GEORGE BROWN PRESS
JOURNALS, BOOKS & PROCEEDINGS

International Journal of Engineering Advances

Article

Adapting Architecture to Climate: Exploring Climate-Responsive Strategies Across U.S. Cities

Xinzhi Chang [1,*]

[1] Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA
* Correspondence: Xinzhi Chang, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA

Abstract: As energy consumption concerns continue to grow in the built environment, there is an increasing demand for design solutions that are responsive to local climate conditions. This study conducts an in-depth examination of the climate profiles of twelve U.S. cities, categorized according to the Köppen climate classification system, utilizing a parametric platform to assess suitable passive design strategies. By evaluating the effectiveness of different passive approaches across diverse climate zones, this paper provides actionable recommendations for incorporating climate-responsive design principles in architecture. The research establishes theoretical models that connect climatic variables with corresponding passive design techniques, thereby contributing to the evolution of passive design theory. Through this, the study advocates for a data-driven, climate-sensitive methodology that aligns with the growing emphasis on sustainability in modern architecture.

Keywords: climate-adaptive design; Köppen climate system; Givoni's psychrometric diagram; parametric framework

Received: 05 January 2025
Revised: 09 January 2025
Accepted: 15 January 2025
Published: 17 January 2025

1. Introduction

The architectural design process now requires a more refined understanding of local climate conditions to develop buildings that are both sustainable and energy-efficient. As climate change amplifies extreme weather patterns and heightens resource scarcity, it has become increasingly crucial to integrate climate-responsive strategies into architectural practices [1]. The European Commission has identified tackling global warming as one of its top priorities [2]. The Energy Performance of Buildings Directive (EPBD) is a significant step in fulfilling commitments to combat climate change. Research has consistently shown that passive houses offer an effective solution for reducing energy consumption. For instance, P. Rohdin et al. [1] compared nine passive houses in Sweden to traditional buildings, primarily focusing on indoor environmental quality and energy consumption. Their study found that thermal comfort and energy consumption in these passive houses were well within the standards set by the local building code. E. Rodriguez [2] conducted a detailed examination of passive design strategies, assessing their effectiveness in achieving the objectives of Net Plus Energy Houses. The study revealed that the thermal performance of most houses was exceptional. Additionally, E. Mushtaha [3] reviewed a simulation-based study aimed at optimizing thermal performance by minimizing cooling loads in the Gaza Strip. The study's results showed that using materials with high heat resistance in the walls, shading devices, and enhanced thermal insulation could reduce total energy consumption by 23.2%, 19.8%, and 53.5%, respectively. I. Ridley [4] tracked the performance of the first new London dwelling certified to the Passive House standard. The monitored dwelling demonstrated excellent potential for passive design, with a total gas and electricity consumption of 65 kWh/m^2, compared to similar UK buildings like BedZed, which uses 90 kWh/ m^2. This body of research highlights the significant potential of passive buildings to minimize energy consumption.

https://doi.org/10.71222/qca5ng14

This paper focuses on passive vernacular residential buildings, which embody an understanding of local climate conditions and reflect sustainable design practices that harmonize with the environment. Residential and commercial buildings account for more than a third of global energy consumption, making energy conservation in residential buildings a critical area of study. Several studies have addressed this topic. H. Zhang et al. [5] analyzed five cities in China within the cold winter and hot summer zone, concluding that various passive strategies are effective at different times of the year. E. Mushtaha [3] investigated the application of passive design strategies in typical homes in the Gaza Strip, a region with significant seasonal climate variation, featuring hot, dry summers and mild winters. The focus of the study was on cooling loads, and the results offer valuable insights for implementing passive design in this region. Saurabh Diddi et al. [6] studied one city from each of India's five climate zones, developing replicable residential unit models that provide useful guidance for passive building design. M.-M. Fernandez-Antolin et al. [7] examined passive design strategies in different climate zones in Spain, offering architects practical guidelines for the early design stages. However, the study mainly addresses temperature and semi-arid climates due to Spain's specific climate conditions. While these studies cover a wide range of passive design strategies, there is limited research on the unique characteristics of vernacular residential buildings in the United States. Furthermore, the use of Ladybug, a parametric platform for integrating environmental factors into the design process, is largely unexplored in this field.

This research is guided by three main objectives, aiming to advance architectural design through the use of passive design strategies.

1) **Theoretical Objective**: The paper seeks to develop a theoretical framework for evaluating passive design, utilizing a parametric platform. This framework will offer a structured method for assessing the effectiveness of passive strategies based on location and climate zone.
2) **Methodological Objective**: The study uses Ladybug, a parametric environmental analysis tool, to establish an analytical process. This methodology facilitates the integration of passive design assessments into the design workflow.
3) **Practical Objective**: Through the application of the analytical process, the paper provides practical guidance for American vernacular homes. The aim is to generate a set of design recommendations derived from the analysis, offering architects and designers a useful resource for passive design implementation.

2. Methodology

The study adopted a systematic approach to evaluate the influence of passive design strategies on thermal comfort across various climate zones. Initially, ArcGIS, combined with the Köppen climate classification, was used to select twelve cities representing different climate types. Next, Ladybug Tools were utilized to create psychrometric charts for these cities, covering both winter and summer seasons. The study then simulated the effects of each passive design strategy on thermal comfort and environmental conditions for the selected cities, aiming to assess the effectiveness of various approaches. At the same time, an extensive literature review was conducted to link the simulated passive measures with practical architectural design techniques. The research process is illustrated in figure 1.

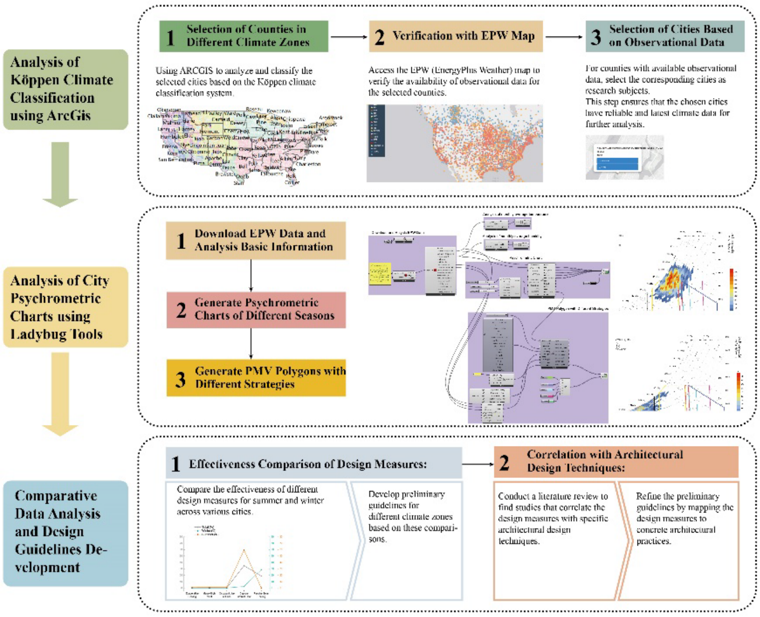


Figure 1. Flow chart of research process.

2.1. City Selection Criteria Using the Köppen Climate Classification System

This study follows a systematic process for selecting cities based on the Köppen climate classification map [8]. First, cities are identified across various climate zones using the Köppen map to ensure a broad representation of climatic conditions. To verify the initial classification, each city's climate zone is cross-checked on the Weatherbase website, providing additional data validation for greater accuracy. Next, the availability of detailed weather data for these cities is confirmed through the EPW map website, which is essential for simulation purposes. This step ensures that reliable climate data is accessible for each selected city.

The cities chosen for this analysis include 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), and Bangor, Maine (Dfb). A climate analysis was conducted for each of these cities, which represent different climate zones. The climatic characteristics of each city are summarized in table 1, and their geographic positions within the Köppen climate classification are depicted in figure 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

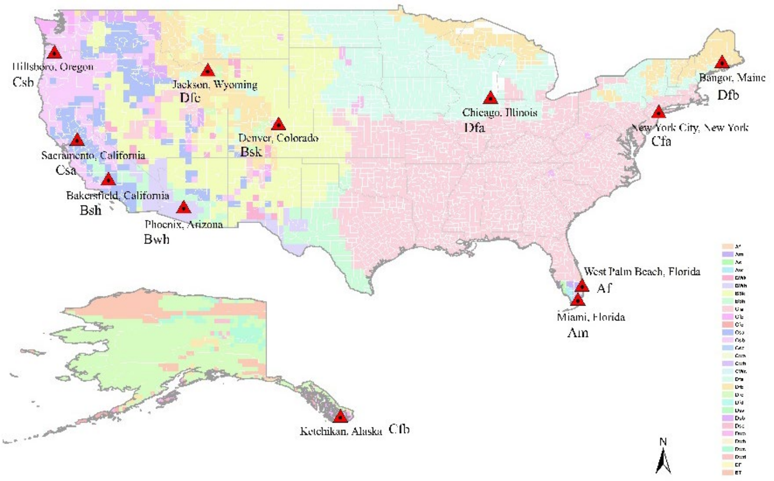


Figure 2. Selection of Cities based on the Köppen climate classification system.

2.2. Evaluation with Givoni's Psychrometric Diagram

The "Bioclimatic Analysis" method is used to qualitatively assess outdoor climate conditions during the architectural design process, helping architects devise strategies that efficiently utilize climatic resources. The concept of climate-responsive design was first introduced in the 1950s by the Olgyay brothers in the United States. Over time, numerous architects and engineers have refined this analytical approach. In 1969, Givoni advanced the method by incorporating a psychrometric chart, traditionally used by HVAC engineers, that combines climate data, human thermal comfort, and passive building design strategies into a single framework. Alongside these methods, other widely used climate design tools include the Mahoney Table Method and the J. Evans Thermal Comfort Triangle Method. The Olgyay method is best suited for lightweight buildings in hot, humid climates that depend on natural ventilation. The Givoni method, however, has a limitation in that it is primarily applicable to residential buildings with minimal internal heat generation. The Mahoney Table Method is focused on hot climates and provides a less detailed analysis for colder regions. Additionally, it doesn't address how to properly connect outdoor climate data to specific design measures or account for the effect of solar radiation on thermal performance. The J. Evans Thermal Comfort Triangle Method is useful for initial qualitative climate analysis but lacks an intuitive way to reflect climate design strategies and results on the chart [9]. After evaluating the four bioclimatic analysis tools, as summarized in table 2, the research chose the Givoni Psychrometric chart for its precision, comprehensiveness, and broad applicability

Table 2. Detailed information of selected cites.

Method	Olgyay Bioclimatic Chart	Givoni Psychrometric Chart	Mahoney Table Method	J. Evans Thermal Comfort Triangle Method
Description	Identifies the most effective strategies based on temperature and humidity analysis.	Displays the range of viable passive design strategies on a psychrometric chart.	Uses a table to derive climate-responsive strategies.	Illustrates the relationship between climate factors using a thermal comfort triangle diagram.
Advantages	Intuitive and easy to understand.	1) High accuracy 2) Thorough 3) Broad applicability.	Straightforward process.	Simple and easy to use.
Limitations	Best suited for lightweight structures in hot, humid climates.	Mostly applicable to homes with minimal internal heat sources.	Focuses on hot climates and lacks detail for cold climates.	Does not account for solar radiation; lacks clarity.

The psychrometric chart is a vital tool in building design, representing the thermodynamic properties of moist air. A central concept in this chart is the "comfort zone," which refers to the range of environmental conditions where most individuals experience thermal comfort. This zone is typically defined using thermal neutrality (Tn), which depends on the local climate and is correlated with the outdoor average temperature (To.av). The formula to determine thermal neutrality is: Tn = 17.6 + 0.31 × To.av. The comfort zone is then delineated by a range of temperatures around Tn, typically from Tn-2°C to Tn+2°C, within which most people feel comfortable. Understanding and calculating this range is crucial in designing buildings that ensure thermal comfort in alignment with the local climate [10].

In addition to the comfort zone, the psychrometric chart can also highlight "control-potential zones," which illustrate the effectiveness of various passive strategies. These strategies fall into five main categories: Passive Solar Heating (utilizing solar energy to naturally heat spaces), Mass Effect with Night Ventilation (leveraging thermal mass and ventilation to maintain comfort), Occupant Use of Fans (improving comfort through increased air movement), Evaporative Cooling (cooling the air by evaporating water, effective in dry climates), and Capture Internal Heat (collecting and reusing heat generated inside a building). It's important to note that these control-potential zones are suggestive, not prescriptive, providing guidance on the viability of different passive strategies [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 [12]. 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 figure.3.

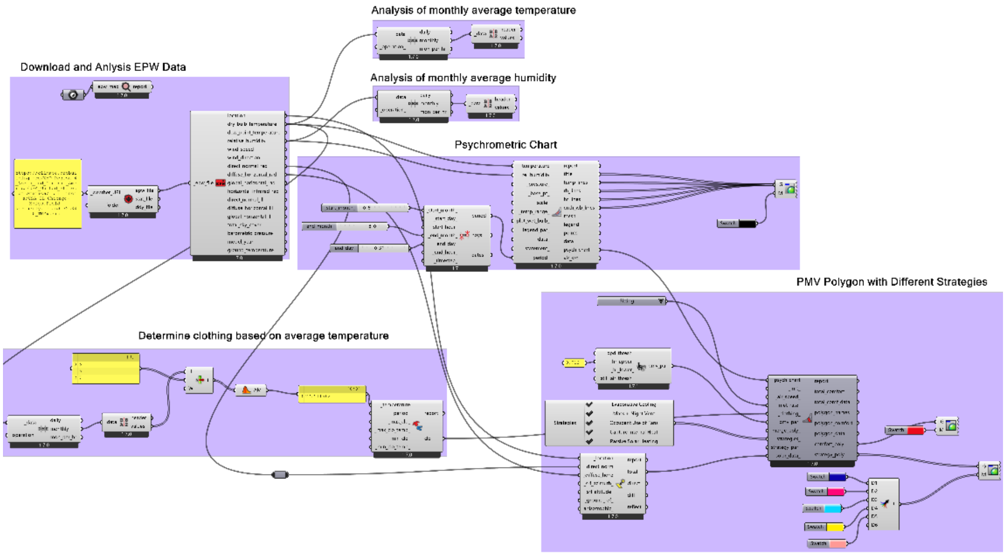


Figure 3. Ladybug Tool's Workflow of this Research.

3. Results and discussion

3.1. Climate Analysis of Selected Cities

The research conducted a detailed analysis of the average temperature and humidity across the selected cities, revealing distinct climate patterns specific to each location, as shown in figure 4. Several cities exhibit notable seasonal temperature variations. Chicago and New York experience cold winters and hot summers, with New York reaching a high of 24.7°C and a low of -1.73°C, while Chicago peaks at 23.75°C and drops to -3°C. Jackson and Bangor have cold winters and mild summers, with Jackson's high at 16.7°C and Bangor's peak at 19.72°C and a low of -8.42°C. Phoenix, on the other hand, has warm winters and extremely hot summers, with temperatures reaching 35.56°C, while the lowest temperatures stay relatively warm at 11.72°C. In contrast, Miami, West Palm Beach, and Ketchikan experience stable temperatures year-round, with Miami and West Palm Beach staying warm and Ketchikan remaining cold. In terms of humidity, Bakersfield, Jackson, and Phoenix show significant seasonal fluctuations. Jackson and Bakersfield experience high winter relative humidity levels near 80%, while in summer, it drops, with Jackson dipping to around 40% and Bakersfield even lower. Phoenix, with its dry climate, experiences relative humidity ranging from 19.84% to 51.59% throughout the year. Meanwhile, cities like Ketchikan, West Palm Beach, Miami, Bangor, and New York maintain relatively consistent humidity levels year-round.

After reviewing the data, the research focused on two key periods: the winter season from December 1st to March 1st, and the summer season from June 1st to September 1st. These seasons represent the most extreme thermal conditions, capturing the full range of temperature and humidity variations that can significantly impact energy demands for heating and cooling [13].

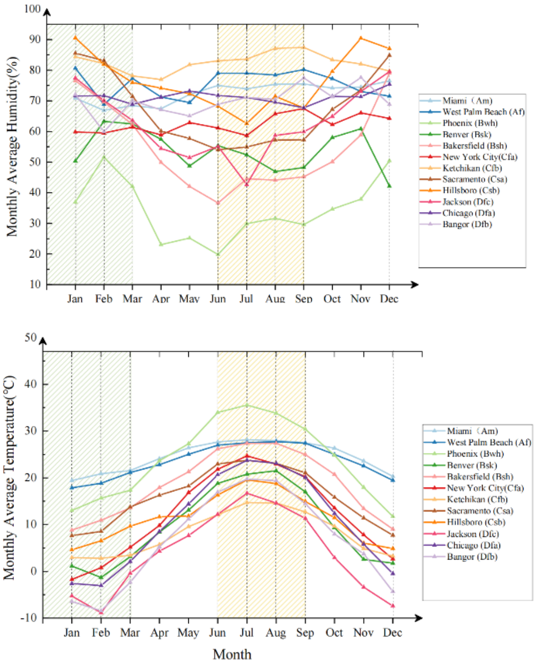
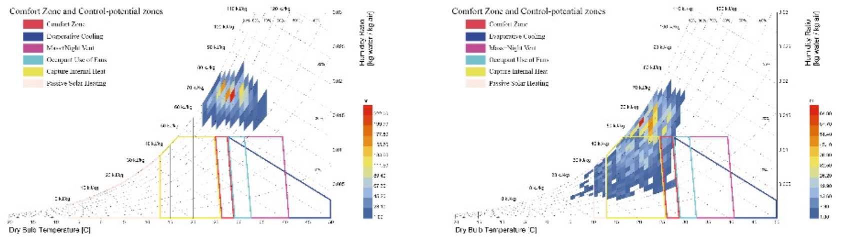


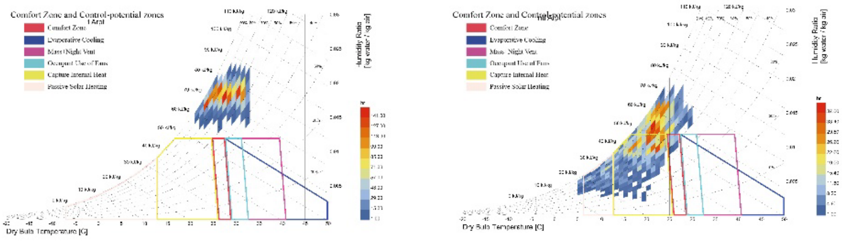
Figure 4. Average temperature and humidity of selected cities.

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 figure 5.



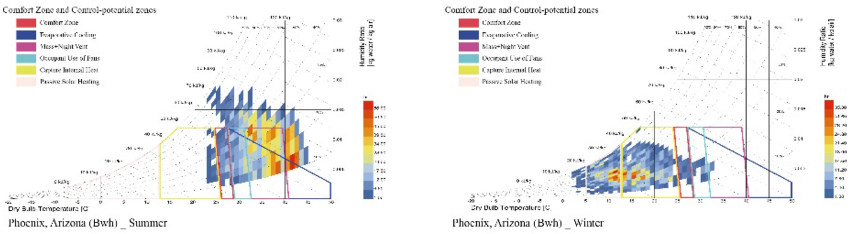
Miami, Florida (Am) _ Summer

Miami, Florida (Am) _ Winter



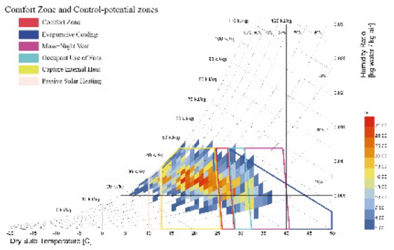
West Palm Beach, Florida (Af) _ Summer

West Palm Beach, Florida (Af) _ Winter

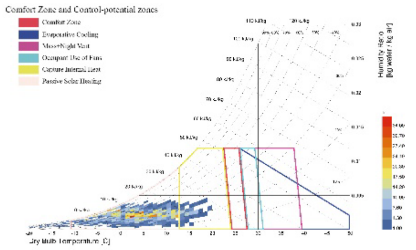


Phoenix, Arizona (Bwh) _ Summer

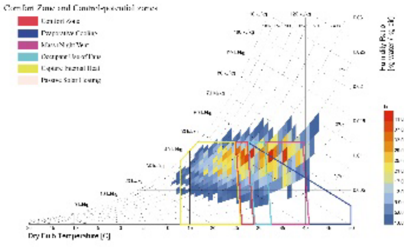
Phoenix, Arizona (Bwh) _ Winter



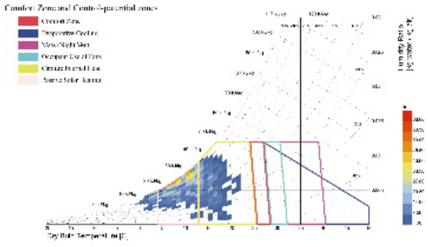
Denver, Colorado (Bsk) _ Summer



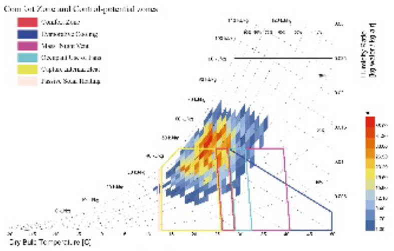
Denver, Colorado (Bsk)_ Winter



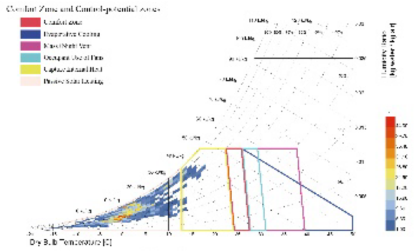
Bakersfield, California (Bsh) _ Summer



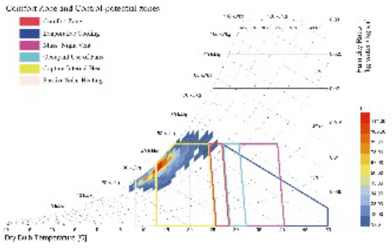
Bakersfield, California (Bsh) _ Winter



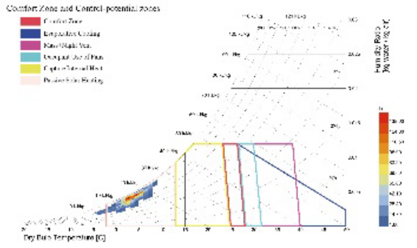
New York City, New York (Cfa) _ Summer



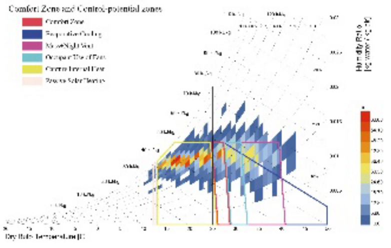
New York City, New York (Cfa) _ Winter



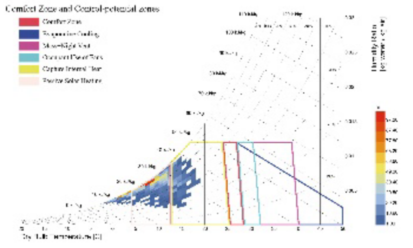
Ketchikan, Alaska (Cfb) _ Summer



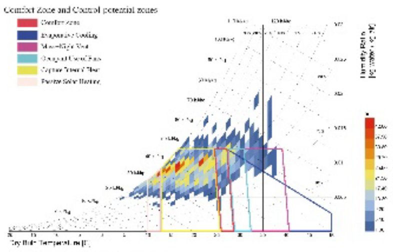
Ketchikan, Alaska (Cfb) _ Winter



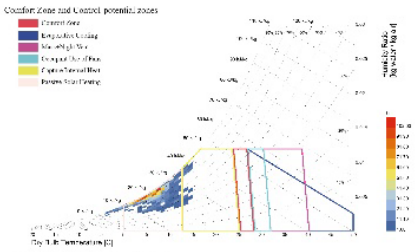
Sacramento, California (Csa) _ Summer



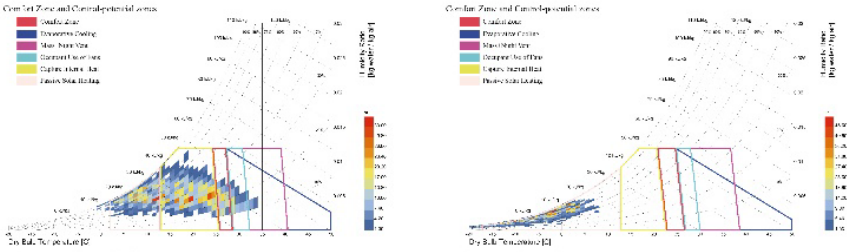
Sacramento, California (Csa) _ Winter



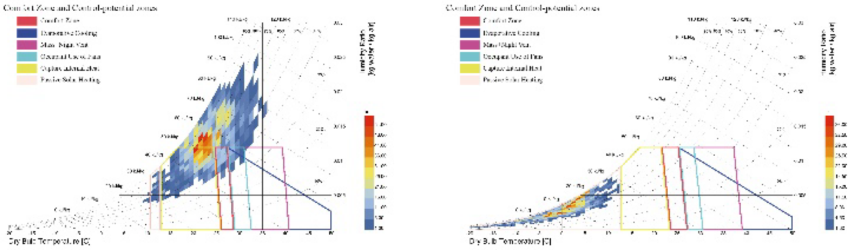
Hillsboro, Oregon (Csb) _ Summer



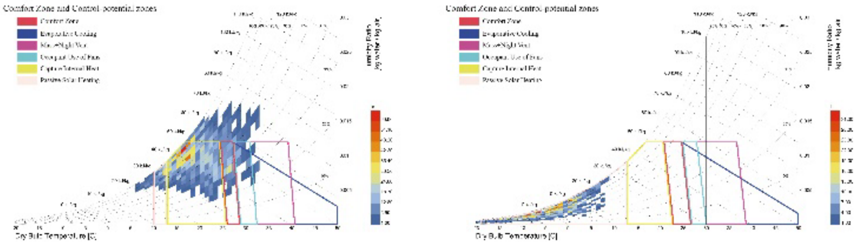
Hillsboro, Oregon (Csb) _ Winter



Jackson, Wyoming (Dfc) _ Summer Jackson, Wyoming (Dfc) _ Winter



Chicago, Illinois (Dfa) _ Summer Chicago, Illinois (Dfa) _ Winter

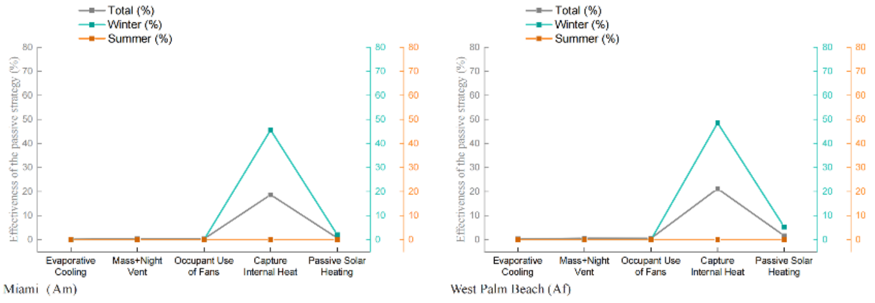


Bangor, Maine (Dfb) _ Summer Bangor, Maine (Dfb) _ Winter

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

3.2. Evaluation of Passive Design Strategies

The research conducted a thorough evaluation of the effectiveness of various passive cooling and heating strategies across different cities, covering winter, summer, and year-round performance, as shown in figure 6. To present the results in a more accessible format, they are organized in table 3.

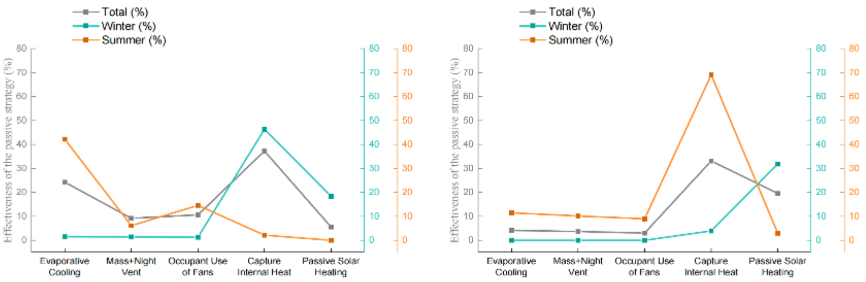


Miami (Am)

Summer: High temperature with high humidity
Winter: mild temperature with high humidity

West Palm Beach (Af)

Summer: High temperature with high humidity
Winter: mild temperature with high humidity

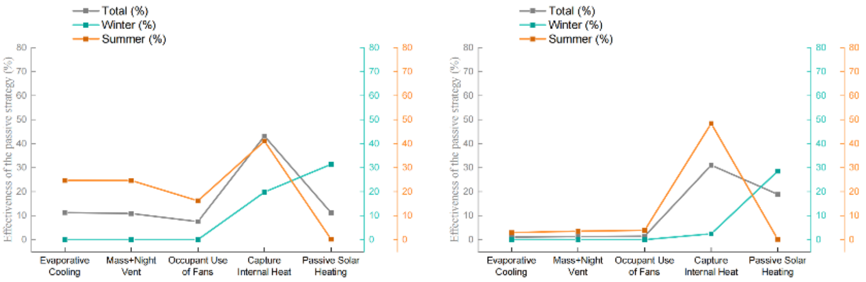


Phoenix (Bwh)

Summer: Extremely high temperature with low humidity
Winter: mild temperature with increased humidity, but still dry

Benver (Bsk)

Summer: Warm temperature with low humidity
Winter: cold temperature with low humidity

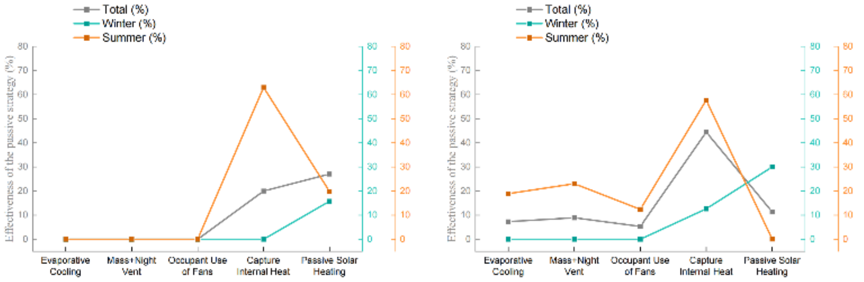


Bakersfield (Bsh)

Summer: Extremely high temperature with low humidity
Winter: mild temperature with increased humidity, but still dry

New York City (Cfa)

Summer: High temperature with mild humidity
Winter: cold temperature with higher humidity

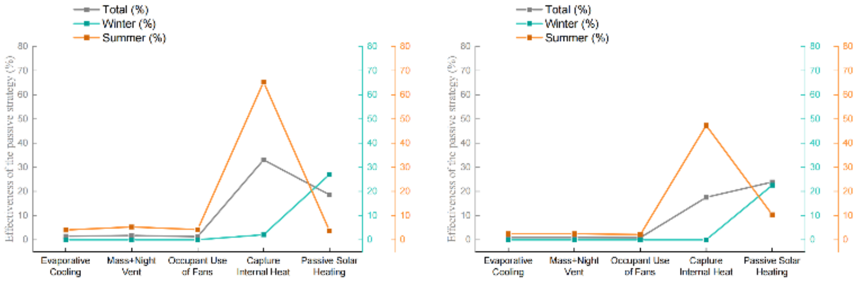


Ketchikan (Cfb)

Summer: Cool temperature with high humidity
Winter: Temperature temperature hover just above freezing with high humidity

Sacramento (Csa)

Summer: High temperature with low humidity
Winter: cooler temperature with increased humidity

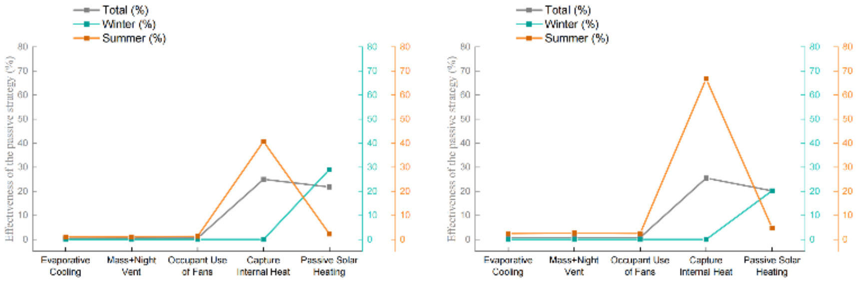


Hillsboro (Csb)

Summer: moderate temperatures and lower humidity levels
Winter: Mild temperature with high humidity

Jackson (Dfc)

Summer: moderate temperatures and moderate humidity
Winter: low temperatures and low humidity



Chicago (Dfa)

Summer: high temperatures and higher humidity levels
Winter: Cold temperature with high humidity

Bangor (Dfb)

Summer: mild temperatures and high humidity
Winter: low temperatures and high humidity

Figure 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					√

Below is a summary of the key findings:

Evaporative Cooling proves to be highly effective in cities with arid summers, such as Phoenix, Arizona (Bwh), Bakersfield, California (Bsh), and Sacramento, California (Csa). The dry climate in these areas allows for efficient cooling with minimal energy consumption. However, this method tends to be less effective during the winter months, as the focus shifts to retaining heat rather than promoting cooling.

Mass + Night Ventilation is an effective strategy during the summer months in locations like Bakersfield (Bsh) and Sacramento (Csa). This method takes advantage of significant diurnal temperature variation, using the building's thermal mass to absorb heat during the day and releasing it through ventilation at night. As a result, it reduces the need for mechanical cooling. However, this technique is less useful in the winter when the emphasis is on retaining indoor warmth, making it less applicable during colder months.

The use of fans by occupants is an effective cooling method in cities such as Phoenix (Bwh), Bakersfield (Bsh), and Sacramento (Csa), where the hot desert or Mediterranean climates result in low humidity. Fans enhance evaporation and circulate warm air, promoting a cooling effect that boosts indoor comfort during summer. However, this strategy is less effective in winter, as the primary focus shifts to heat retention rather than cooling.

Capturing internal heat in passive building design involves utilizing the heat accumulated within the building to improve energy efficiency and comfort. This internal heat gain, driven by temperature differences, is referred to as a sensible load. During the summer, this strategy works particularly well in cities with cooler climates, where ambient temperatures remain moderate or cool, such as Denver (Bsk), New York City (Cfa), Ketchikan (Cfb), Hillsboro (Csb), Jackson (Dfc), Chicago (Dfa), and Bangor (Dfb). In contrast, during winter, it is most effective in warmer cities like Miami (Am), West Palm

Beach (Af), and Phoenix (Bwh), where the external temperatures are high enough for internal heat to contribute to maintaining comfort indoors. This method is also beneficial in cities with mild winters, such as Bakersfield (Bsh) and Sacramento (Csa).

Passive solar heating proves to be an efficient method for warming buildings during winter in regions like Phoenix (Bwh), Denver (Bsk), Bakersfield (Bsh), New York City (Cfa), Ketchikan (Cfb), Sacramento (Csa), Hillsboro (Csb), Jackson (Dfc), Chicago (Dfa), and Bangor (Dfb). This strategy works well in areas with abundant sunshine and clear skies during the winter, as cloud cover can significantly reduce the effectiveness of solar heating.

In cities like Miami and West Palm Beach, capturing internal heat plays a key role in enhancing thermal comfort during the cooler months, contributing to overall energy efficiency. During winter, this method can help expand the comfort zone beyond its usual boundaries. However, in the summer, high temperatures and humidity make it challenging to achieve comfort through passive design, necessitating the use of air conditioning to ensure indoor comfort.

3.3. Development of Passive Design Guidelines

Evaporative cooling is an age-old yet highly effective technique that utilizes the process of water evaporation to reduce indoor temperatures without relying on mechanical refrigeration. This method is commonly used in hot and dry climates to enhance comfort and improve energy efficiency. There are three primary forms of evaporative cooling:

1) **Mashrabiya:** A traditional feature in Islamic architecture, the mashrabiya is a wooden screen or window that offers shade, protection from the sun, and facilitates natural ventilation. It allows cool breezes to flow into the building, helping to lower indoor temperatures.
2) **Wind Towers:** Wind towers are an ancient passive cooling design that captures wind at different heights and directs it down into the building. As the wind passes through the tower, it moves over moist surfaces, causing evaporation. This process cools the air before it enters the living space, providing natural ventilation.
3) **Roof-Pond:** In this method, a shallow pond or water layer is created on the roof of the building. During the summer, the airflow over the pond causes evaporation, cooling both the pond and the roof structure. This cooling effect helps dissipate heat from the building interior, acting as a natural heat sink [15].

Mass and Night Ventilation (Mass + Night Vent) is a passive design strategy that utilizes the building's thermal mass to store and release heat, combined with nighttime natural ventilation to cool the interior. Below are six passive design methods that enhance the performance of the Mass + Night Vent system:

1) **Combined Wall-Roof Solar Chimney**: This method incorporates a vertical shaft linking the building's thermal mass with the roof. During the day, sunlight heats the air inside the chimney, causing it to rise and draw cooler air through the building. At night, the cooler air is drawn into the building through the bottom of the chimney, releasing the cool air stored in the thermal mass [16].
2) **Using Materials with Higher Densities**: Switching to materials with greater density increases the building’s thermal mass, which helps reduce peak indoor temperatures. Dense materials absorb heat during the day and release it slowly at night, contributing to thermal regulation [17].
3) **Reducing Window-to-Floor Ratio (WFR)**: Decreasing the window size helps lower peak indoor temperatures across all envelope materials, as smaller windows reduce the amount of heat entering during the day [17].
4) **Optimization of Window Shading Devices**: Shading devices are essential for preventing overheating during the day. They also allow for effective cooling through natural ventilation at night, helping maintain indoor comfort levels.

5) **Heavy Ventilated Internal Wall (HVIW)**: Incorporating a Heavy Ventilated Internal Wall increases the building’s thermal mass. This wall, when ventilated at night, helps lower room temperatures, enhancing the cooling effect [18].
6) **Building Materials with Phase Change Materials (PCMs)**: Integrating PCMs into building walls allows the material to absorb and store thermal energy during the day as it transitions from solid to liquid. At night, as the PCMs solidify, they release the stored heat, further aiding the building's cooling process [19].

The use of ceiling fans by building occupants can significantly improve thermal comfort and reduce the need for mechanical cooling systems. Several strategies can optimize ceiling fan performance:

1) **Optimization of Blade Geometry**: Research explored how the shape of the blades, along with the blade tip width and root and tip angles, influences performance. The study concluded that interactions between these design variables play a crucial role in the fan's effectiveness [20].
2) **Optimization of Winglet and Spike Geometry**: A study examined the airflow patterns created by ceiling fans and identified eight major flow regions. The findings suggested that improving the geometry of winglets and spikes could enhance fan performance by improving airflow dynamics [21].
3) **Avoiding Installation Near Obstacles**: To maximize airflow efficiency, it's essential to avoid placing the fan near obstacles. These obstructions can disrupt the airflow pattern, leading to uneven air distribution and reduced circulation efficiency.
4) **Optimizing the Position of Thermal Mannequins**: Study installing a ceiling fan above a person sitting at a desk can significantly improve thermal comfort. The airflow produced by the fan decreases as it nears the floor, and the layout of the thermal mannequin strongly affects internal airflow patterns. Thus, the relative position of the mannequin is critical in optimizing the fan's impact [22].
5) **Capturing Internal Heat**: Strategies to capture internal heat focus on enhancing the building's energy efficiency and thermal comfort by retaining heat generated inside. In modern, well-insulated buildings with high internal heat gains, there may be little need for additional heating, as the retained heat is often sufficient to meet demand [23]. Achieving this requires improving the building envelope’s insulation by using high-quality materials, increasing the thickness of the envelope to enhance thermal resistance, strategically placing windows to minimize heat loss while maximizing natural light, and implementing double-skin facades to improve insulation and regulate temperature.

Passive solar heating is a sustainable architectural strategy that leverages the sun’s energy to heat a building without relying on mechanical systems. Below are four key design strategies that enhance the effectiveness of passive solar heating:

Optimal Window Design: Lee et al. [24] investigated the impact of various window properties, such as U-value, solar heat gain coefficient (SHGC), and visible transmittance (Tvis), in relation to different window-to-wall ratios (WWRs) and orientations across various climate zones. The study provided guidelines for selecting appropriate window systems tailored to different climates.

1) **Solar Room with Phase Change Materials (PCMs)**: A solar room is designed to capture and store solar energy, providing heating for the building. To prevent overheating, PCMs are integrated for thermal storage. Research has shown that using PCMs on large surfaces within a passive solar building effectively stores solar energy and enhances thermal comfort. For instance, a PCM wall can absorb significant solar radiation, storing it for later use in heating and ventilation [19,25].
2) **Trombe Wall**: The Trombe wall is a passive solar heating system that involves an opaque wall exposed to direct sunlight, positioned between a glazing and the interior space. Solar energy passes through the glazing and is absorbed by

the wall, where it is converted to heat. This heat is then circulated into the living space via natural convection, with vents at the top and bottom of the thermal mass. The system works by storing heat and gradually releasing it, ensuring stable temperatures even when outside temperatures drop, thus providing efficient heating with minimal energy use [26].

3) **Barra-Costantini System**: This system, proposed by Barra and Costantini, combines a Trombe wall with air circulation through the ceiling. It acts as a natural temperature regulator by storing heat during the day and redistributing it in the evening. Research by Imessad, Messaoudene, and Belhamel [27] demonstrated the system's adaptability to Algerian climates.

The strategies discussed, along with their architectural implementations, are summarized in the table below, as depicted in figure 7.

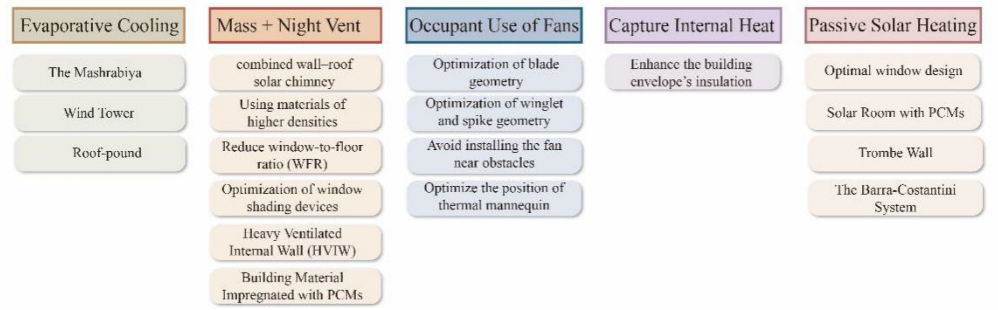


Figure 7. Design methods of passive strategies.

4. Conclusion

4.1. Theoretical Implication

This research explores the development of a theoretical model that uses a parametric platform to link geographical data with passive design strategies. Through a comparative analysis of 12 U.S. cities across different Köppen climate zones, the model incorporates environmental factors such as solar exposure, temperature, and humidity to create a data-driven method for optimizing energy efficiency and occupant comfort. By integrating these factors within a parametric framework, the design process becomes more streamlined, enabling the development of passive design solutions tailored to the unique conditions of each location. Additionally, the theoretical model offers an approach that can be easily incorporated into the design workflow. As a fast computational tool embedded in Rhino, Ladybug allows for the quick and efficient evaluation of passive design strategies from the early stages of the design process.

4.2. Managerial Implication

The managerial implications of this research are significant, providing practical guidance for architects and building managers. The findings suggest that evaporative cooling and the strategic use of fans are especially effective in arid, hot climates. For example, in Phoenix during the summer, the combination of evaporative cooling and fan use by occupants can maintain thermal comfort for 56.79% of the season. In Bakersfield, this approach could sustain thermal comfort for 40.85% of the summer. Thermal mass, coupled with night-time ventilation, proves advantageous in areas with large diurnal temperature variations. In Bakersfield's summer, this strategy could potentially ensure thermal comfort for about 24.64% of the period. In temperate climates, capturing internal heat is identified as a means to achieve thermal comfort. During Phoenix's winter, with an average temperature of 13.39°C, utilizing internal heat could provide thermal comfort for nearly half of the season. Passive solar heating is particularly effective in climates with abundant sunlight and cooler temperatures. However, in humid and hot climates, like those in Miami and West Palm Beach during the summer, relying solely on passive design for thermal comfort proves challenging and often necessitates the inclusion of active cooling solutions.

4.3. Limitation and Outlook

The passive design strategies suggested in this thesis, based on theoretical models and simulations from the climatic analysis tool Ladybug, require further empirical validation to confirm their practical effectiveness. This validation process should include in-depth case studies of buildings that have applied these measures, evaluating their performance using key metrics such as energy consumption, indoor environmental quality, and occupant satisfaction. Additionally, field testing could offer valuable insights into how these strategies perform under real-world conditions. Such empirical studies would not only validate the proposed measures but also highlight areas that may require further improvement.

References

1. P. Rohdin, A. Molin, and B. Moshfegh, "Experiences from nine passive houses in Sweden – Indoor thermal environment and energy use," *Build. Environ.*, vol. 71, pp. 176–185, Jan. 2014, doi: 10.1016/j.buildenv.2013.09.017.
2. E. Rodriguez-Ubinas et al., "Passive design strategies and performance of Net Energy Plus Houses," *Energy Build.*, vol. 83, pp. 10–22, Nov. 2014, doi: 10.1016/j.enbuild.2014.03.074.
3. E. Mushtaha et al., "The impact of passive design strategies on cooling loads of buildings in temperate climate," *Case Stud. Therm. Eng.*, vol. 28, p. 101588, Dec. 2021, doi: 10.1016/j.csite.2021.101588.
4. I. Ridley et al., "The monitored performance of the first new London dwelling certified to the Passive House standard," *Energy Build.*, vol. 63, pp. 67–78, Aug. 2013, doi: 10.1016/j.enbuild.2013.03.052.
5. H. Zhang, H. Wang, and X. Zhou, "Applicability research on passive design of residential buildings in hot summer and cold winter zone in China," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 61, p. 012066, Apr. 2017, doi: 10.1088/1755-1315/61/1/012066.
6. S. Diddi et al., "BEE_Handbook of Replicable Designs for Energy Efficient Residential Buildings.pdf."
7. M.-M. Fernandez-Antolin, J. Del Río, V. Costanzo, F. Nocera, and R.-A. Gonzalez-Lezcano, "Passive Design Strategies for Residential Buildings in Different Spanish Climate Zones," *Sustainability*, vol. 11, no. 18, p. 4816, Sep. 2019, doi: 10.3390/su11184816.
8. "WORLD MAPS OF KÖPPEN-GEIGER CLIMATE CLASSIFICATION." [Online]. Available: https://koeppen-geiger.vu-wien.ac.at/.
9. H. S. Bala, B. Li, and C. Du, "Bioclimatic design strategy in hot summer and cold winter region of China," *Int. J. Res. Appl. Sci. Eng. Technol.*, 2023, doi: 10.22214/ijraset.2023.57081.
10. J. C. Lam, L. Yang, and J. Liu, "Development of passive design zones in China using bioclimatic approach," *Energy Conversion and Management*, vol. 47, no. 6, pp. 746–762, 2006, doi: 10.1016/j.enconman.2005.05.025.
11. S. V. Szokolay, "Climate analysis based on the psychrometric chart," *Int. J. Ambient Energy*, vol. 7, no. 4, pp. 171–182, Oct. 1986, doi: 10.1080/01430750.1986.9675499.
12. E. Naboni, M. Meloni, S. Coccolo, J. Kaempf, and J.-L. Scartezzini, "An overview of simulation tools for predicting the mean radiant temperature in an outdoor space," *Energy Procedia*, vol. 122, pp. 1111–1116, Sep. 2017, doi: 10.1016/j.egypro.2017.07.471.
13. Y. I. Ibrahim, T. Kershaw, and P. Shepherd, "A methodology for modelling microclimate: A Ladybug-tools and ENVI-met verification study," in *Proceedings of the 35th PLEA Conference Sustainable Architecture and Urban Design*, A Coruña, Spain, 2020.
14. F. Manzano-Agugliaro, F. G. Montoya, A. Sabio-Ortega, and A. García-Cruz, "Review of bioclimatic architecture strategies for achieving thermal comfort," *Renew. Sustain. Energy Rev.*, vol. 49, pp. 736–755, Sep. 2015, doi: 10.1016/j.rser.2015.04.095.
15. O. Amer, R. Boukhanouf, and H. G. Ibrahim, "A Review of Evaporative Cooling Technologies," *Int. J. Environ. Sci. Dev.*, vol. 6, no. 2, pp. 111–117, 2015, doi: 10.7763/IJESD.2015.V6.571.
16. M. M. AboulNaga and S. N. Abdrabboh, "Improving night ventilation into low-rise buildings in hot-arid climates exploring a combined wall–roof solar chimney," *Renew. Energy*, vol. 19, no. 1–2, pp. 47–54, Jan. 2000, doi: 10.1016/S0960-1481(99)00014-2.
17. S. Amos-Abanyie, F. O. Akuffo, and V. Kutin-Sanwu, "Effects of Thermal Mass, Window Size, and Night-Time Ventilation on Peak Indoor Air Temperature in the Warm-Humid Climate of Ghana," *Sci. World J.*, vol. 2013, no. 1, p. 621095, Jan. 2013, doi: 10.1155/2013/621095.
18. G. Fraisse, K. Johannes, V. Trillat-Berdal, and G. Achard, "The use of a heavy internal wall with a ventilated air gap to store solar energy and improve summer comfort in timber frame houses," *Energy Build.*, vol. 38, no. 4, pp. 293–302, Apr. 2006, doi: 10.1016/j.enbuild.2005.06.010.
19. A. Pasupathy, R. Velraj, and R. V. Seeniraj, "Phase change material-based building architecture for thermal management in residential and commercial establishments," *Renew. Sustain. Energy Rev.*, vol. 12, no. 1, pp. 39–64, Jan. 2008, doi: 10.1016/j.rser.2006.05.010.

20. E. Adeeb, A. Maqsood, A. Mushtaq, and C. H. Sohn, "Parametric study and optimization of ceiling fan blades for improved aerodynamic performance," *J. Appl. Fluid Mech.*, vol. 9, no. 6, pp. 2905–2916, 2016, doi: 10.29252/jafm.09.06.25808.
21. A. Jain, R. R. Upadhyay, S. Chandra, M. Saini, and S. Kale, "Experimental Investigation of the Flow Field of a Ceiling Fan," in *Volume 3*, Charlotte, North Carolina, USA: ASMEDC, Jan. 2004, pp. 93–99, doi: 10.1115/HT-FED2004-56226.
22. S.-W. Hsiao, H.-H. Lin, and C.-H. Lo, "A study of thermal comfort enhancement by the optimization of airflow induced by a ceiling fan," *J. Interdiscip. Math.*, vol. 19, no. 4, pp. 859–891, Jul. 2016, doi: 10.1080/09720502.2016.1225935.
23. V. Lapinskienė, V. Motuzienė, R. Džiugaitė-Tumėnienė, and R. Mikučionienė, "Impact of Internal Heat Gains on Building's Energy Performance," in *Proceedings of 10th International Conference "Environmental Engineering"*, Vilnius Gediminas Technical University, Lithuania: VGTU Technika, Aug. 2017, doi: 10.3846/enviro.2017.265.
24. J. W. Lee, H. J. Jung, J. Y. Park, J. B. Lee, and Y. Yoon, "Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements," *Renew. Energy*, vol. 50, pp. 522–531, Feb. 2013, doi: 10.1016/j.renene.2012.07.029.
25. A. K. Z. M. I. Noor, A. Arif, and M. A. S. M. Zaki, "Optimization of building's windows design for tropical climate," *Energy Procedia*, vol. 105, pp. 1495–1500, 2017, doi: 10.1016/j.egypro.2017.03.407.
26. L. Finocchiaro, L. Georges, and A. G. Hestnes, "Passive solar space heating," in *Advances in Solar Heating and Cooling*, Elsevier, 2016, pp. 95–116, doi: 10.1016/B978-0-08-100301-5.00006-0.
27. K. Imessad, N. A. Messaoudene, and M. Belhamel, "Performances of the Barra–Costantini passive heating system under Algerian climate conditions," *Renew. Energy*, vol. 29, no. 3, pp. 357–367, Mar. 2004, doi: 10.1016/S0960-1481(03)00255-6.