Performance-based climatic zoning method for building energy efficiency applications using cluster analysis

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Abstract

Climatic zoning for buildings is an important topic in the field of building energy efficiency. Defining climatic zones is challenging, as it involves many variables sparsely distributed in time and space. Many methods exist today to define climatic zoning, most of them focused on weather-centred definitions. The actual response of buildings in terms of performance is rarely considered in the climatic zoning definition, leading to significant levels of misclassification. Early initiatives of performance-based climatic zoning show the large potential of this approach. However, these initiatives have shortcomings on handling complex building-stocks, defining boundaries between zones, and quality-assurance of results. This paper proposes a performance-based approach for climatic zoning addressing these shortcomings, relying on the intensive use of archetypes, building performance simulation, and GIS. The method was tested in south-eastern USA, using simulation results for 52 building models from the USA Department of Energy (DOE) building stock for 95 locations. Results were clustered using the k-means method considering 3 different zoning levels. An existing climatic zoning performance indicator, the Mean Percentage of Misclassified Areas (MPMA), was calculated for each alternative. The best-case scenario (3-zones) reached less than 2% of MPMA, which is low when compared with existing methods (10% for ASHRAE169-2013, 15% for ASHRAE169-2009).

Keywords: Climatic zoning, building energy performance, cluster analysis, performance-oriented climatic zoning.

1. Introduction

Climatic zoning has a prominent place in the building energy efficiency policy of many countries [1]. However, the identification of suitable climatic zones is challenging, as it often involves several variables sparsely distributed in time and space. Many methods exist today to define climatic zones, with the most widely used based on weather-centred approaches [1–13]. In weather-centred approaches, the zoning is based only on climatic variables and the actual response of the building performance in terms of cooling, heating or comfort is not directly taken into account. As different building types show different sensitivities to climatic variables, this approach poses a problem for climatic zoning applications aiming to support building codes and design guidelines that improve the building performance [14–18].

The limitations of weather-centred approaches in this regard have been demonstrated in recent studies, as a result of the introduction of a technique to assess the validity of climatic zones [14,15,19]. These studies indicate that widely used weather-centred approaches may fail to identify the correct zone for a given location within 10% to 25% of a territory. This high occurrence of potentially misclassified areas appears in climatic zones for regulations for buildings with heating, ventilation, and air conditioning (misclassified areas around 10%) [14,19], as well as in zoning targeting naturally ventilated buildings (misclassified areas around 20%) [15]. Similar results were reported in a recent study where different climatic zoning methods were assessed using performance data of office buildings considering 411 Brazilian cities [16]. Results of that study suggest that two globally well-known weather-centred approaches (the Degree days method and Köppen-Geiger), average from 14% up to 37% of performance overlap considering an indicator named ‘uniqueness’ which is calculated using performance data obtained through simulation [16]. Misclassified areas may have a harmful impact on the building industry, as they may be used to enforce building requirements that are not suitable for a particular location. There is a need for alternative approaches for the design of more reliable climatic zoning.

Examples available of early initiatives involving buildings performance provided good indications of the large potential of these approaches to support informed decision-making in the climatic zoning process [20–28]. Rather than using only climatic variables; performance-based approaches are based on the building’s response to the climate in terms of chosen performance metrics. Despite the potential of these approaches, their complexity makes their use less common than weather-centred approaches, as they require detailed models of the building stock, expertise in simulation and an efficient means to process and analyse large data sets over large geographical areas.

Recent works on performance-based validation for climatic zoning [14–16] have applied and/or developed techniques that could, in principle, be used in the zoning process. However, none of them have attempted to do so as there are substantial challenges to be overcome. Evidence of these challenges can be seen in three recent papers proposing performance-based zoning approaches applied to China [25,27] and to the region of Andalusia in Spain [28]. In the studies applied to China [25,27] only one building geometry is used, instead of multiple building types representing the whole stock which is essential in achieving a climatic zoning that has meaning across the whole building industry. Moreover, both papers provide little support for the decision-making process of placing zone boundaries in a given location, a decision with significant implications as shown by a recent study [14]. Finally, and most importantly, both papers rely on abstract statistics to check the quality of their zonings [25,27] which may lead to debatable results as seen in Figure 1. This figure shows the current China climatic zoning (a) versus a performance-based climatic zoning proposed using abstract statistics for data analysis and quality-assurance [27]. The proposed Cluster 2 in Figure 1b comprises an extensive climatic zone covering areas previously classified as temperate, hot summer, cold winter, cold and severe cold. The method proposed by Deng X *et al* [27] fails to explain this peculiar result as there is no comprehensive post-processing and analysis of building performance data. The proposed Cluster 5 in Figure 1b comprises a very small area (the Hainan Island with 0.3% of the area of China, 0.7% of the Chinese population and 1% of the weather files used in the study). The method proposed also does not show the applicability of such a small zone in face of the magnitude of climatic difference between this zone and the south coast of China (the island, as seen in the current Chinese climatic zoning in Figure 1a, belongs to the same zone as the southeast coast of China).

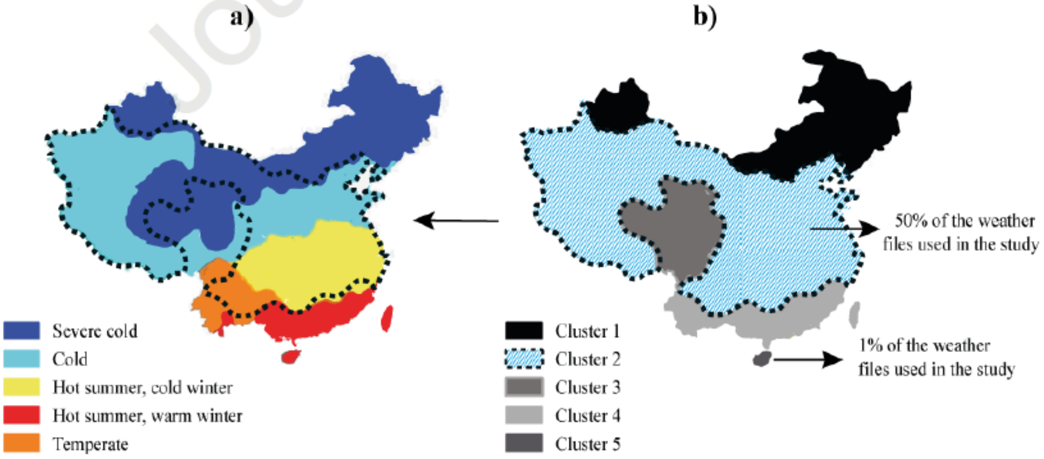

Figure 1 Current China climatic zoning (a) versus a zone proposed by Deng X et al* [27] *. Bold line shows Cluster 2 boundaries (from Figure 1b) overlaid in Figure 1a.

The potential and challenges of performance-based approaches for zoning were also indicated in a case study applied to the region of Andalusia in Spain [28]. This case adopts performance data obtained by simulation to propose improvements in the existing climatic zoning adopted for this region. The case study, however, did not attempt to provide a general method for performance-based zoning. The approach adopted in this case study is not applicable to cases where a single climatic zoning considering all seasons is envisaged (the most common scenario [1]), as they adopt separate zonings for winter and summer. The Andalusia case study is also limited by the criteria used for validation of results (silhouette coefficient) instead of adopting more suitable indicators developed specifically for climatic zoning (such as the MPMA [15]).

Considering the limitations of current methods on handling complex building stocks, defining boundaries for the zones, and using quality-assurance of the zoning results, the current study presents and tests a method for climatic zoning using the performance-based approach addressing these issues. The method adopts lessons learned from previous studies, e.g. the need of using multiple buildings to represent the building stock [23], the need of separating performance for different seasons [20,21], as well as the use of clustering techniques [4,6,11,18,25,28–31], and building energy modelling tools already tested and validated. The main new contributions of this study when compared to other existing methods are a) the flexibility to adopt different performance indicators in the zoning process (such as comfort hours for natural ventilated buildings, peak temperatures, CO_2 emissions, the ratio of energy consumed and renewable energy produced, among others) and different weather data sets *(e.g.* current, future weather files [32]), b) a clear process to deal with performance data of multiple buildings with different sensitivities to the climate to produce a single climatic zoning map, c) the adoption of a validation process applicable to any existing zoning method facilitating comparison between the new method and existing methods, and d) the ease of application in spite of the complexity of the method thanks to the development of an open-source toolbox to apply performance-based climatic zoning.

The method is described in Section 2, which introduces the key steps proposed for climatic zoning, followed by a discussion of each of them. Sections 3 and 4 describe an application of the proposed approach for three states in the southeast of the USA. Clustering results were analysed and compared with the current ASHRAE climatic zoning method using climatic zoning metrics previously reported in the literature [14,15,19]. Section 5 summarizes the key findings of this research. In addition to the analysis presented in this paper, metadata used in the climatic zoning process include pre- and post-processing scripts which will be made available. Future research can use this information as a test bench to support the development of new, more reliable, and transparent climatic zoning methodologies.

2. A performance-based approach for climatic zoning to support building energy regulations.

2.1 Overview of the proposed zoning method.

Considering the need to define climatic zones for a given area, the proposed method comprises the following steps (as summarized in Figure 2):

- Definition of goals for the climatic zoning.
- Characterization of the building stock impacted by the zoning.
- Selection of suitable performance indicators for the building stock.
- Identification of climatic data suitable for hourly energy simulation for dispersed locations across the territory (including data quality assurance (QA) checks).
- Modelling of the stock using a building energy simulation program (including QA).
- Simulation of all archetypes in the stock for all points where climatic data is available and for all relevant performance indicators.
- Production of performance maps for each performance indicator.
- Definition of the zoning options using clustering analysis (considering different numbers of clusters).
- Validation of each option using the MPMA metric.

- Selection of one option to support defined policy-making goals and constraints.

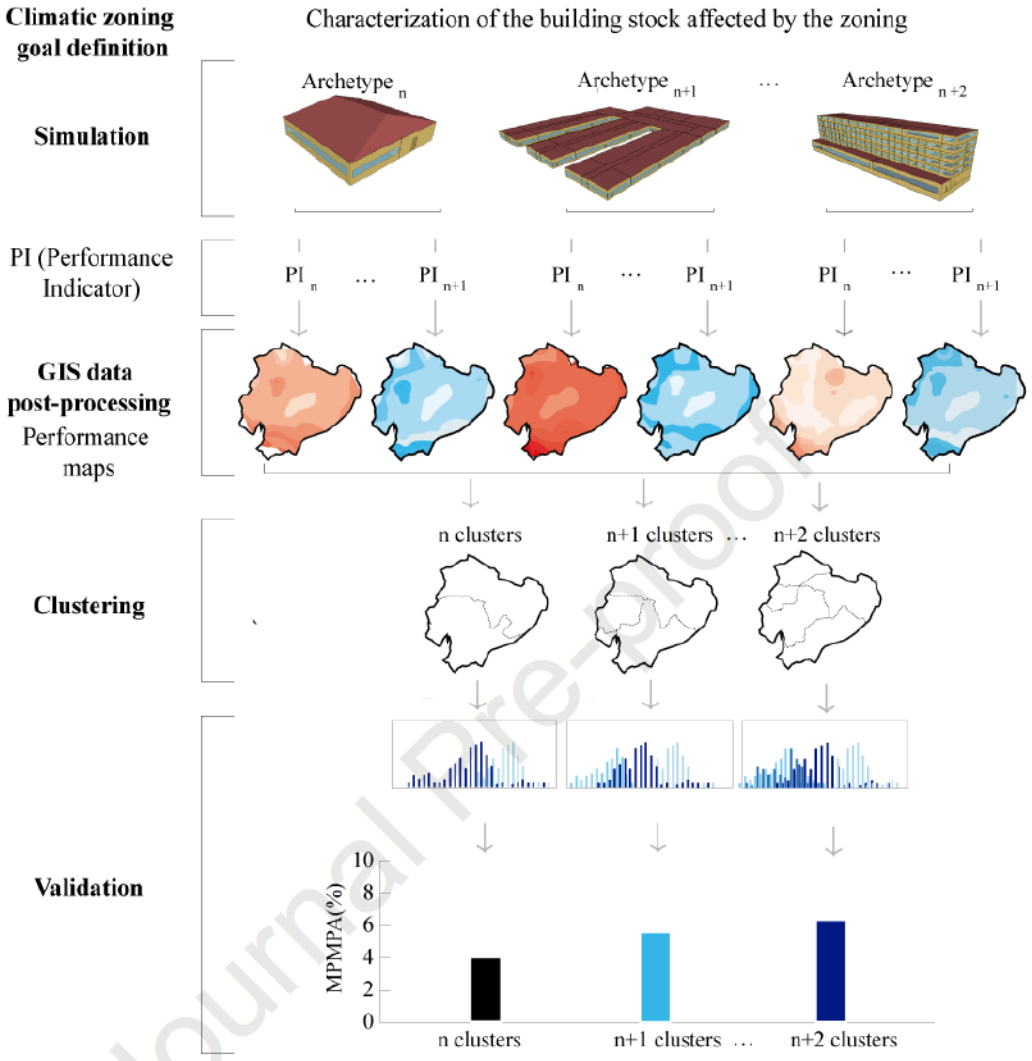

Figure 2 Schematic of the climatic zoning method workflow

Each of these steps is discussed in the following subsections, presenting the rationale behind its adoption.

2.2 Clarification of the climatic zoning goal and climatic zoning definition.

A climatic zone for building energy applications is defined for this work as a geographical region where variations in climatic variables do not substantially impact the performance of one or more representative buildings (with identical characteristics, occupancy patterns and HVAC systems). In other words, a particular building should have approximately the same performance at any location within the climatic zone. This definition makes a clear connection between the many aspects relevant for the definition of climatic zones, such as weather, building properties and building performance. This definition also shapes the presented method as it targets the reduction of the mismatch between building performance and climatic zoning.

Considering such a definition, situation-specific climatic zoning should be preceded by defining the targeted buildings or codes. Building energy codes are intended primarily for new constructions [33], however, in some countries, building energy codes also are defined for deep renovations of existing buildings [34]. Older buildings typically have inefficient building envelopes and high energy consumption patterns offering greater potential for energy savings [35–37]. This situation puts existing buildings at the core of building energy policy concerns in some regions of the world [38]. In addition to this, two thirds of countries lacked mandatory building energy codes in 2020, meaning that as recently as 2019, more than 5 billion m^2 of new buildings were built without mandatory building energy requirements [39]. The overall result is that the country-specific characteristics of the current and future building stock are key drivers in climatic zoning. A climatic zoning for building energy codes targeting existing buildings should be defined according to the characteristics of the current building stock and renovation/energy retrofits opportunities [38,40], while climatic zoning for new buildings should be based on scenarios for the future building stock and future climate scenarios [7,10,41,42].

The level of stringency of building energy codes also differs from country to country. In most developed economies, a transition towards high-performance/nearly-zero energy buildings is taking place [43–45]. High-performance buildings moderate the interaction between indoor and outdoor environments more efficiently [46] in comparison with regular buildings. In addition, the use of renewables is common in high-performance buildings [47]. In such buildings, the balance between energy produced and energy demand becomes a key performance indicator. These characteristics imply different interactions between the climate and performance of high-performance buildings in comparison with regular buildings, suggesting that the optimal climatic zones for regular buildings may be different from those addressing high-performance buildings.

Climatic zones can be adopted to define design guidelines for passively heated, cooled and/or ventilated buildings that are applicable in the early stage of design. The climatic zones for passive buildings [11,48–51] are different from zones specific to energy consumption in conditioned buildings [31], as the former heavily relies on the characteristics of available climate-related heat sources/sinks or wind patterns for comfort-targeted natural ventilation, rather than energy efficiency [18]. For this reason, zoning for passive designs is primarily driven by comfort performance indicators rather than energy efficiency.

Climatic zones can also be developed to support building energy codes targeting subsystems of buildings [52], such as HVAC systems, renewables systems or specific thermophysical properties of the building envelope [53]. In each case, climate zones are driven by different performance indicators derived from the specific relationship between the weather and each subsystem.

2.3 Characterization of the building stock affected by the zoning.

The relationship between performance and climatic zoning depends on the sensitivity of buildings to climate variation. Performance also varies substantially from building to building. Each building has a different sensitivity to climatic variables due to its particular geometry, fenestration design, and orientation [20,24,54]. This difference can be exemplified by the comparison of compact buildings with a low glazing-to-envelope ratio versus buildings with a high envelope-to-floor area and glazing-to-envelope ratio. The former has little sensitivity to climatic conditions, being in some cases almost decoupled from the external environment. In these buildings, significant energy consumption for space conditioning is related to internal heat gains and forced ventilation, which are not directly related to climate and would probably lead to very large climatic zones. The opposite is found in buildings with a high envelope-to-floor area and glazing-to-envelope ratio, which are highly influenced by the local climate due to larger building envelopes and high impact of glazing, as a result of solar gains and conduction losses. In such buildings, small variations in location (and consequently in climate) may have a high impact in the building performance, which would probably lead to smaller climatic zones. These differences in sensitivity for different building types implies that the definition of climatic zones must be preceded by the definition of one or more representative buildings (in line with the goal of climatic zoning). The quality of the climatic zoning will be directly related to the definition of buildings able to represent the existing and/or future building stock.

2.4 Selection of suitable performance indicators for the building stock.

The connection between performance indicators and climatic zones is already acknowledged by countries with different zoning or indicators for winter and summer [1]. In the method proposed here, the performance indicators relevant for the building stock and the aim of the zoning should be clearly stated prior to the development of climatic zoning options. Performance indicators may comprise, for example, heating and cooling energy demand, peak power of HVAC systems, renewable energy production, and/or overheating and overcooling hours.

2.5 Modelling and simulating all archetypes in the stock, for all points where climatic data is available, for all relevant performance indicators (including QA).

The development of models to represent the building stock is a challenging task, and there is considerable literature in this topic [55–59]. The present procedure for climatic zoning does not prescribe a particular approach for the definition of representative models for the building stock, nor a particular simulation program to conduct simulations. These are decisions to be taken as part of the climatic zoning process, in face of the resources available, constraints and goals of the project. It is however important to highlight the need for quality assurance measures and validation of simulations. Comparison with real data to calibrate the models and uncertainty analysis are strongly recommended.

Moreover, as each building should be simulated for each location, it is critical to have a structured approach to automate pre-processing, simulations, and post-processing. The automation not only reduces human errors and the burden of conducting the extensive amount of simulations, but also provides means to generate typical plots (e.g. daily patterns of variables, energy balance in particular zones) for each simulation. The use of such plots for quality assurance is important, as errors in the simulations can be easily masked in the analysis, which is concentrated on annual values for the performance indicators.

2.6 Obtention of climatic data suitable for hourly energy simulation for points across the territory (including QA).

One of the main inputs for performance-oriented climatic zoning is the reference weather data for simulation. Many different methods have been developed to define representative or typical years for simulation [60] which are suitable for particular applications, such as energy assessment in current conditions, climate change resilience, and potential for renewable energy generation [61–64]. The choice of climatic data should be in line with the purpose of the zoning.

Quality assurance methods should be adopted to assess the suitability of climatic data sets for the zoning process. This assessment may rely on statistical descriptors, graphs and maps of climatic variables and related ones (e.g. topography) to facilitate the identification of outliers in the data set.

2.7 Production of performance maps, for each performance indicator.

Building performance data obtained through simulation is used as input data to generate performance maps [15]. Performance maps show how a set of chosen indicators, such as energy consumption or thermal comfort, vary throughout the territory (country or region) for given archetype buildings for a typical year of climatic data [15]. These maps can be produced by several tools, such as the mapping toolbox of Matlab [65], Python libraries [66], or by using Geographical Information Systems (GIS) programs such as ArcGIS [67], Quantum GIS [68], among others.

Performance maps are not only important for the definition of zones, but also as a tool to visualize simulation results and detect eventual anomalies in the results of a particular model and performance indicator. The comparison of performance maps obtained for different models can also facilitate the identification of models with particularly high or low sensitivity to the climate, which should be investigated to assure model settings are correct.

2.8 Definition of the zoning options using clustering analysis (considering different numbers of cluster).

Once multiple performance maps have been developed in addressing all archetypes and performance indicators, these maps can then be used in the zoning process. From the available techniques for geoprocessing, clustering has demonstrated excellent results when coping with multiple datasets [4,6,11,18,25,28–31]. Experimentation with clustering analysis settings is recommended, generating several provisional alternatives for the zoning. From the many settings that can be explored two are of major importance.

The first is the number of clusters itself. The adoption of less zones simplifies the implementation of the zoning, but it may create zones so large that building performance will not be the same across the whole zone. The increase in the number of clusters reduces the dimension of each zone, reducing the climatic variation across the zone. However, increasing the number of zones also creates more complex zoning, with more areas of transition between zones which often lead to misclassification [14,15]. The trade-offs in having many or a few zones should be addressed in the context of the policy this zoning will be adopted in.

The second clustering setting with high impact in the zoning outcome is the use of continuity constraints. Having continuous zones in space largely facilitates understanding and adopting of such zones. Examples of zonings with continuity can be seen in many countries [31,69,70]. Zones with no continuity can be excessively fragmented and increases the number of transition areas between zones (which may increase the changes of misclassification of such areas). Despite these problems, fragmented zones can better group areas in the territory where climate and/or performance are similar, in spite of not being placed in adjacent locations. Zonings with no spatial continuity are also adopted in many countries [71–73] and this setting must be explored in the zoning process and analyzed in light of the goals and constraints of the policy-making process.

2.9 Validation of each option using the mean percentage of misclassified areas.

There are several possible approaches to assess the quality of clusters in climatic zoning such as: the Silhouette Coefficient, Calinski-Harabasz index, Davies–Bouldin index [74], the uniqueness and dispersion [16] among others [75]. The current study adopted the MPMA method [15] to validate our climatic zoning. While other metrics are abstract and sometimes contradictory, MPMA identifies areas where a proposed climatic zoning fails to match climate and building performance, quantifying them as a percentage of the total territory. The calculation of MPMA can also be used to show which areas of the territory may have been misclassified, for which building types and/or performance indicators. The higher the MPMA, the higher the likelihood that the performance of a given building in a given point in the zone is not similar to the performance of this same building in the same zone, and it is instead closer to the performance seen in other zones. This allows the comparison of different options obtained by cluster analysis, such as continuous versus fragmented zones and options with different numbers of zones. This also allows the comparison of the zoning obtained using the method proposed in this paper with zonings obtained by other techniques. The literature provides comparisons of zonings options based on MPMA for different zoning techniques and locations [14,15,19] demonstrating the usefulness of this metric to judge the quality of a given climatic zoning option.

The MPMA is calculated as follow:

$$\boldsymbol{MPMA = \frac{\sum_{i=0}^{n}\sum_{k=0}^{p} PMA_{i,k}}{(n.p)}}\ \textbf{Eq.(1)}$$

n – number of building types simulated.

p – number of performance indicators simulated for each building type.

$PMA_{n,p}$ – percentage of misclassified areas for the building type n, considering the performance indicator p

$$\boldsymbol{PMA = 100\frac{\sum_{l=0}^{j} a_l}{j}}\ \textbf{Eq. (2)}$$

j – total number of equally spaced points under analysis in the area covered by the climatic zoning, where a performance indicator was simulated for a given building type (and posteriorly interpolated in a uniform grid)

$$a_l = \begin{cases} 1, \mathit{if\ the\ simulated\ performance\ is}\ \boldsymbol{out\ of\ the\ typical\ range}\ K\ \mathit{for\ that\ zone} \\ 0, \mathit{if\ it\ is}\ \boldsymbol{in\ the\ typical\ range} \end{cases}$$

The typical range, K, is calculated for each given building type and performance indicator, following this procedure below:

- Each point in space O is identified based on the climatic zone it falls in O_{CZ},
- Performance data for all j points in each zone CZ is divided in B bins.
- The number of points in each climatic zone and in each bin $O_{CZ,B}$ are calculated
- For each bin, the zone with maximum $O_{CZ,B}$ is identified. For that performance bin, this zone is considered as dominant.
- K is defined as the range of performance where each zone is dominant.

2.10 Selection of one option based on policy-making goals and constraints.

The definition of climatic zoning and its implementation as part of energy policy instruments are not simple tasks, as many factors, stakeholders, and instruments are involved. Therefore, climatic zoning goes beyond the data analysis described in this paper and other practical considerations must be taken into account. For this reason, it is not surprising that many countries adopt administrative divisions as boundaries for climatic zoning [1,31], even though administrative limits do not necessarily reflect the influence of climate on building energy performance.

While the method proposed in this paper does not address the whole complexity of energy policy definition, the performance-based zoning described in the previous sections provides a significant improvement in the quality of climatic zoning, substantially reducing the occurrence of misclassified areas. This is demonstrated in the following sections, where an area is zoned using the proposed method and results are compared with the most commonly used zoning techniques.

3. Case study: a proposal of climatic zoning for the states of Florida, Georgia and Tennessee in the USA.

A case study was conducted to target climatic zoning for new buildings. This study covers three states of the United States of America: Florida, Georgia, and Tennessee. This region extends over four climatic zones according to the ASHRAE Standard 169-2013. From 1A (Very Hot and Humid: typical city Miami), 2A (Hot: typical city Houston), 3A (Warm – Humid: typical city Memphis), to 4A (Mild and Humid: typical city Baltimore) (see Figure 3). This area covers around 433,365 km^2 and hosts almost 32 million people. Some of the largest cities in the area of study are Jacksonville, Nashville, Memphis, Atlanta, Miami, Tampa, Orlando, Augusta, Columbus, and Knoxville. This area was chosen as it was already addressed in a previous study, where the existing zoning was subject to validation [14,19].

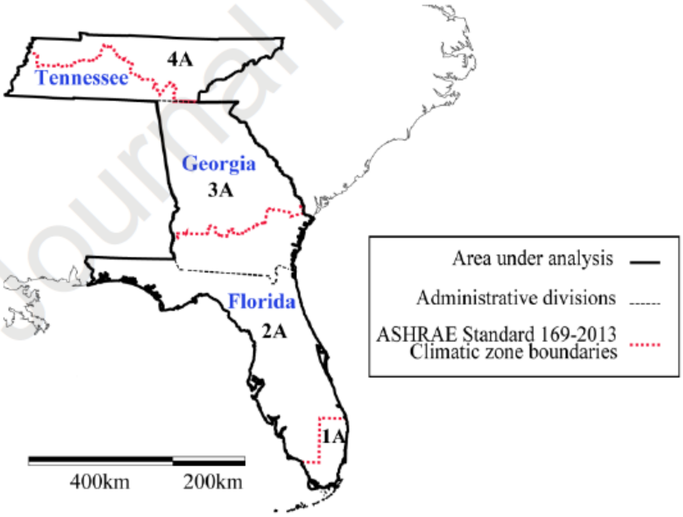

Figure 3 Area under analysis

3.1 Weather data.

A total of 95 separate weather files produced by the DOE were adopted in this study [76]. Where there are multiple weather files for the same location, priority was given to the most recent data [61,77]. Such data represents typical conditions for each location and is useful for comparing different locations in the area of interest. Weather files from neighbouring states (Alabama, South Carolina, and Kentucky) were also included in the analysis to improve the quality of performance maps close to the limits of the area addressed in the zoning (see Figure 4).

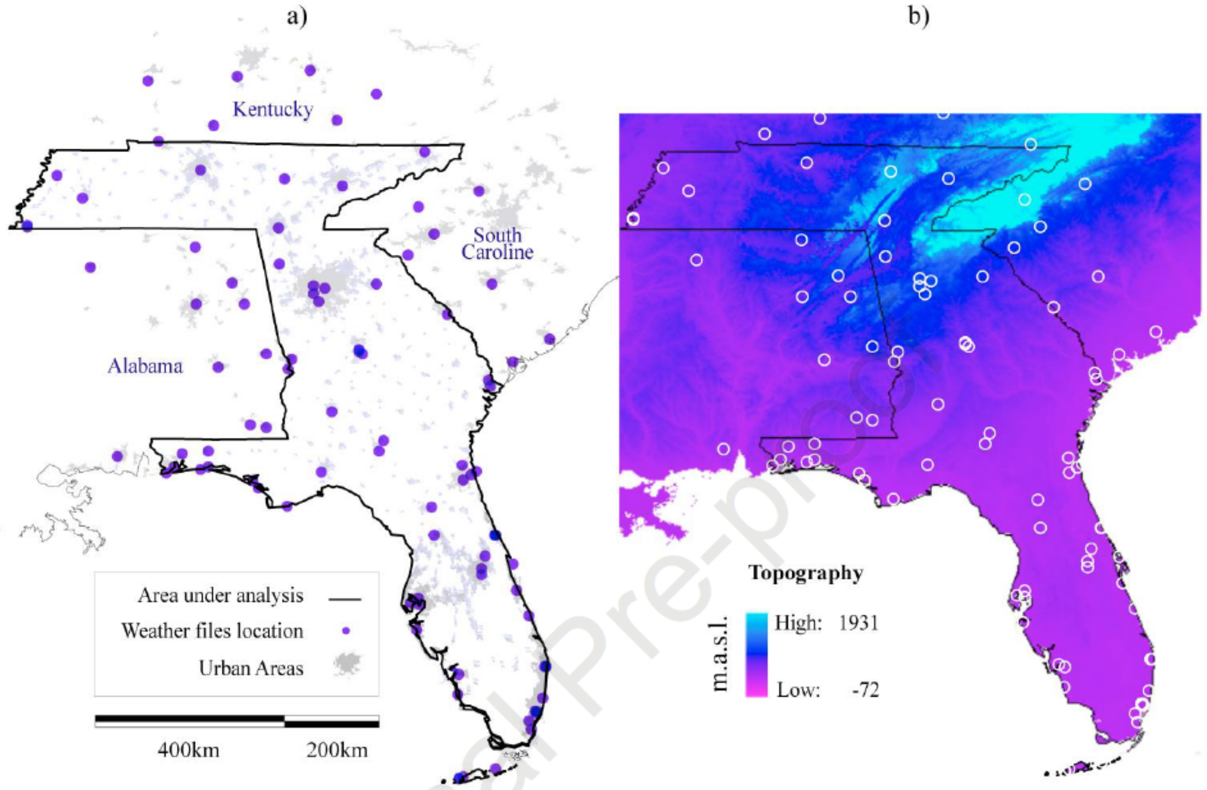

Figure 4 a) Weather files adopted in this study and urban areas [78]***, b) Topography*** [79]**.**

Extensive analysis of the climatic data, prior to their use in simulation, consisted on comparing the climatic files with available high-resolution maps of climatic variables (approximately 1 km^2) in order to assure the data was within the expected range [80]. In most cases, climatic files have shown similar values and trends found in the high-resolution maps (variations up to 7% in temperature values). In some cases, climate files have shown a sharp variation in values when compared to the surrounding locations. These cases were analysed and the variation was consistent with the proximity to urban areas (Figure 4a) and/or changes in the topography (Figure 4b). This analysis was essential to support the zoning process providing confidence in the quality of the climatic data.

3.2 Characterization of the building stock, suitable performance indicators and energy modelling.

In this study, building models prepared by DOE were adopted, as they took into account a number of quality assurance measures which qualify them as a valid description of the stock for the purposes of this paper [81]. This set comprises 16 different building types complying with the ASHRAE Standard 90.1-2013 (see [42]). In this study, 13 models from that set were adopted. These models represent multi-family buildings, hotels, offices, restaurants, retails, and schools. Hospitals, Outpatient Healthcare and Warehouses were not included in the analysis. On one hand, Hospitals and Outpatient Healthcare are complex models with high internal heat gains and multiple zones, consequently the simulations and performance analysis are complex and time-consuming. On the other hand, Warehouses have very low energy demand for cooling and heating partly due to the set point temperatures which are not primarily intended to reach comfortable indoor conditions for users. The set of buildings adopted in this study have different sensitivity to climate variation providing a good example of complexity that could be found in real case applications. The graphical representation of archetypes used for this study are displayed in Figure 5.

Figure 5 Graphical representation of models used in this study.

Models of each of the 13 building types were provided by DOE in four configurations (totalizing 52 models), based on the building energy requirements of the ASHRAE Standard 90.1-2013 according to climatic Zones

1A to 4A. The main differences between the four models of each building type are related to the insulation level for the envelope (opaque and glazing) and the Solar Heat Gain Coefficient (SHGC) of the glazing. Table 1 exemplifies the differences among these models for the case of the mid-rise apartment archetype. Further details can be found in [42,81]. Results for all the models were analyzed in terms of cooling and heating energy demand per area.

Table 1 Parameters of Mid-Rise Apartments based on compliance with ASHRAE Standard 90.1-2013 requirements [82].

Item		**Descriptions**			
Building type (principal building function)		**Multi-family**			
Building prototype		**Mid-Rise Apartment**			
Total floor area (m^2)		3130.8			
Aspect ratio		2.74			
Number of floors		4			
Window-to-wall ratio (%)		20			
Floor-to-floor height (m)		3.05			
Floor-to-ceiling height (m)		3.05			
Infiltration: Flow per exterior area(m^3/s-m^2) in most of the apartments.		0.00056896			
Envelope properties		**Zone 1A** **Miami**	**Zone 2A** **Houston**	**Zone 3A** **Memphis**	**Zone 4A** **Baltimore**
Roof	**Solar absorptance (-)**	0.45	0.45	0.45	0.70
	U-value (W/m^2K)	0.221	0.221	0.221	0.182
Wall	**Solar absorptance (-)**	0.70	0.70	0.70	0.70
	U-value (W/m^2K)	0.704	0.363	0.363	0.363
Glazing	**Window U-value (W/m^2K)**	3.511	3.511	3.191	2.371
	SHGC (-)	0.227	0.227	0.218	0.397

3.3 Building performance simulation.

Simulations for each of the 52 archetype models were carried out for the 95 locations, using Energy Plus V8.3 [83]. The workflow was fully automated using Matlab and python scripts, producing and extracting performance data (cooling and heating demand) and generating 104 performance maps.

As the number of simulations reached almost 5000 cases, with multiple output values per case (heating, cooling), specific measures for quality assurance were applied to allow a thorough assessment of results. In-depth analysis of a small sample of simulation results was carried out as a basic quality assurance measure. Considering the whole simulation set, automation was used to produce plots for each individual simulation, including typical day plots, histograms, boxplots, among others. These plots were individually checked for: results magnitude within the expected range (reported in the literature [42]); load breakdown in line with the literature; energy consumption patterns in agreement with control settings (star-end time and set-points); energy consumption correlation with variations in outdoor temperature; and solar radiation levels. These checks are essential to provide confidence in the simulation results and consequently to the validation of the developed climatic zoning method.

3.4 Clustering analysis and validation.

This study adopted the k-mean algorithm [84,85], to determine clusters in the data. The clustering was applied using the Spatial Statistic toolbox of ArcGIS 10.6. A total of 104 input variables were used to run the clusters based on heating and cooling energy demand of each of the 52 models described in Section 3.3. Three different alternatives were explored based on 3, 4 and 5 clusters. Three was considered the minimum number of clusters to obtain zones with similar dimensions of the current ASHRAE climatic zones. The number of clusters was increased gradually up to five. Three zoning alternatives were considered enough to observe the influence of the number of zones in the MPMA and to demonstrate the applicability of the method. Clustering was performed adopting no Spatial Constraint. Seed features were selected to optimize performance using the default option (FIND_SEEDS_LOCATIONS). Further details about clustering settings can be found in [86].

Climatic zoning results were analysed and compared based on their MPMA. Results were compared with validation data for existing zoning developed with CDD and HDD data, previously reported in the literature [14,19].

4. Results of the case study.

4.1 Energy performance analysis.

Figure 6 illustrates the cooling and heating energy demand variation of each building type included in this study. Results suggest that there are significant variations in the area under analysis. Energy demand for heating and cooling varies from 140% up to 260% considering the mean values of heating and cooling energy demand of each building type. This suggests there are regions where the same building consumes 3 times more energy than others in the same area. Such variations justify the need for different performance targets for different zones. This is consistent with the current ASHRAE Standard 169-2013 [87] that defines different climatic zones to support building codes over the area under study.

Among all the building archetypes, 'Small Offices' are the buildings having the lowest energy demand per unit area, while 'Fast Food Restaurants' and 'Sit Down Restaurants' have high energy demand for both cooling and heating. Energy demand in restaurants is also highly influenced by large loads for cooking, food preparation and laundry, leading to higher energy use intensity in comparison with the other building types. For this reason, a different scale was used to present these results as seen in Figure 6.

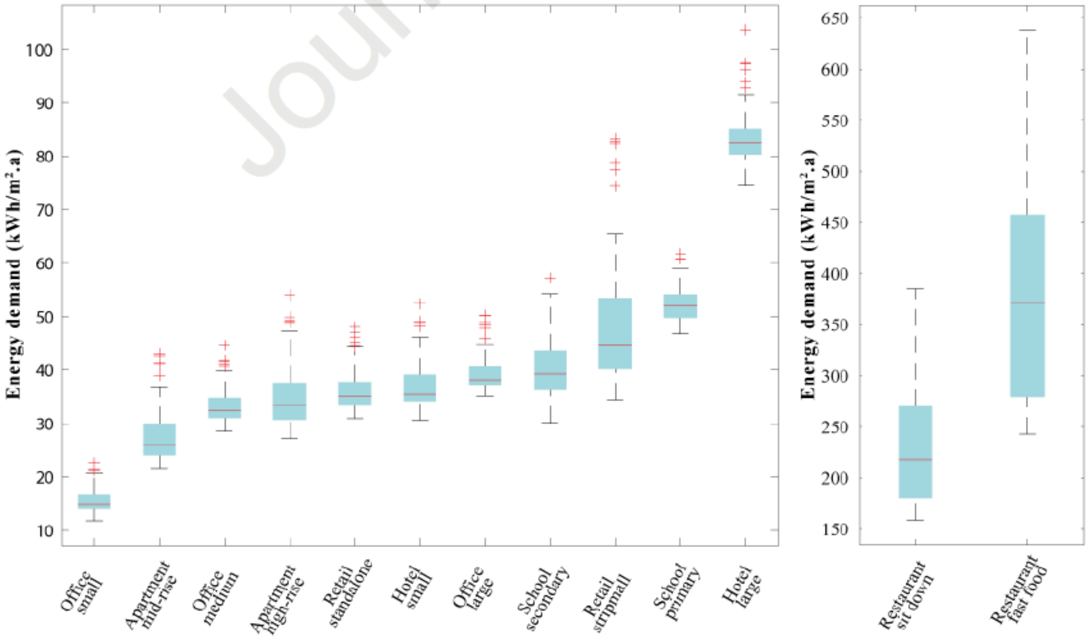

Figure 6 Average energy demand for cooling and heating through the area of study for each building archetype

4.2 Performance maps for each archetype and performance indicator.

In this section, a sample of the simulated models are used to illustrate results. Figure 7 exemplifies performance maps showing the cooling and heating variation of three archetype buildings representing a) a mid-rise apartment, b) a large office and c) a secondary school. The maps show that each building type has different sensitivity to the climate variation. Some patterns identified from these maps are:

- The mid-rise apartment has the lowest values for energy consumption per unit area in comparison with large offices and secondary schools. The occupancy density is considerably higher for schools (2.65 m^2/person) and offices (19 m^2/person) in comparison with apartments (35 m^2/person). Additionally, the model for a mid-rise apartment depicted in Figure 7a complies with the building energy requirements of zone 4A (Mild and Humid), while the office and school comply with zone 1A (Very Hot and Humid) requirements. This suggests that model (a) is more insulated than model (b) and (c). These characteristics could, to some extent, explain the difference in energy demand.
- Building (c) has a higher form factor and is more sensitive to climatic variations than building (b) and (a) when considering cooling energy demand.
- The maps showing the heating energy demand are remarkably similar in quantitative terms with a degree of observed spatial variation but similar overall magnitude. For example, while the mid-rise apartment (more insulated) indicates a larger area with no heating demand (the southern area), offices and schools show smaller areas with the same response.

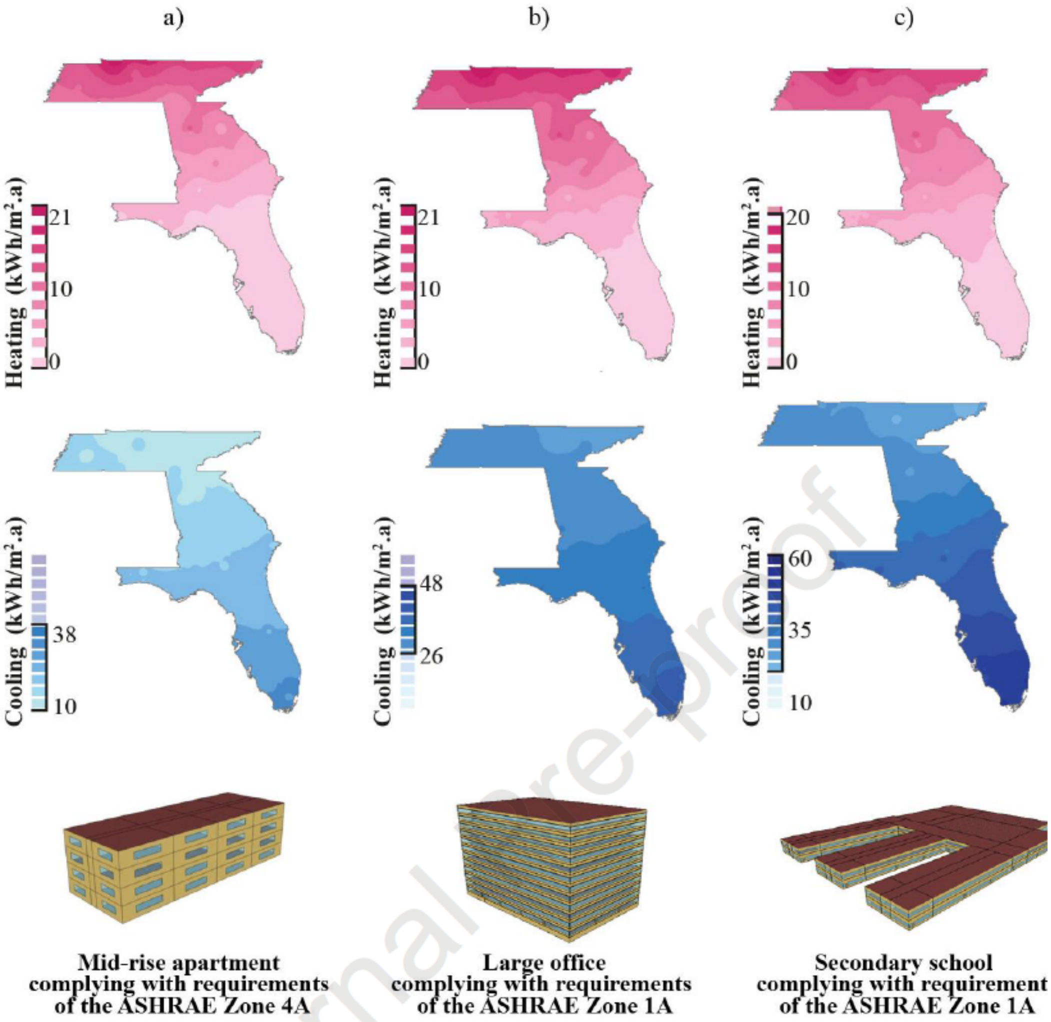

Figure 7 Performance maps of a) Mid-rise apartment, b) Large office, and c) Secondary school

4.3 Clustering results and validation.

Figure 8 displays three clustering options developed using cluster analysis. In all the options, zoning follows the pattern of climatic variation in the area, with warmer zones in the south and colder in the north. To better analyse and illustrate the complexity of the results captured by this zoning option, a sample of one building archetype misclassification is presented in Section 4.4 .

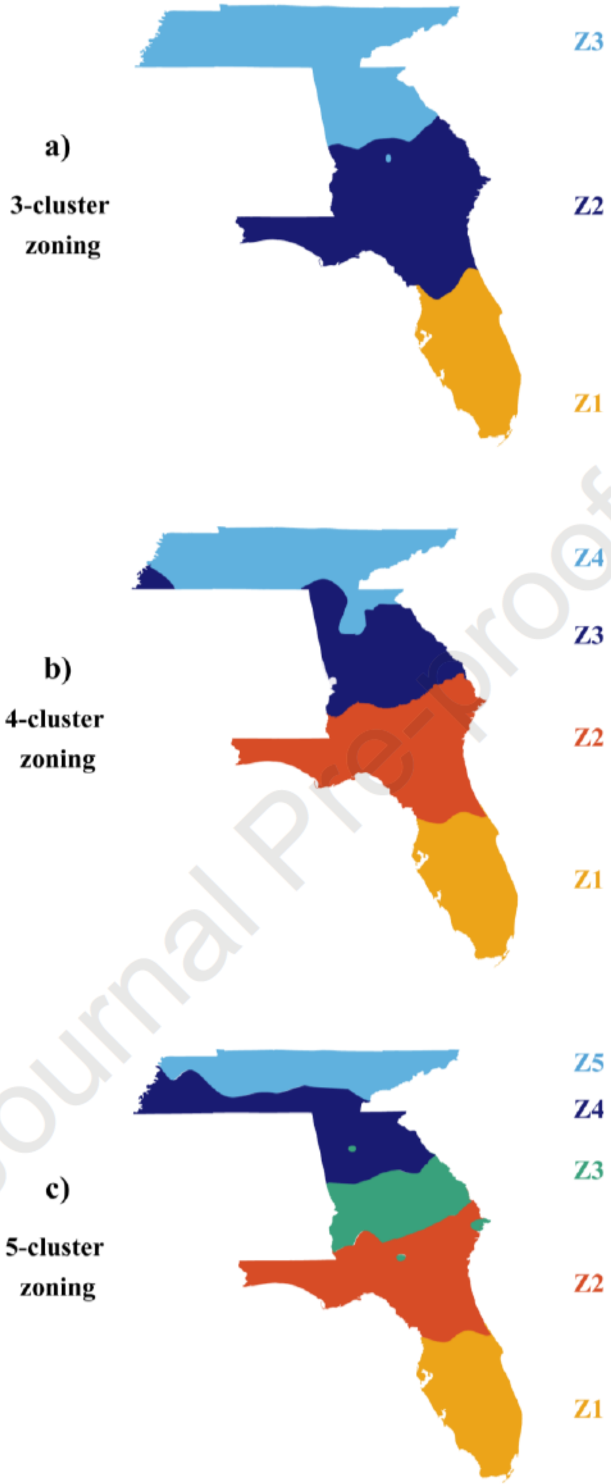

Figure 8 ***Cluster zonings options: a) 3-clusters, b) 4-clusters and c) 5-clusters***

Figure 9 shows an example of one building archetype (a mid-rise apartment in compliance with the requirements of the ASHRAE Zone 4A–highly insulated), considering cooling energy demand throughout the 4-cluster zoning as shown in Figure 8. Results suggest that cooling performance variation is qualitatively aligned with the 4 zones, however there are performance overlaps between zones. The magnitude of such overlaps is calculated using the MPMA described in Section 2.9.

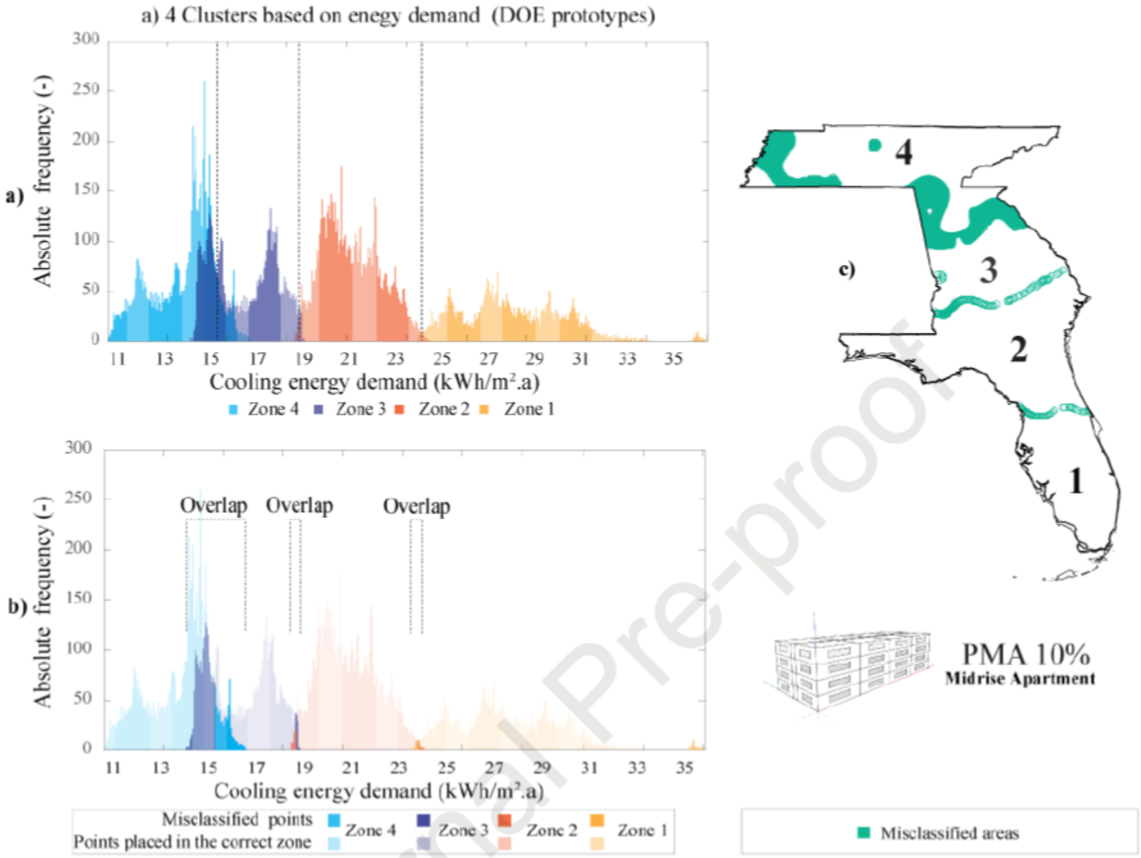

Figure 9 a) ***Histograms of cooling energy demand for a Midrise apartment considering the 4-cluster zoning, b) frequency bars related to misclassified points and c) misclassified areas.***

Figure 9a shows the histograms for cooling energy demand of the 'Midrise Apartment' within each zone. Zone 1 is the hottest zone (located in the south of Florida) while zone 4 is the coldest (located at the north). Overlap occurs among all the zones, particularly between zone 3 and 4 in the range of performance that varies from 14 up to 17 kWh/m^2.a. (see Figure 9b and c). The PMA, considering all overlaps highlighted in Figure 9b, represents 10% of the total area under analysis. The PMA was automatically calculated for all models, performance indicators and climatic zoning alternatives under analysis. The overall results are discussed as follows.

Figure 10 illustrates the occurrence of misclassification of all the models separated by cooling and heating to better appreciate the results. Darker regions represent areas where misclassification occurs with higher frequency. Misclassification occurs mainly in areas of transition between zones, particularly between the north of Georgia and the southeast of Tennessee. In that region, there are abrupt changes in elevation that may cause complex microclimatic conditions that influence building energy performance (see Figure 4b). Misclassified areas increase as the number of zones increases, (in line with results from previous studies [15]). Misclassification is higher when cooling energy demand is considered, reflecting the fact that in some models cooling is highly influenced by internal gains and less affected by climatic variation (see Figure 7b).

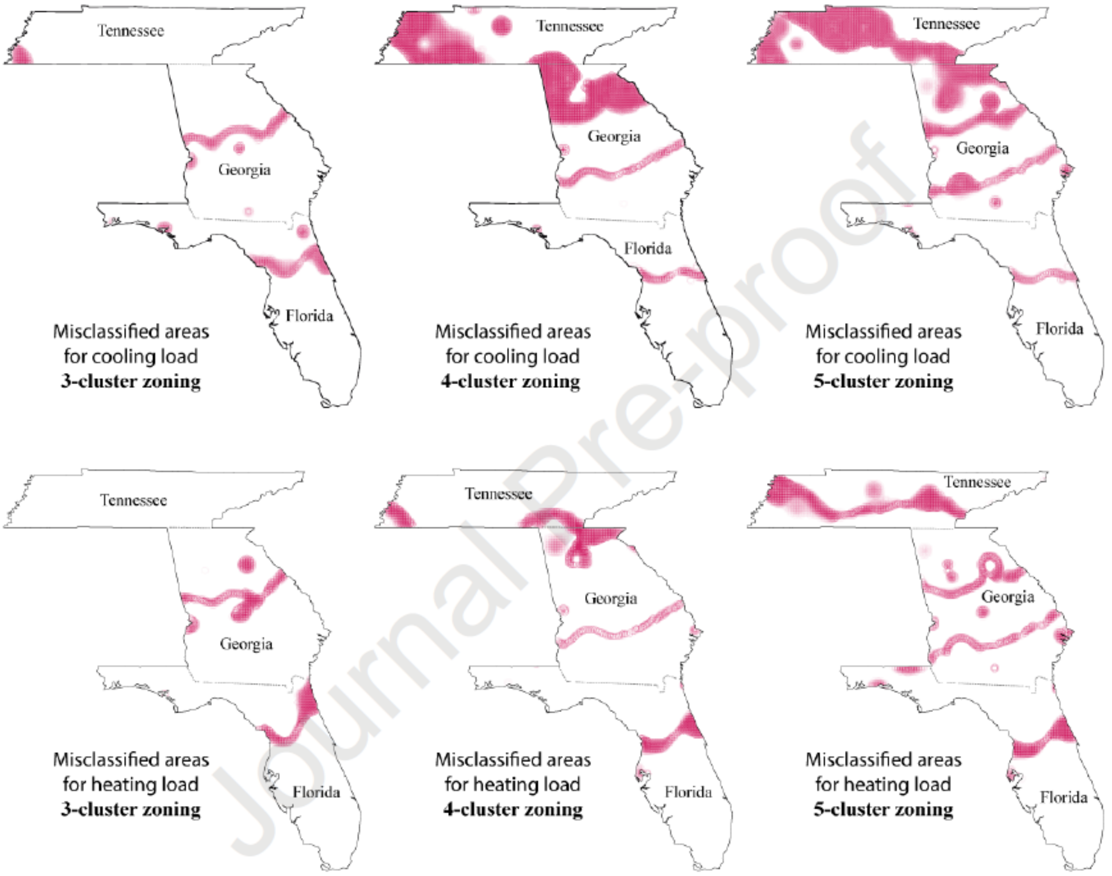

Figure 10 ***Occurrence of misclassified areas per number of clusters and performance indicator.***

Figure 11 illustrates the PMA calculated for each individual model and performance indicator (cooling and heating) considering the three zoning options. MPMA for each zoning is also indicated in the Figure 11. Results suggest that the 3-cluster zoning represents the lowest values of PMA for all the models, while the 5-cluster zoning represents the highest values. Results also suggest that the 4 and 5–cluster zoning work better considering the heating energy demand (red bars) when compared to the cooling energy demand (light blue bars), for the buildings adopted in this study. From these outputs, we can deduce that the cooling energy demand variation is more difficult to capture when the number of zones increases considering a wide range of building archetypes and cases where this performance indicator is not strongly affected by climatic variation.

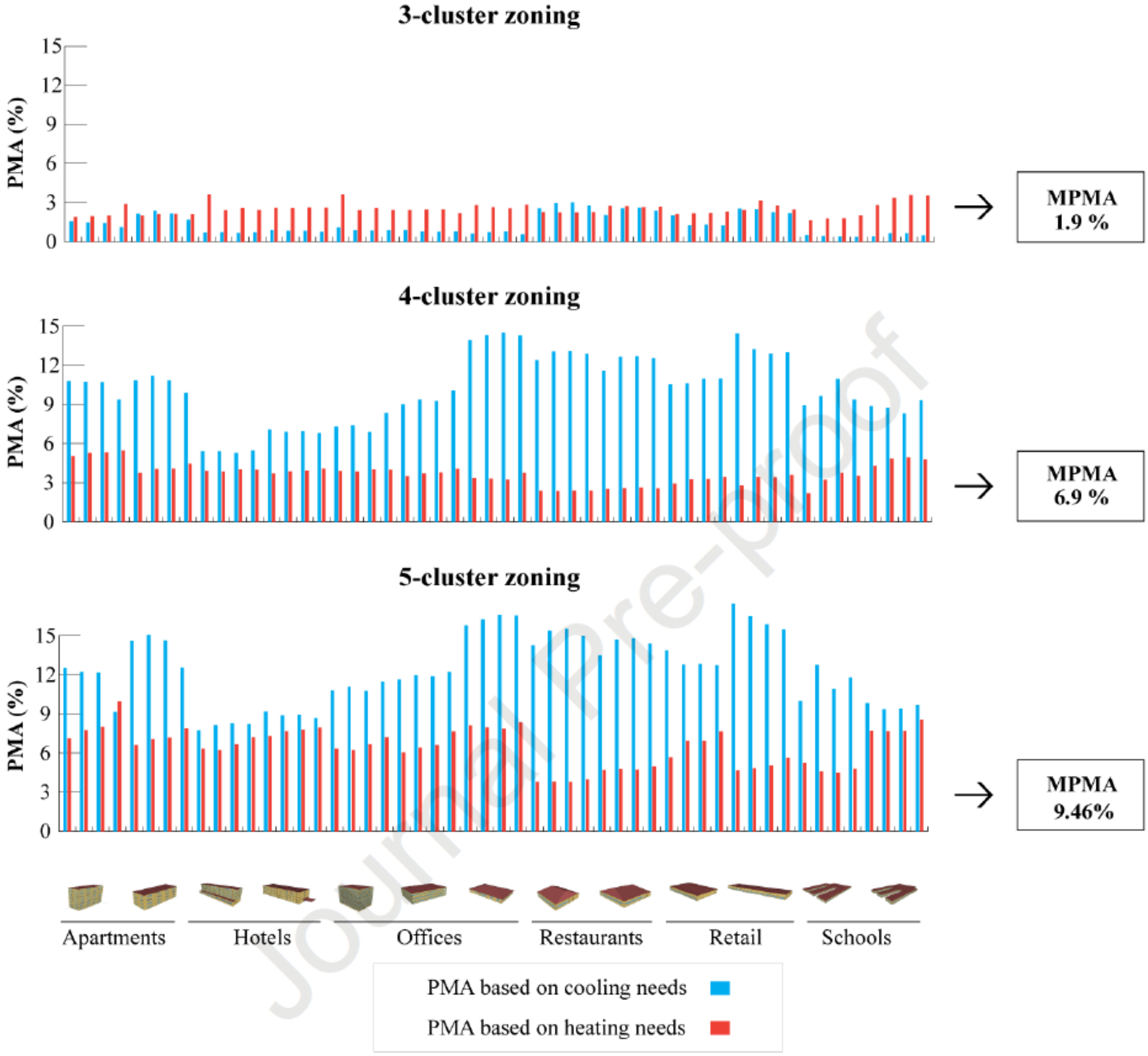

Figure 11 PMA of 52 building archetypes and MPMA for zoning with 3, 4 and 5 clusters.

4.4 Comparing climatic zoning options.

MPMA shows the overall performance of each cluster zoning alternative considering a wide range of building prototypes (52 models). Results vary from around 2% in the 3-cluster zoning, to 7% in the 4-cluster zoning, and up to 10% in the 5-cluster zoning. These values are low when compared with current methodologies based on degree-days. To illustrate this comparison, Figure 12 shows the clustering results and the results based on the ASHRAE climatic zoning considering the original (Standard 169-2009, MPMA 15%) and the updated version

(Standard 169-2013, MPMA 10%) [14,19] previously calculated. This comparison indicates that the mismatch between climatic zoning and performance can be substantially reduced, even when a high number of building types with different uses and sensitivities are considered. However, it is important to highlight that the ASHRAE climatic zoning covers the whole country, while the current demonstrative case study covers only three states of the USA. Results may be sensitive to the area under analysis.

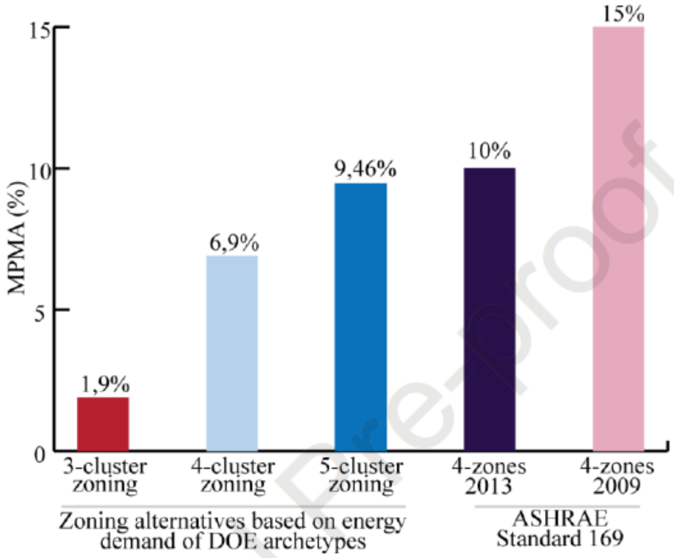

Figure 12 ***Comparison of MPMPA of clustering results and the climatic zoning of the ASHRAE Standards***

It should be acknowledged that the aim of this study was only to propose and test the implementation of clustering analysis using available data from the DOE (building archetypes and weather files), rather than proposing a climatic zoning solution for the USA. Any climatic zoning definition should be specific to a particular purpose and the building stock archetypes should be selected in accordance with that purpose, i.e. new buildings, high performing buildings, positive buildings, etc.

5. Conclusions.

This paper introduced a new climatic zoning method to reduce the mismatch between performance and climatic zoning. Based on the results of this paper, it can be concluded that:

- The proposed method provides a coherent and comprehensive set of steps to support performance-based climatic zoning.

- It also provides flexibility to adopt different performance indicators, different weather data sets, and building types targeted by policy makers.
- It provides a clear methodology to deal with multiple buildings archetypes with different geometries, HVAC systems and thermophysical properties.
- Validation of the proposed method have shown substantial improvement when compared with the widely adopted zoning methodology based on degree-days.

This paper only addresses the reduction of the mismatch between climatic zoning and building performance, and does not consider the link between climatic zoning and building energy policies, recommendations or performance-based requirements. Further studies should address these topics to ensure that policy makers can take informed decisions about the impact of their policies under different scenarios and evaluating the trade-off between energy efficiency measures and cost implications. Enhanced methods to support defining a number of zones should also be addressed by future studies.

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Highlights

- A performance-based approach for climatic zoning is proposed
- It provides flexibility to adopt different performance metrics and building types
- Different weather data sets can be adopted including current and future scenarios
- The mismatch between climatic zoning and building performance was reduced
- Misclassification was lowered to 2% against 10% and 15% of the Degree-days method

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: