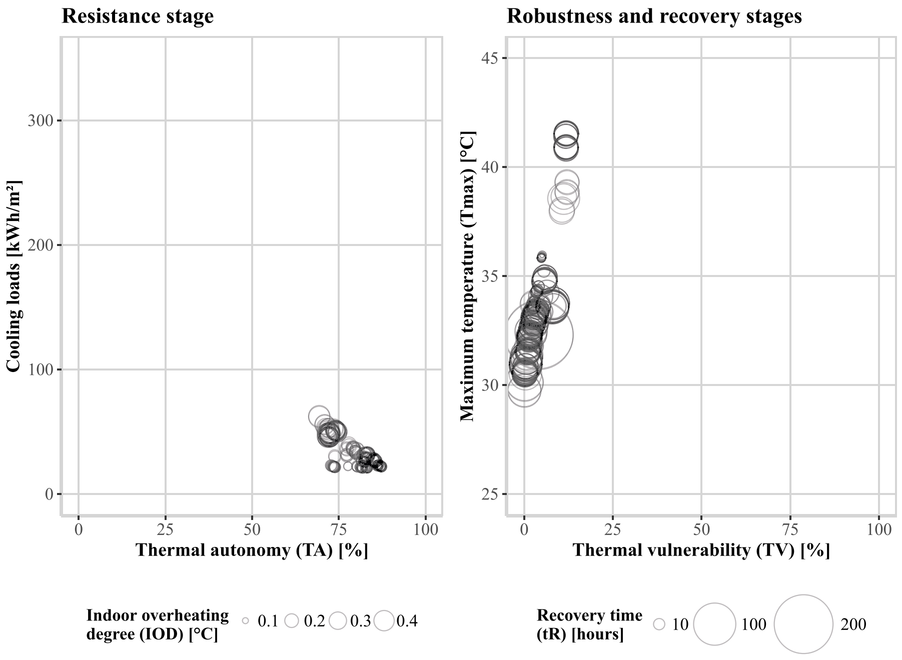


Fig. 10. Thermal resilience profile for cases in Florianópolis.

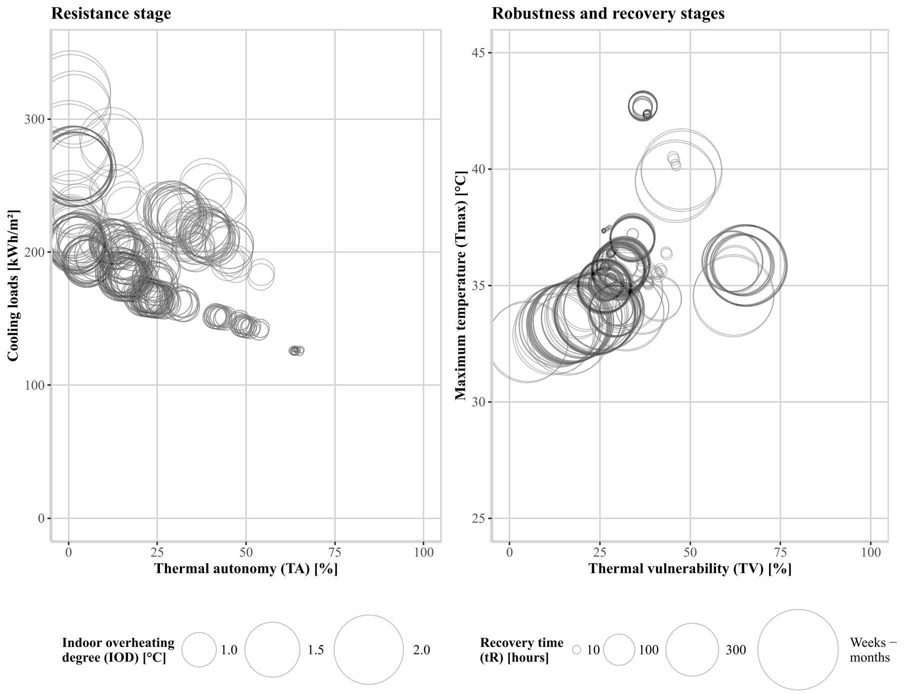


Fig. 11. Thermal resilience profile for cases in São Luís.

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

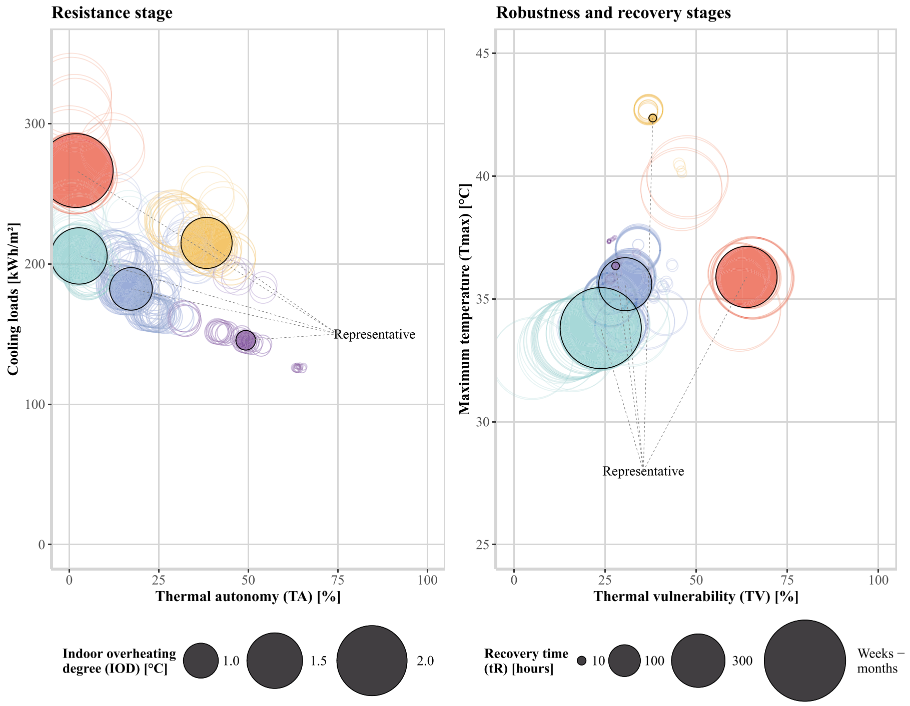


Fig. 12. Thermal resilience profile with representative cases for São Luís.

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 °C 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: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **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.

Data availability

Data will be made available on request.

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Appendix A

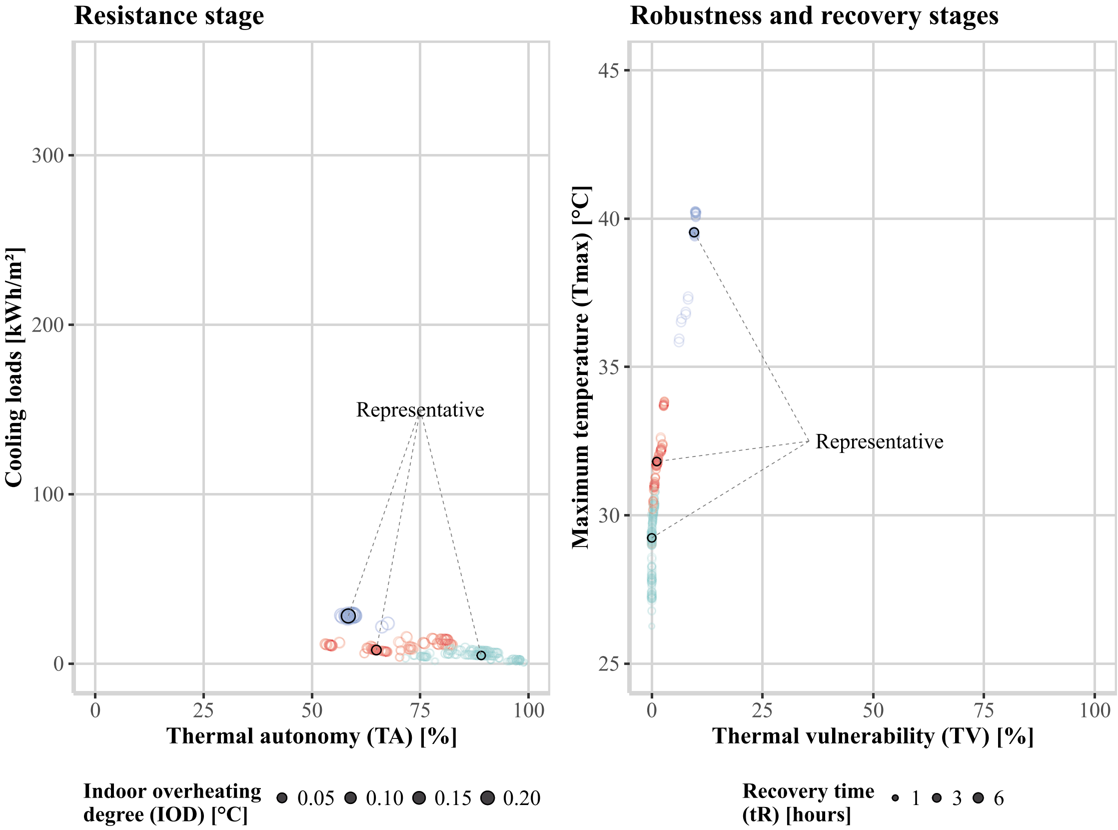

Fig. A.1. Thermal resilience profile with representative cases for Curitiba

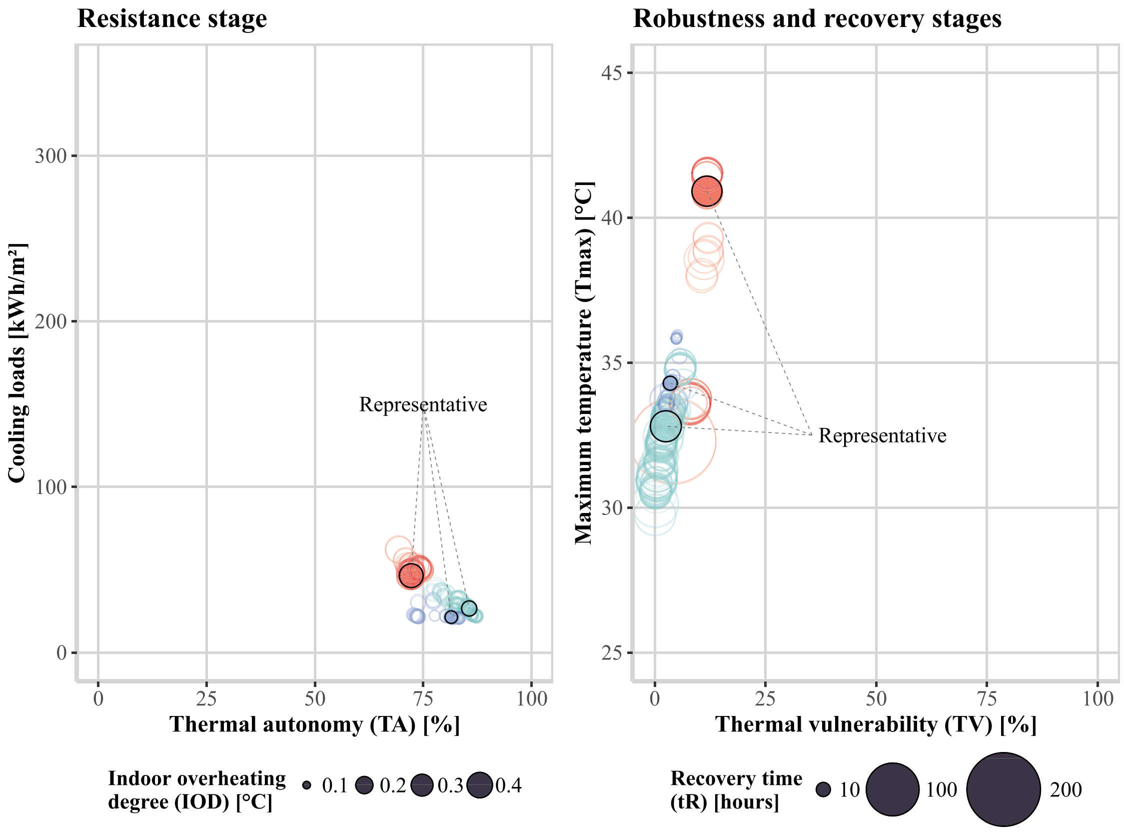

Fig. A.2. Thermal resilience profile with representative cases for Florianópolis

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