Climate-Responsive Architectural Design: Analyzing and Adapting to Diverse Climates in U.S. Cities

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Abstract. The energy consumption challenge within the built environment is growing in urgency, underscoring an imperative for climate-responsive design solutions. This paper presents an in-depth analysis of the climatic characteristics of 12 U.S. cities, with a parametric platform, categorized under different Köppen climate classifications, with the aim of informing effective passive design strategies. Upon meticulously assessing the efficacy of various passive strategies tailored to distinct climate zones, this paper distills actionable guidance for deploying architectural methods that embody climate-responsive design principles. Theoretical models are developed to correlate climatic variables with specific passive design interventions. The research contributes to the theoretical discourse on passive design by advocation for a data-driven, climate-responsive design guidance that aligns with contemporary sustainability goals.

Keywords: Climate-responsive design; Köppen classification; Givoni's psychrometric chart; parametric platform.

1. Introduction

The architectural design process increasingly demands a nuanced understanding of the local climate to create sustainable, energy-efficient buildings. With climate change exacerbating weather extremes and resource scarcity, integrating climate-responsive strategies into architectural practice is more critical than ever [1]. The EU Commission has stated that one on its highest priority tasks is to address global warming [2]. The Energy Performance of Buildings Directive (EPBD) constitutes a significant step to meet the commitments on climate change. Passive houses have been widely demonstrated by numerous studies to be a highly effective solution in reducing energy consumption. P.Rohdin, etc. [1] compared nine passive houses built in Sweden with conventional buildings, mainly from an indoor environment perspective and energy use. The research shows that the thermal comfort and energy use for these newly built passive houses is well within the limits in the local building code. E.Rodriguez [2] provides an in-depth analysis of passive strategies and their effectiveness in achieving the performance goals of Net Plus Energy Houses. This research found that the thermal performance of most of the houses was remarkable. E.Mushtaha [3] summarized a simulation-based study to optimize thermal performance by minimizing the building's cooling loads in the Gaza Strip. The results suggest that using a high heat resistance material in the walls, shading devices and thermal insulation can reduce total energy consumption by 23.2%, 19.8% and 53.5%. I.Ridley [4] monitored the performance of the first new London dwelling certified to the Passive House standard. The monitored house shows great potential in passive design with a total metered gas and electricity consumption of 65kWh/㎡. For comparison comparable UK exemplars are BedZed 90 kWh/㎡. This body of study consistently demonstrates the capacity of passive buildings to achieve the objective of minimizing energy usage.

The research subject of this paper is passive vernacular residential building. Vernacular buildings demonstrate an understanding of local climatic conditions, showcasing sustainable design practices that are attuned to the environment. Residential and commercial buildings consume over a third of the world's total energy. Therefore, the study of energy conservation in residential buildings is of paramount importance. Numerous studies have conducted similar research. H. Zhang, etc.[5] focused on five cities in China within cold winter and hot summer zone. The conclusions from this study indicate that different passive strategies are suitable for different periods throughout the year. E.Mushtaha [3] aimed to examine the integration of practical passive design strategies into typical residences in the Gaza Strip. Despite its temperate climate, the region experiences significant seasonal

variations, with hot, dry summers and calm, mild winters. Consequently, it focuses on cooling loads. The findings provide valuable guidance on implementing passive design in the Gaza Strip. Saurabh Diddi, ect. [6] selects a city from each of India's five distinct climate zones as study subjects. The handbook develops several types of replicable residential unit models, offering valuable guidance for passive building design. M.-M. Fernandez-Antolin, etc.[7] investigates the effectiveness of passive design strategies across different climate zones in Spain, successfully providing architects with valuable guidelines for passive design during the preliminary design phase. However, due to the limitations of Spain's climate, the study primarily focuses on temperature and semi-arid climate. The studies previously mentioned encompasses a broad spectrum of research on passive design strategies, yet the existing body of work does not extensively cover the unique context of vernacular residential buildings in the United States. Moreover, the use of Ladybug as a parametric platform for assessing and integrating environmental factors into the design process is notably absent within this research domain.

This research has three main objectives, aiming to make contributions to the field of architectural design through the lens of passive design strategies. 1) Theoretical Objective: The paper endeavors to construct a theoretical framework for the assessment of passive design utilizing a parametric platform. This framework is intended to provide a structured approach to evaluating the potential of passive design strategies within the context of location and climate zone. 2)Methodological Objective: The research employs Ladybug, a parametric environmental analysis tool, to develop an analytical process. This process introduces a structured methodology for seamlessly incorporating the assessment of passive strategies within the design process. 3) Practical Objective: By applying the established analytical process, the paper conducts a practical guidance for American vernacular residences. The goal is to generate a set of design guidelines informed by the analysis, which can serve as a valuable resource for architects and designers.

2. Methodology

The research employed a systematic approach to analyze the impact of passive design measures on thermal comfort across various climatic zones. The process begins with using ArcGIS in combination with the Köppen climate classification to select twelve cities representing different climate zones. Subsequently, the research used Ladybug Tools to generate psychrometric charts for the selected cites for both winter and summer seasons. Then, the research simulated the impact of each passive measure on the thermal environment and comfort ranges for the selected cities. The goal was to understand the effectiveness of different strategies. Concurrently, a thorough literature review was conducted to correlate the simulated passive measures with concrete architectural design practices. The research process is shown in Fig.1.

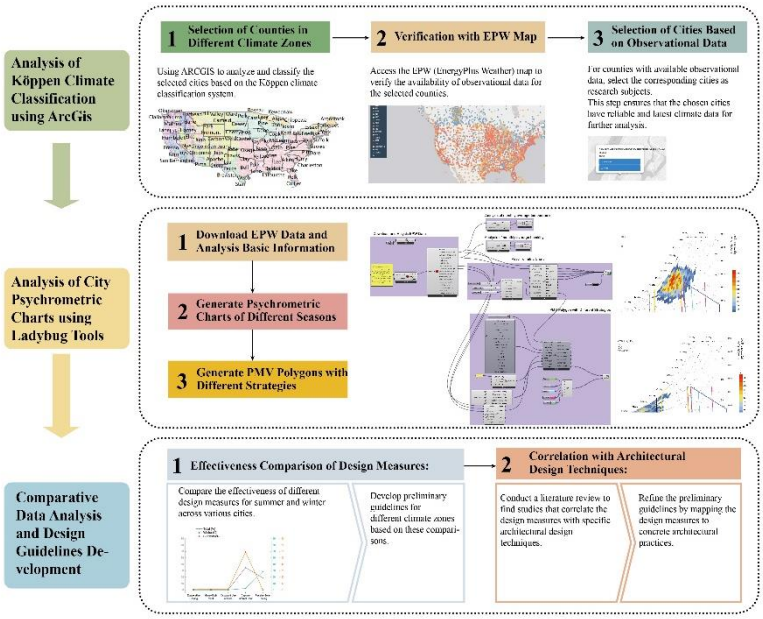


Fig. 1 Flow chart of research process

2.1 Selection Criteria for Cities Based on the Köppen Climate Classification System

This research involves a systematic process to select cities for analysis based on the Köppen climate classification map[8]. Initially, locations within different climate zones are identified using the Köppen climate classification map. This step ensures a diverse representation of climatic conditions. To check the accuracy of the initial classification, the Köppen climate classification of each selected city is verified on the Weatherbase website. This step is crucial as it cross-references multiple data sources, thereby enhancing the reliability of the climate zone determination. Following this, the availability of comprehensive weather data for these cities is verified on the EPW map website. The EPW map is an essential tool that provides detailed climate data required for simulation. By confirming the presence of weather data, the research ensures that each selected city can be thoroughly analyzed using simulation tools.

The selected cities are Miami, Florida (Am), West Palm Beach, Florida (Af), Denver, Colorado (Bsk), Phoenix, Arizona (Bwh), Bakersfield, California (Bsh), Hillsboro, Oregon (Csb), New York City, New York (Cfa), Ketchikan, Alaska (Cfb), Sacramento, California (Csa), Jackson, Wyoming (Dfc), Chicago, Illinois (Dfa), Bangor, Main (Dfb). This research conducted a climate analysis on the selected cities, each representing different climatic zone. To offer a concise synthesis, the climatic attributes of each city are neatly encapsulated in table 1. Additionally, the geographical placement of each city within the Köppen climate classification is illustrated in Fig. 2.

Table 1 Detailed information of selected cites

City	Latitude	Longitude	Temperature ave (℃)	Relative Humidity ave (%)	Climate Analysis
Miami, FL (Am)	25.82	-80.3	24.51	72.51	High Temperature year-round, have feature wet and dry seasons
West Palm Beach, FL (Af)	26.68	-80.1	23.55	75.54	Hot and wet throughout the year

Phoenix, AZ (Bwh)	33.45	-111.98	23.8	34.34	Summer: extremely hot and dry Winter: mild temperature and increased humidity
Denver, CO (Bsk)	39.74	-105.18	9.76	53.85	Summer: hot and dry Winter: mild temperature and increased humidity
Bakersfield, CA (Bsh)	35.43	-119.05	18.51	54.87	Extremely variable temperature conditions, relatively dry
Hillsboro, OR (Csb)	45.53	-122.95	11.39	76.79	Summer: dry and moderate temperature Winter: humid and mild temperature
New York City, NY (Cfa)	40.78	-73.97	12.11	62.35	Relatively high temperature and evenly distributed precipitation
Ketchikan, AK (Cfb)	55.33	-131.63	8.07	82.49	Few extremes of temperature and ample precipitation in all months
Sacramento, CA (Csa)	38.70	-121.58	15.90	67.17	Summer: hot and dry Winter: cooler and wetter
Jackson, WY (Dfc)	43.60	-110.73	3.77	62.55	Summer: short, mild Winter: long, cold and dry
Chicago, IL (Dfa)	41.856	-87.609	10.47	71.23	Summer: warm to hot, humid Winter: cold, humid
Bangor, ME (Dfb)	44.8	-68.80	6.51	70.04	Summer: mild and humid Winter: long, cold and humid

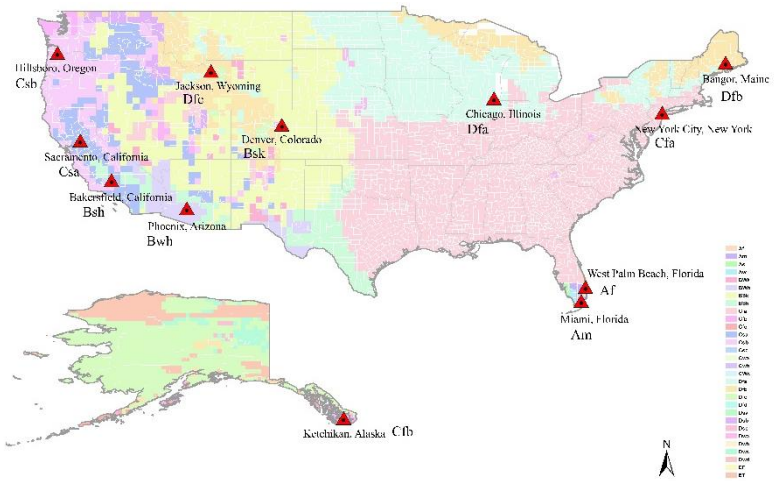


Fig. 2 Selection of Cities based on the Köppen climate classification system

2.2 Analysis Using Givoni's Psychrometric Chart

The "Bioclimatic Analysis" method qualitatively assesses a building's outdoor climate conditions during the architectural design phase, guiding architects in devising strategies and effectively harnessing climatic resources. The concept and method of climate design were first proposed in the 1950s by the Olgyay brothers in the United States. Subsequently, many architects and engineers continuously refined and developed this analytical method. By 1969, Givoni, combining the psychrometric chart used by HVAC engineers, which integrates climate, human thermal comfort, and passive building design methods into a single chart. In addition to these two design methods, other widely applied architectural climate design methods mainly include the Mahoney Table Method and the J. Evans Thermal Comfort Triangle Method. The Olgyay method is primarily suitable for lightweight building forms in hot humid climates that rely on natural ventilation. The Givoni method's limitation lies in its applicability only to residential buildings with few internal heat sources. The Mahoney Table Method mainly targets hot climate regions, with overly coarse climate analysis for cold regions. Moreover, architects cannot determine whether the relationship between outdoor climate analysis indicators and specific architectural design measures is correct or how to specifically correct or improve them, and it does not consider the impact of solar radiation on the building's thermal performance. J.Evans' Thermal Comfort Triangle Method is suitable for architects' initial qualitative climate analysis, but the analysis result of climate design strategies and data cannot be intuitively reflected in the chart.[9] After comparing the four bioclimatic analysis tools as shown in table 2, the research decided to use Givoni Psychrometric chart, primarily due to its precision, comprehensiveness and wide application.

Table 2 Detailed information of selected cites

	Olgyay Bioclimatic Chart	Givoni Psychrometric Chart	Mahoney Table Method	J. Evans Thermal Comfort Triangle Method
Description	Identify optimal strategies by evaluating temperature and humidity data.	Represent the applicable range of passive strategies on a psychrometric chart.	Derive climate responsive strategies through tabular analysis	Use thermal comfort triangle diagram to illustrate the relationship among climate factors
Advantage	Intuitive	1) Precision 2) Comprehensiveness	Clear Process	Simple

Limitation	Applicable to light weight buidings Applicable to hot and humid climate areas	3) Wide Application applicable to residential buildings with few internal heat sources	Focus on hot climate zone Lack clarity Solar radiation is not considered	Climate responsive strategies do not have an intuitive correspondence with meteorological data

The psychrometric chart is a fundamental reference in the field of building design, representing the thermodynamic properties of moist air. A key concept within the psychrometric chart is the "comfort zone", which represents the range of climatic conditions within which the majority of people feel thermally comfortable. This zone is typically defined using thermal neutrality (Tn). This thermal neutrality value is influenced by local climate and is related to the outdoor average temperature (To.av). The formula to calculate thermal neutrality is: $Tn=17.6+0.31\times To.av$. The comfort zone is then defined by the range of temperatures around Tn, typically taken as Tn-2℃ to Tn+2℃. This range represents the temperatures within which the majority of individuals feel comfortable. The calculation and understanding of this range help in designing buildings and environments that align with the local climate, ensuring thermal comfort for occupants.[10]

Beyond the basic comfort zone, the psychrometric chart can be used to identify "control-potential zones", which indicate the effectiveness of different passive strategies. These strategies can be grouped into five major categories: Passive Solar Heating (Utilizing solar radiation to heat spaces naturally), Mass Effect with Night Ventilation (Exploiting thermal mass and stack ventilation to maintain comfortable indoor conditions), Occupant Use of Fan (Enhancing comfort through increased air movement), Evaporative Cooling (Reducing air temperature by evaporating water, which can be highly effective in dry climate), Capture Internal Heat (the collection and reuse of the heat that is generated within a system or a building). It is important to note that the potential zones for these control techniques are indicative rather than prescriptive. [11]

2.3 Climate Responsive Analysis based on Parametric Platform

Ladybug is a parametric environmental tool for Grasshopper that excels at incorporating detailed environmental data into architectural design. It facilitates the analysis of local weather data on a psychrometric chart, pinpointing the comfort zone and control potential zone's typical temperature and humidity ranges. As a result, Ladybug serves as a foundation for the passive design guidance and enables a comprehensive understanding of the effectiveness of passive design strategies. The use of Ladybug in this research involves several key steps that leverage its components to create a comprehensive analysis work flow as shown in fig.3.

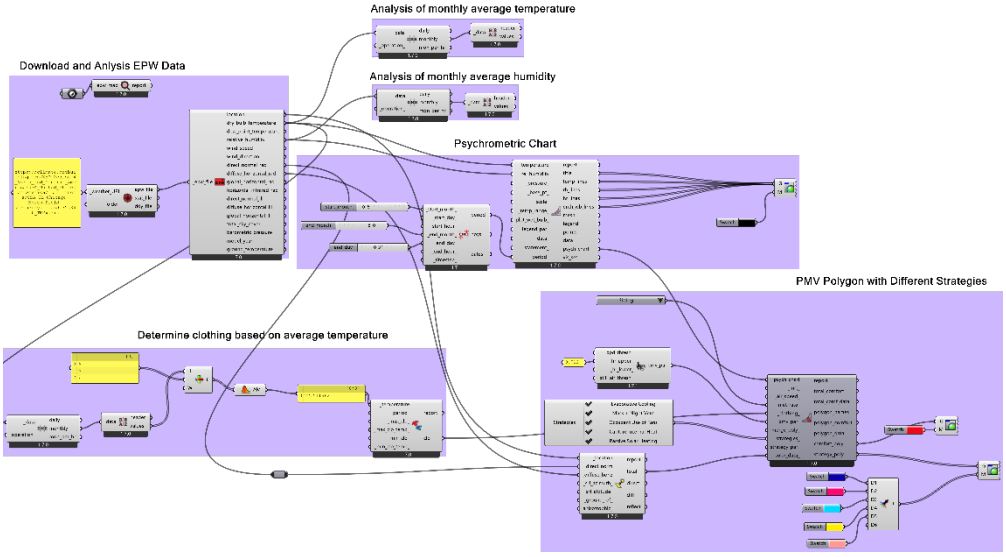


Fig. 3 Ladybug Tool's Workflow of this Research

3. Results and discussion

3.1 Climate Analysis of Selected Cities

The research conducted a comprehensive analysis of the average temperature and humidity across the selected cities, revealing distinct patterns that are characteristic of their respective climates shown in fig.4. Several cities experience significant seasonal temperature changes. Chicago and New York experience cold winters and hot summers. New York experiences a high of 24.7°C and a low of -1.73°C. Chicago's temperatures peak at 23.75°C and bottom out at -3°C; Jackson and Bangor are characterized by cold winter and mild summer. Jackson experiences a high of 16.7℃. Bangor's temperatures peak at 19.72℃ and bottom out at -8.42℃; Phoenix stands out with warm winters and extremely hot summers. n Phoenix, temperatures climb to a high of 35.56°C, and even the lowest temperatures remain relatively warm at 11.72°C. On the other hand, Miami, West Palm Beach, and Ketchikan enjoy stable temperatures year-round, with Miami and West Palm Beach remaining warm and Ketchikan staying cold. Regarding humidity, Bakersfield, Jackson, and Phoenix see significant seasonal variations. Both Jackson and Bakersfield see their peak winter relative humidity levels hover near 80%. In the summer, humidity significantly decreases, with Jackson recording a minimum of around 40% and Bakersfield dipping even lower. Throughout the year, Phoenix is characterized by its dry climate, with relative humidity fluctuating between a low of 19.84% and a high of 51.59%. Meanwhile, Ketchikan, West Palm Beach, Miami, Bangor, and New York maintain a consistent level of humidity all year round.

After a thorough examination of the data, a strategic decision was made to focus the research on the winter season, from December 1st to March 1st, and the summer season, from June 1st to September 1st. These periods represent the most pronounced thermal conditions of the year, capturing the full spectrum of temperature and humidity extremes that can significantly influence energy demands for heating and cooling.

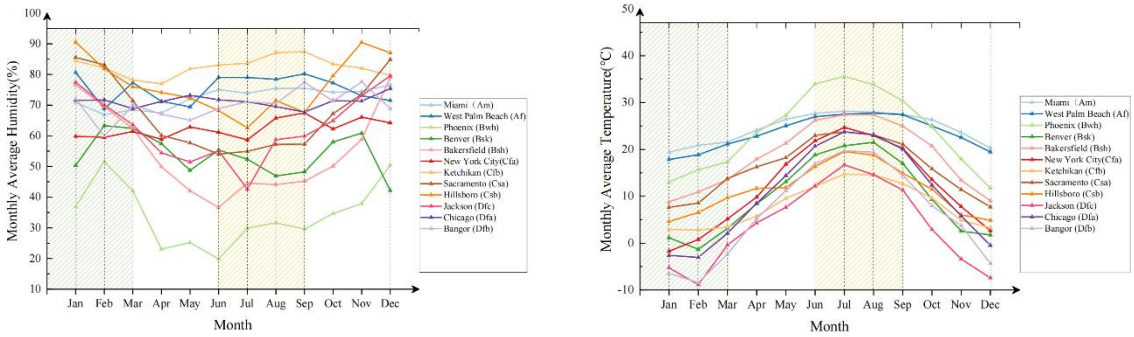
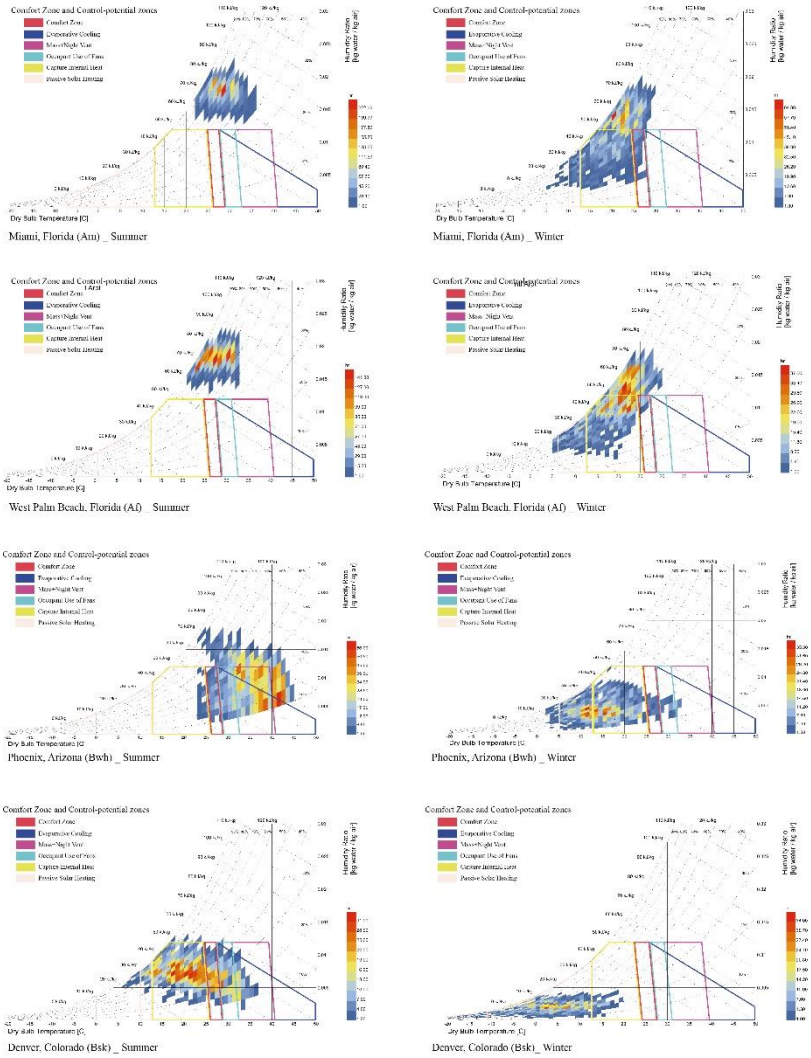


Fig.4 Average temperature and humidity of selected cities

The research crafted psychrometric charts for each of the selected cities during their summer and winter seasons, offering a visual representation of the thermodynamic properties, including temperature and humidity. This analysis serves as a valuable tool for understanding the climate characteristics of the cities under study, shown in fig.5.



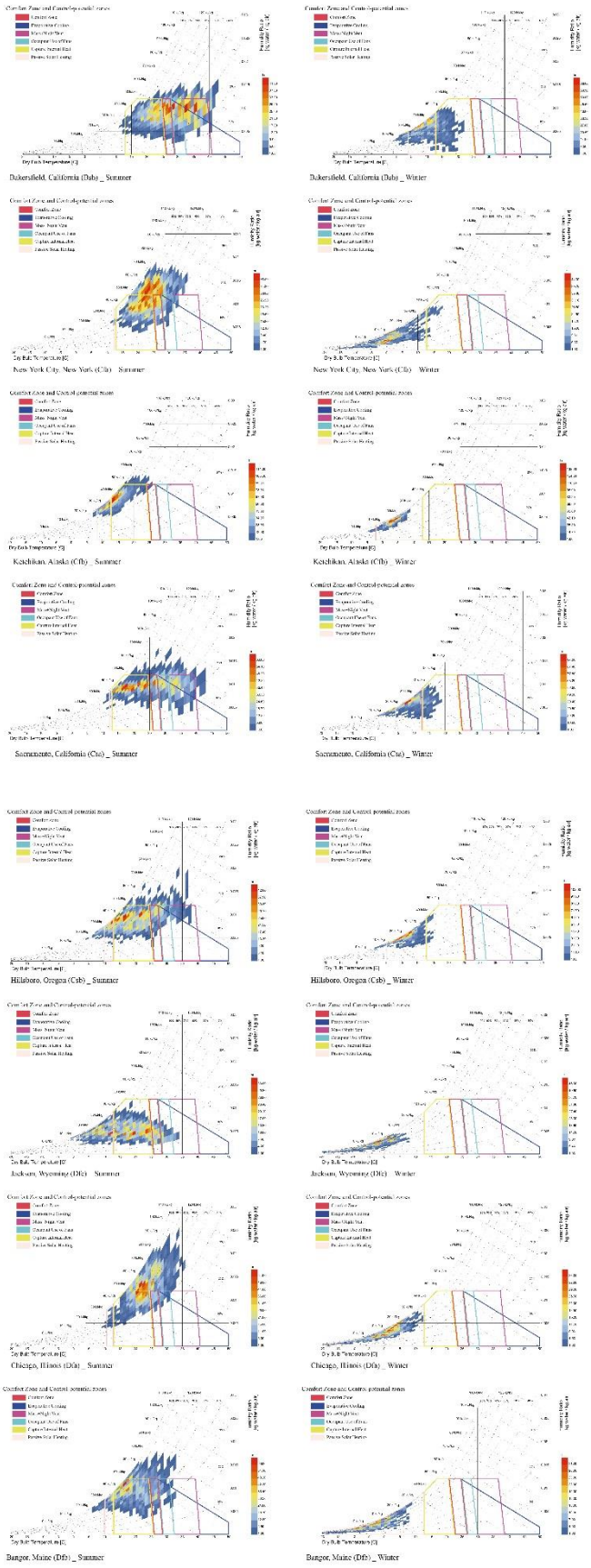


Fig.5 Psychrometric chart of selected cities and passive measures on the comfort zon

3.2 Evaluation of Passive Design Strategies

The research conducted an in-depth analysis of the effectiveness of various passive measures in the selected cities across the winter, summer, and throughout the year, shown in Fig.6. To convey the results in a visually accessible manner, they are organized and presented within the table 3. Here is a descriptive overview of the findings:

Evaporative Cooling is highly effective in locales with arid summers, such as Phoenix, Arizona (Bwh), Bakersfield, California (Bsh) and Sacramento, California (Csa), where the arid conditions allow for efficient cooling with minimal energy use. However, this method is generally less effective during winter months as the focus is on heat retention rather than cooling.

Mass + Night Ventilation is a strategy that operates effectively during the summer months in Bakersfield, California (Bsh) and Sacramento, California (Csa). This method is particularly effective in regions where there is a significant diurnal temperature variation. It leverages the thermal mass of buildings to store heat during the day and release it at night through ventilation, thereby reducing the need for mechanical cooling. However, its effectiveness is not as pronounced during the winter season, when the priority is on maintaining indoor warmth, making this cooling technique less applicable.

The occupant use of fans is a highly effective cooling method during the summer in cities like Phoenix, Arizona (Bwh) with its hot desert climate, Bakersfield, California (Bsh) with a Mediterranean climate, and Sacramento, California (Csa) which falls under the hot-summer Mediterranean climate. Given that these cities experience summers with lower humidity, the use of fans helps to circulate the warm air, enhancing evaporation and creating a cooling effect that improves indoor comfort. However, this method is generally ineffective during the winter months, as the focus shifts to heat retention.

Capture internal heat in passive building design involves utilizing the accumulated heat within the building to enhance energy efficiency and comfort. This internal gain is only due to temperature differences and is described as a sensible load.[14] During the summer, capturing internal heat is particularly effective in cities with cooler climates where the ambient temperature remains moderate or cool. For example, in places like Benver (Bsk), New York City (Cfa), Ketchikan (Cfb), Hillsboro (Csb), Jackson (Dfc), Chicago (Dfa), and Bangor (Dfb). During the winter, this method is effective in warmer climates such as Miami (Am), West Palm Beach (Af), and Phoenix (Bwh), where the external temperatures are already high, and the internal heat can contribute to maintaining a comfortable indoor environment. It also works in cities like Bakersfield (Bsh) and Sacramento (Csa), which have mild winters.

Passive solar heating is an efficient strategy for warming buildings during the winter in a variety of climates, such as those found in Phoenix (Bwh), Denver (Bsk), Bakersfield (Bsh), New York City (Cfa), Ketchikan (Cfb), Sacramento (Csa), Hillsboro (Csb), Jackson (Dfc), Chicago (Dfa), and Bangor (Dfb). This method will be efficient in areas with clear skies and abundant sunshine during the winter, as cloud cover can reduce the effectiveness of solar heating.

In Miami and West Palm Beach, the strategy of capturing internal heat plays a significant role in enhancing thermal comfort during the cooler months and contributes to overall energy efficiency. In winter, this method is effective in pushing the comfort zone beyond its typical boundaries. The summer months are characterized by high temperature and humidity levels, which make it challenging to achieve comfort levels through passive design strategies. As a result, air conditioning becomes a necessity to ensure a comfortable indoor environment.

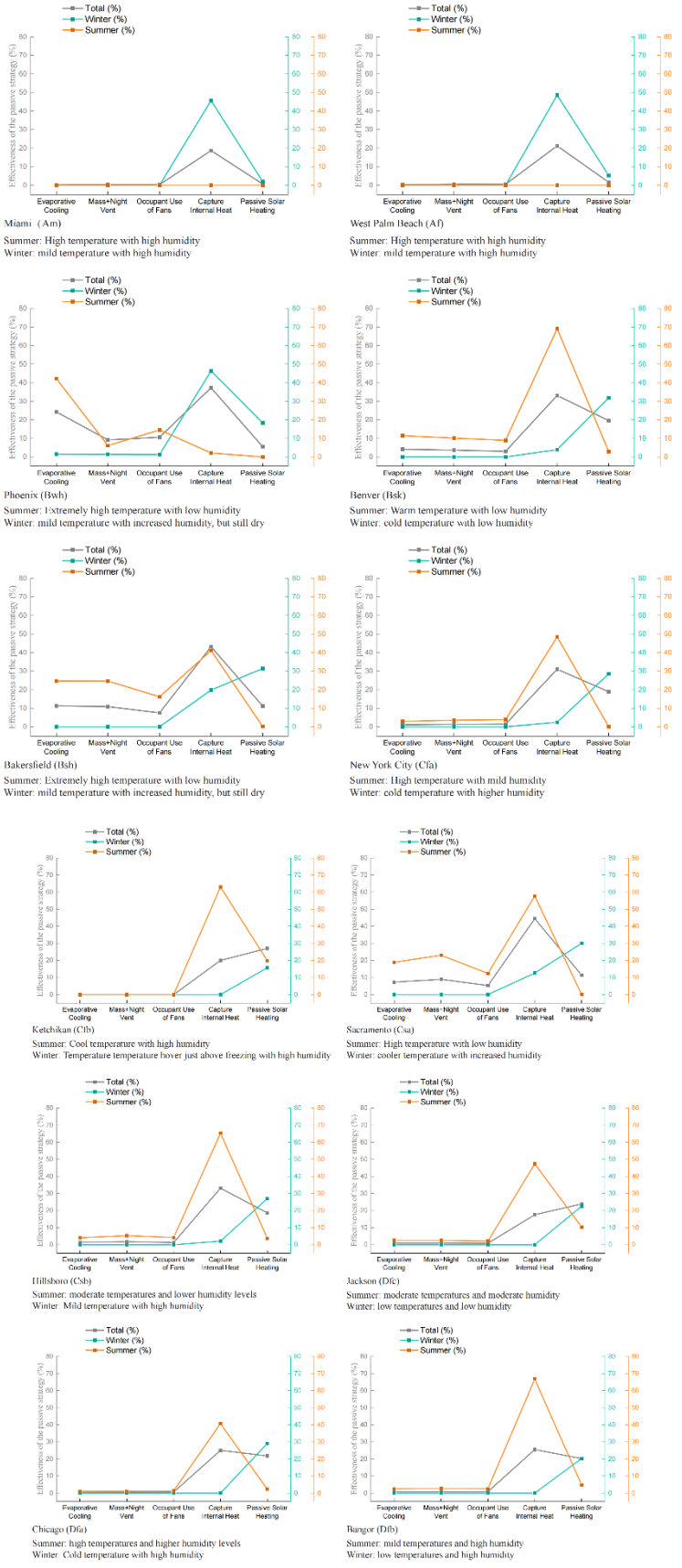


Fig.6 Effectiveness of passive strategies

Table 3 Effectiveness of Passive Strategies based on Location and Season

	Season	Evaporative Cooling	Mass + Night Vent	Occupant Use of Fans	Capture of Internal Heat	Passive Solar Heating
Miami, FL (Am)	Summer					
	Winter				√	
West Palm Beach, FL (Af)	Summer					
	Winter				√	
Phoenix, AZ (Bwh)	Summer	√		√		
	Winter				√	√
Denver, CO (Bsk)	Summer	√	√		√	
	Winter					√
Bakersfield, CA (Bsh)	Summer	√	√	√	√	
	Winter				√	√
Hillsboro, OR (Csb)	Summer				√	
	Winter					√
New York City, NY (Cfa)	Summer				√	
	Winter					√
Ketchikan, AK (Cfb)	Summer				√	
	Winter					√
Sacramento, CA (Csa)	Summer	√	√	√	√	
	Winter				√	√
Jackson, WY (Dfc)	Summer				√	√
	Winter					√
Chicago, IL (Dfa)	Summer				√	
	Winter					√
Bangor, ME (Dfb)	Summer				√	
	Winter					√

3.3 Development of Passive Design Guidelines

Evaporative cooling is an ancient yet effective method that harnesses the power of water evaporation to lower indoor temperatures without the use of mechanical refrigeration. This technique is commonly employed in arid and hot climates to provide comfort and energy efficiency. There are three forms of evaporative cooling: 1) The mashrabiya: The mashrabiya is a traditional Islamic architecture element used for natural ventilation and cooling of buildings. It is wooden sreens/windows provides shad, protection from the sum and allows breezes to flow through into the building for cooling purpose. 2) Wind towers: The wind tower is a traditional passive cooling technique of buildings. They are designed to capture wind at different heights and funnel it down into the building. As the wind passes through the tower, it can draw air through spaces and chambers that have been moistened, causing evaporation and thereby cooling the air before it enters the living space. 3) Roof-pound: This method involves creating a shallow pond or water layer on the roof of the building. During summer, the ambient air flow over the pond causes the water to evaporate, thus, cools the pond and the roof structure which act as a heat sink of the building interior.[15]

Mass and Night Ventilation (Mass + Night Vent) is a passive design strategy that leverages the thermal mass of a building to store and release heat, combined with the natural ventilation at night to cool the building. Here are six passive design methods that enhance the effectiveness of the Mass + Night Vent system: 1) Combined Wall-Roof Solar Chimney: This technique involves creating a vertical shaft that connects the building's thermal mass with the roof. During the day, the sun heats the air inside the chimney, causing it to rise and draw cooler air through the building. At night, the process is reversed, with cooler air being drawn in through the bottom of the chimney and the stored cool air from the thermal mass being released.[16] 2) Using Materials of Higher Densities: Increasing the thermal mass by changing to materials of higher densities led to a reduction in peak indoor air temperature. Materials of higher densities can absorb heat during the day and slowly release it at night.[17] 3) Reduce Window-to-Floor Ratio (WFR): A decrease in window size leads to reduction in peak indoor air temperature for all the envelope materials tested.[17] 4) Optimization of Window Shading Devices: Shading devices prevent overheating during the day while allowing for effective cooling through natural ventilation at night. 5) Heavy Ventilated Internal Wall (HVIW): Utilizing a HVIM will increase the thermal mass of the building. During the summer, its night-ventilation leads to low room temperatures.[18] 6) Building Material Impregnated with PCMs: The integration of Phase Change Materials (PCMs) in building walls can absorb and store a large amount of thermal energy during the day as they change from a solid to a liquid state. At night, as the resolidify, they release the stored heat, aiding cooling in the building.[19]

The use of fans by occupants can substantially enhance the performance of a building by improving thermal comfort and reducing the reliance on mechanical cooling systems. There are several approaches of optimizing the design of ceiling fans: 1) Optimization of blade geometry: [20] studied the shape of blade in conjunction with blade tip width, root and tip angle of attack. It found that the interactions between the design variables play a significant role in determining the performance. 2) Optimization of winglet and spike geometry: [21] did a research of the flow induced by the operation of a ceiling fan and identified eight major flow regions. It concluded that optimization of winglet and spike geometry could lead to further improvement in ceiling fan performance. 3) Avoid installing the fan near obstacles: In the design of ceiling fans, it is crucial to avoid installing the fan near obstacles because such obstructions can disrupt the airflow pattern, leading to an uneven distribution of air and reduced circulation efficiency. 4) Optimize the position of thermal mannequin: [22] indicates that when a ceiling fan is installed above a person sitting at a desk, it can effectively enhance favorable thermal comfort. Moreover, the airflow generated by the fan decreases as it approaches the floor, and the internal airflow is greatly affected by the layout of the thermal mannequin. The relative position of the thermal mannequin is one of the most critical considerations.

Capturing internal heat involves strategies that enhance the building’s energy efficiency and thermal comfort by retaining the heat generated within the building. Increasing energy efficiency in buildings have led to the situation, when new, well insulated buildings, with high internal gains may cover low heating energy demand.[23] This is accomplished by enhancing the building envelope's insulation through the use of superior insulation materials, increasing the envelope's thickness to boost thermal resistance, strategically placing windows to limit heat loss while allowing natural light, and implementing double-skin facades.

Passive solar heating is an architectural approach that optimizes a building’s design to capture and utilize the sun’s energy for heating purposes without the need for mechanical systems. Here are four design strategies that enhance the effectiveness of passive solar heating: 1) Optimal window design: A study by Lee et al.[24] evaluated various window properties such as U-value, solar heat gain coefficient (SHGC), and visible transmittance (Tvis) with different window wall ratios (WWRs) and orientations in different climate zones. This paper presented design guidelines for window systems across various climate zones. 2) Solar Room with PCMs: A solar room in passive solar design is strategically positioned and constructed to capture and utilize the sun’s energy for heating purpose. To avoid overheating in the solar room, PCMs are utilized for heat storage. It has been approved that PCM applied over a large surface area in a passive solar building is efficient for storage of solar gains

and improvement of thermal comfort.[25] For example, a PCM wall is capable of capturing a large proportion of solar radiation incident on the walls or roof of a building. The stored heat was used for heating and ventilation of a house.[19] 3) Trombe Wall: A Trombe wall, an indirect passive solar heating system, functions by utilizing an opaque wall that is exposed to direct solar radiation and positioned between a glazing and the space to be heated. Solar energy that passes through the glazed area is converted into heat within the cavity behind the wall. This heat is then transferred into the living space through natural convection, facilitated by vents at the top and bottom of the thermal mass, creating a loop that circulates hot air from the cavity into the room. The process will be active until there is a difference of temperature between the bottom and the top of the wall. The system is designed to store heat and release it slowly over time, maintaining a comfortable temperature even when the external temperature drops, thus providing a stable and efficient means of space heating with minimal energy consumption.[26] 4）The Barra-Costantini System: Barra and Costantini proposed another solution which incorporates air circulation through the ceiling in addition to the Trombe wall. This system has the advantage of being a natural regulator by storing heat during the day and restoring it during the evening. The research by Imessad, Messaoudene, Belhamel [27] showed the adaptability of this system to Algerian climatic conditions.

The passive strategies mentioned earlier, along with their corresponding architectural approaches, are thoroughly summarized in the table below, as shown in fig.7.

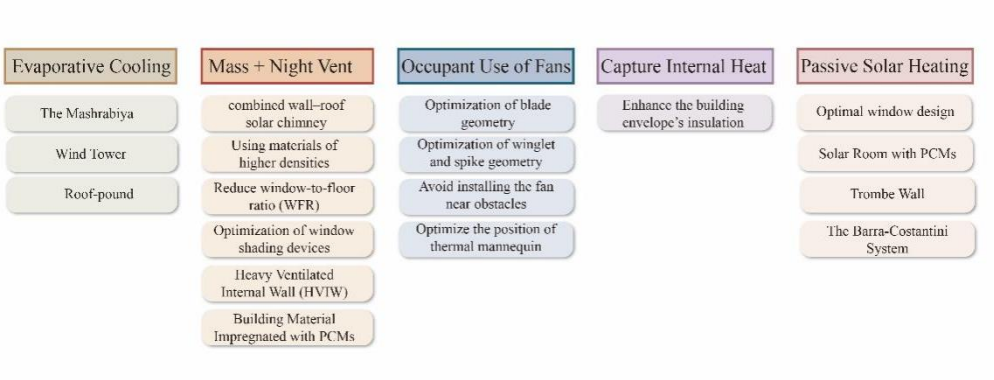


Fig.7 Design methods of passive strategies

4. Conclusion

4.1 Theoretical Implication

The theoretical implications of this research delve into the development of a theoretical model that leverages a parametric platform to correlate geographical information with passive design techniques, as illuminated through the comparative analysis of 12 U.S. cities across various Köppen climate classifications. The model, taking into account the specific environmental factors such as solar exposure, temperature, humidity, offers a data-driven approach in achieving energy efficiency and occupant comfort. The integration of these elements within a parametric framework not only streamlines the design process but also paves the way for delivering appropriate passive design solutions tailored to the unique characteristics of diverse locations. Moreover, the theoretical model introduces an approach seamlessly adaptable within the design workflow. As a high-speed computational tool integrated within Rhino, Ladybug enables the swift and efficacious validation of passive design strategies from the outset of the design phase.

4.2 Managerial Implication

The managerial implication of this research is crucial by offering actionable insights for architects and building managers. Findings of this research indicate that evaporative cooling and the strategic use of fans by occupants are particularly effective in arid, high-temperature climates. For instance, In Phoenix's summer months, the synergy of evaporative cooling and occupant use of fan holds the

promise of sustaining thermal comfort for 56.79% of the season. Bakersfield's summer could see thermal comfort maintained for 40.85% of the time through these same passive cooling techniques. Thermal mass coupled with night-time ventilation proves beneficial in regions with significant temperature fluctuations between day and night. In summer season of Bakersfield, employing the strategy will potentially ensure thermal comfort for approximately 24.64% of the period. Capturing internal heat is identified as a method for achieving thermal comfort in temperate climate. During Phoenix's winter months, with the average temperature of 13.39℃, harnessing internal heat could potentially ensure thermal comfort for nearly half of the season. Passive solar heating excels in conditions with ample sunlight and cold temperature. However, in climates with elevated humidity and temperature, such as during the summer in Miami and West Palm Beach, achieving thermal comfort through passive design alone is challenging and often requires the incorporation of active cooling solutions.

4.3 Limitation and Outlook

The passive design measures proposed in this thesis, while grounded in theoretical models and simulations derived from the climatic analysis ladybug, necessitate further empirical validation to substantiate their real-world effectiveness. This validation process would ideally involve detailed case studies of buildings that have implemented these measures, assessing their performance against key indicators such as energy consumption, indoor environmental quality, and occupant satisfaction. Additionally, field testing could provide practical insights into how these design strategies perform under various real-time conditions. Such empirical research would not only verify the efficacy of the proposed measures but also identify areas for refinement.

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